INVESTIGATING CREATIVE AND DESIGN-ORIENTED PRACTICES IN K-12 ENRICHMENT COURSES

by

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A Dissertation

Submitted to the Faculty of Purdue University

In Partial Fulfillment of the Requirements for the degree of

Doctor of Philosophy

Department of Educational Studies

West Lafayette, Indiana

August 2020

THE PURDUE UNIVERSITY GRADUATE SCHOOL
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Dedicated to

my encouraging parents Mahin Amini and SahebAli Ghahremani

my wonderful, loving wife, Sareh Karami

my bouncing, energetic daughter Termeh Ghahremani

ACKNOWLEDGMENTS

I would have not been able to finish this dissertation without the kind support and help of many individuals in my life, to only some of whom it is possible to give particular mention here.

I would like to say thank you to my dissertation committee, first to my co-advisors, Dr. Gentry and Dr. Pereira. I would not have been able to finish this dissertation without your support and help, especially in terms of the valuable and constructive feedback I received. I learned so much from you during the past six years, and I do appreciate your professional manner and especially high expectations! And I am thankful for this learning opportunity.

Also, thank you to my other committee members, Dr. Olenchak and Dr. Traynor, for your time, flexibility, and supports. It was a pleasure having you on my committee and working with you. I was involved in two funded research, an NSF project and also my second PRF, because of Dr. Olenchak's support, and the collaborative atmosphere he created. Thank you so much! Thank you to Dr. Traynor for her availability, and for sharing her knowledge, and for all the great courses I took with her.

Thank you to my co-researchers, Dr. Ophélie Desmet; Zafer Ozen, and Aakash Chowkase. I hope we continue our collaboration. Thank you to Anne Gray, Corinne Green, Alisa Salazar, Andres Parra Martinez and all my GERI family, for all kind supports. I will miss you, especially during the summers.

Dr. Renzulli, Dr. Plucker, Dr. Ambrose, Dr. Robinson, Dr. Ziegler, Dr. Bosetti, Dr. Rogat, Dr. Milani, Dr. Pakpour, Dr. Tabatabaei Ghomi, I just wanted to write to let you know how much I appreciate the positive influence you have had on my life. Thank you for your concern and useful advice! Special thanks to the H-family—Hosein, Hoda, and Hadi—for their friendship and help!

And finally, my mother, Mahin Amini, and my father, SahebAli Ghahremani, I would not have been able to make it so far without your love, care, support, kindness, prayers, and generosity. Thank you for being there for me when I call you and need someone to pray for me. My beloved wife, my best friend, my love, Sareh Karami, for being such a great partner! I would never become who I am without you. And I hope we counite our partnership! Termeh, you have filled my life with pleasure and amusement and had spread so many colors around it. Thank you!

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ABSTRACT

This thesis is an article-based (3-paper format) dissertation. In the first article, the research team adapted an input-process-outcome (IPO) model of group-level processes in the classroom, as a theoretical framework, to examine students' experiences regarding pre-college engineering curricula, classroom environments, and their experiences with the creative process in the two engineering courses offered in a university-based summer enrichment program. Applying provisional and open coding to semi-structured interview data from 16 participants, an Input-Process-Outcome Model of Collaborative Creativity (IPOCC model) was developed. In this study, I grouped our findings under Inputs, Group Processes, Outcomes, and Mediating Factors. The IPOCC model expands the 4P model of creativity to incorporate more collaborative contexts. According to the 4P model, creativity can be viewed from four different perspectives: Person, Process, Product, and Press. The IPOCC model suggests that in K-12 collaborative practice, creativity involves group-level considerations in addition to individual-level components. The IPOCC model offer insights for educators in terms of input components, group processes, and mediating factors that can facilitate learners' engagement in creative teamwork. Findings of this study indicated that a combination of challenging tasks, open-ended problems, and student teamwork provides a rich environment for learners' engagement to think creatively.

The purpose of the second study was to systematically investigate how novice/K-12 students' visual representation of design ideas has been operationalized, measured, or assessed in the research literature. In the different phases of screening in this systematic review, inclusion, exclusion, and quality criteria were applied. From an initial sample of 958 articles, 40 studies were included in the final step of the coding process and qualitative synthesis. Applying provisional and open coding, three broad themes, and 23 characteristics were identified that have been used by researchers to conceptualize sketching of ideas, in novice/K-12 design activities: Communicating Ideas, Visual-Spatial Characteristics, and Design Creativity. We propose this Three-pronged Design Sketching (3-pDS) framework to examine K-12 design sketches.

In K-12 settings, one major challenge of conducting research on the influence of engineering education programs and curricula involves assessment. There is a need for developing alternative, effective, and reliable assessment measures to evaluate students' design activities. The third study aimed to address this need by developing the idea-Sketching Early

Engineering Design (i-SEED) Scale to assess pre-college learners' freehand sketches in response to a design task. Applying the Three-pronged Design Sketching (3-pDS) as a theoretical framework, the purpose of this study was to examine evidence of content validity, construct validity, and internal consistency of the i-SEED Scale data. The data collection took place in a residential summer enrichment program for students with gifts and talents at a Midwestern university. Following different stages of scale-development design, a sample of 113 design sketches were scored in this study, and the scores were used to provide evidence of the validity of the data for the i-SEED Scale. The sketches were generated by 120 middle- and high-school students in a collaborative design-oriented course. Exploratory factor analysis results supported a three-factor model for the i-SEED Scale, including Visual-Spatial Characteristics, Design Creativity, and Communicating Ideas.

CHAPTER 1: INTRODUCTION

This thesis is an article-based (3-paper format) dissertation. In this chapter, I will describe the purpose and nature of each three articles and the scholarly importance of these studies. This research was part of a larger project focusing on implementing creativity development in summer enrichment courses and engineering outreach programs. This project was funded by a Purdue Research Foundation (PRF) research grant during the 2016-2107 academic year.

First Article: An IPO Model of Collaborative Creativity

In this qualitative inquiry, the research team adopted an Input-Process-Outcome (IPO; Webb & Palincsar, 1996) model of group-level processes in the classroom, as a theoretical framework, to examine students' experiences regarding pre-college engineering curricula, classroom environments, and their experiences with the collaborative creative process in the two engineering enrichment courses. The purpose of this study was to develop an IPO model to conceptualize middle- and high-school students' experience regarding collaborative creativity in the context of engineering practices. The IPO framework provides a tool for categorizing and integrating components of group-level factors. Similar to many other qualitative types of research in the social sciences, semi-structured interview data formed the empirical backbone of this inquiry (Campbell et al., 2013; Saldaña, 2013).

This study took place at a residential summer enrichment program for students with gifts and talents at a Midwestern university in July 2017. In this summer residential camp, students who have had completed grades 5 through 12 took challenging courses in different areas of their interest. This study focused on the two courses, STEAM Labs and Toy Design, which emphasized engineering design activities and building prototypes. Sixteen middle- and high-school students (grades 7-11; including nine boys and seven girls) from diverse ethnic backgrounds, who were enrolled in these two courses, participated in this study and interviews. The interview transcriptions were coded using NVivo software. Following Creswell's (2012) description of the inter-coder agreement process, we sought to develop a codebook that would be appropriate for our data analysis and to establish an inter-coding agreement higher than 80%. The initial codebook was based on Treffinger et al.'s (2013) framework of creative behaviors.

This initial codebook that served as a *start list* (Saldaña, 2013) gradually evolved during the process of open coding. After coding all of the transcripts and initial analysis of the data, I decided that applying an IPO model would be an appropriate way to present the results. Grouping different categories under Inputs, Group Processes, Outcomes, and Mediating Factors resulted in developing the IPO Model of Collaborative Creativity (IPOCC model). This study is presented in Chapter Two.

Second Article: Three-pronged Design Sketching (3-pDS) Framework

In the first study, participants mentioned a range of learning-related outcomes as a result of their joint creative endeavors in design-oriented activities, including a better understanding of the engineering and engineering design process. Regarding the engineering design process, nine out of sixteen students addressed learning idea-sketching and drawing abilities, as an important skill in the design visualization. This area was the focus of the second and third studies. The purpose of the second study was to systematically examine how novice and K-12 students' visual representation of design ideas has been operationalized, measured, or assessed in the research literature. The research question guided this study was: *What research and evaluation methods, coding protocol, or criteria had been used to study novice and K-12 visual representation of a design (e.g., sketches)?* In this systematic review of design studies, I considered articles within three disciplines: Education, Mechanical Engineering, and Engineering Education.

I followed steps suggested by Borrego et al. (2014) for systematic reviews in engineering education and other developing interdisciplinary fields, which include (a) deciding to conduct a systematic review; (b) identifying the scope and research questions; (c) defining inclusion/exclusion criteria; (d) finding and cataloging sources; (e) critique and appraisal; (f) coding process and qualitative synthesis; and (g) presenting the results. I applied our inclusion/exclusion criteria to the initial sample of 958 articles in different phases of screening, which resulted in the inclusion of 40 studies in the final step of the coding process and qualitative synthesis. Applying provisional and open coding, three broad themes and 23 characteristics were identified that have been used by researchers to conceptualize sketching of ideas, in novice and K-12 design activities. Based on these emergent themes, we propose the Three-pronged Design Sketching (3-pDS) framework to examine K-12 design sketches. This study is presented in Chapter Three.

Third Article: Towards Informed Design Sketching

In K-12 settings, one major challenge in researching the influence of engineering education programs and curricula involves assessment. There is a need for developing alternative, effective, and reliable assessment measures to evaluate students' design activities. This study aimed to address this need through developing the idea-Sketching Early Engineering Design (i-SEED) scale to assess pre-college learners' free-hand sketches in response to a design task. We followed different stages of scale-development design, suggested by DeVellis (2017) and McCoach et al. (2013), including generating an item pool, selecting a scaling format, obtaining expert review, conducting a pre-pilot study, analyzing data, and revising the instrument based on results. The following research questions guided this research: (1) What content validity evidence exists from the data used to develop the i-SEED scale? (2) What construct validity evidence exists from the data used to develop the i-SEED scale? (3) What internal consistency evidence exists from the data used to develop the i-SEED scale?

The Three-pronged Design Sketching (3-pDS) framework served as the theoretical framework of the i-SEED scale development. This framework was developed through a systematic literature review in the second study. I generated the initial item pool based on the 23 characteristics that were identified in the systematic review of design studies. To evaluate sketching quality, we used a common 5-point Likert-type measure to develop a closed-form multi-item scale (McCoach et al., 2013). Additionally, we designed a Content Validity Form for our scale and sent the form to 15 experts to examine the validity evidence of the items' content.

The data collection took place in a residential summer enrichment program for students with gifts and talents at a Midwestern university. The research team scored a sample of 113 design sketches generated by 120 middle- and high-school students in a design-oriented course and used these scores to develop our scale. The research team used a modified version of the Consensual Assessment Technique (Amabile, 1982, 1983, 1996; Baer & Kaufman, 2019) for scoring sketches. After the rating phase, the scores were checked for the assumptions required of multivariate statistical techniques, specifically for exploratory factor analysis, such as adequate sample size, factorability of the variables, multicollinearity, and normality. Then, I proceeded to conduct exploratory factor analysis (EFA) to provide evidence of the construct validity and the initial factor structure of the data used in developing the i-SEED scale. Through this scale-development study, I provided evidence of content validity, construct validity, and internal consistency of the data we used to develop the i-SEED scale.

Scholarly Significance of these Studies

Over the past decade, national-level K-12 standards and curriculum have focused on adding engineering design to their vision for STEM and science education. For example, the *Framework for K–12 Science Education* (National Research Council, 2012), the *Next Generation Science Standards* (NGSS Lead States, 2013), and *STEM Integration in K-12 Education* (National Academy of Engineering, 2014) included engineering design and practices as an important element in their current vision for K-12 education. Engineering design activities are suitable and effective ways to infuse innovation and creative thinking into the curriculum, as design-based challenges inherently allow for creativity (Darbellay et al., 2017; Cropley, 2015; Hathcock & Dickerson, 2017).

The several required characteristics of design-based engineering practice are a natural fit for many students with gifts and talents (Mann et al., 2011; Robinson, 2017). Robinson stated, "The engagement of learning in science and the creativity in engineering design are enviable matches to the characteristics and needs of talented children in the early years of school" (p. 28). Engineering design-based challenges can provide appropriate opportunities to engage students in creative-thinking processes, which has long been associated with gifted education (Hathcock & Dickerson, 2017). Creativity is one of the key aspects of giftedness and talent development (Dai, 2010; Davis et al., 2011; Callahan & Hertberg-Davis, 2013; Sternberg et al., 2011).

As many outreach programs have demonstrated, engineering education has enormous potential to increase conceptual understanding of Science, Technology, Engineering, and Mathematics (STEM) disciplines for students (Brophy et al., 2008; Crismond & Adams, 2012), and has promoted as pedagogical support for learning scientific content (McFadden & Roehrig, 2019). Specifically, engineering design is considered as a *central piece* (NRC, 2011) for K-12 learners, as it provides students with domain-specific disciplinary engagement intended to mirror engineering practice (NGSS Lead States, 2013). Design experiences play a substantial role in pre-college students' STEM education and career preparation (Crismond & Adams, 2012; Kelley & Sung, 2017). Design-oriented practice activates higher-order thinking skills (McFadden & Roehrig, 2019) that enable learners to analyze, evaluate, and make decisions during the design process (Fan & Yu, 2017). Idea-sketching is a fundamental area of design (Booth et al., 2016; Crismond & Adams, 2012) that includes brainstorming, documenting ideas, and communicating ideas to others (Cardella et al., 2006; Jordan et al., 2016; Kelley & Sung, 2017).

However, little empirical research exists on how students learn to apply their knowledge and abilities through collaborative design (Purzer et al., 2015). Although design practices increasingly play a key role in engineering education within K–12 settings, there are few inquiries to purposefully link research findings on how pre-college students design and what educators need to improve K–12 learners' design skills (Crismond & Adams, 2012). These three studies aimed to investigate K-12 collaborative design-oriented practices and to provide insights into the research and curriculum development to nurture engineering talent in K-12 formal settings and non-formal enrichment programs.

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CHAPTER TWO. STUDENTS' EXPERIENCES IN SUMMER ENRICHMENT ENGINEERING COURSES: AN INPUT-PROCESS-OUTCOME MODEL OF COLLABORATIVE CREATIVITY

Abstract

The logical dependency of engineering on creative thinking is self-evident in the design focus of engineering activities. In this study, the research team adapted an input-process-outcome (IPO) model of group-level processes in the classroom, as a theoretical framework, to examine students' experiences regarding pre-college engineering curricula, classroom environments, and their experiences with the creative process in the two engineering courses offered in a university-based summer enrichment program. Applying provisional and open coding to semi-structured interview data from 16 participants, an Input-Process-Outcome Model of Collaborative Creativity (IPOCC model) was developed. In this study, I grouped our findings under Inputs, Group Processes, Outcomes, and Mediating Factors. The IPOCC model expands the 4P model of creativity to incorporate more collaborative contexts. According to the 4P model, creativity can be viewed from four different perspectives: Person, Process, Product, and Press. The IPOCC model suggests that in K-12 collaborative practice, creativity involves group-level considerations in addition to individual-level components. The IPOCC model offer insights for educators in terms of input components, group processes, and mediating factors that can facilitate learners' engagement in creative teamwork. Findings of this study indicated that a combination of challenging tasks, open-ended problems, and student teamwork provides a rich environment for learners' engagement to think creatively.

Creativity, innovation, strong analytic aptitude, cooperation, and excellent technical knowledge have often been described as essential elements of engineering (Fromm, 2003). These traits allow engineers to design new technologies and solve society's biggest problems. Thus, the logical dependency of engineering on creative thinking is self-evident in the design focus of engineering activities (Daly et al., 2014). However, limited research exists on curricula connecting engineering and creativity. For instance, Kazerounian and Foley (2007) found that students in the engineering field do not feel that their instructors valued thinking creatively. Therefore we adopted an input-process-outcome (IPO; Webb & Palincsar, 1996) model of group-level processes in the classroom as a conceptual framework to examine students' experiences regarding pre-college engineering curricula, classroom environments, and their experiences with the collaborative creative process in two engineering enrichment courses.

Literature Review

Defining Creativity

Creativity is a complex and multi-faceted concept defined in many ways. For example, Rhodes (1961) reviewed the creativity literature and developed the Four P's Model of Creativity, which divides creativity into four parts: person, product, process, and press (i.e., environment). Later Torrance (1974) defined creativity as:

> A process of becoming sensitive to problems, deficiencies, gaps in knowledge, missing elements, disharmonies, and so on; identifying the difficulty; searching for solutions, making guesses, or formulating hypotheses about the deficiencies; testing and retesting these hypotheses and possibly modifying and retesting them; and finally communicating the results. (p. 8)

More recently, Plucker et al. (2004) defined creativity as, "…the interaction among aptitude, process, and environment by which an individual or group produces a perceptible product that is both novel and useful as defined within a social context" (p. 90). This definition aligns with what Runco and Jaeger (2012) identified as the two standard criteria of creativity: originality (often referred to as novelty) and effectiveness (often referred to as usefulness). However, by adding the element of context, Plucker et al. (2004) accounted for domain-specific differences in creativity. We explored a variety of definitions, but we believe that the definition of creativity by Plucker et al. (2004) accounts for multiple aspects of the previously mentioned definitions, and therefore, in this study, we will follow Plucker et al. (2004) definition of creativity.

Fostering Creative Behaviors

Lee and Kemple (2014) proposed a model including nine creativity-fostering behaviors for teachers, such as probing students' ideas to encourage flexibility, providing students with the creative opportunity, and encouraging student judgement of their ideas and work. Sternberg (2003) also discussed the importance of stimulating students to create, invent, discover, explore, imagine, and suppose. Educators should encourage confidence and risk-taking (Nickerson, 2000; Starko, 2014) and provide adequate levels of challenge to increase students' engagement in learning activities (Brophy, 2004; Csikszentmihalyi, 1990; Laevers et al., 2006; Lietaert et al., 2013) and their chances of reaching flow—a mental state of complete absorption in the current experience (Csikszentmihalyi, 1990). Research also indicates the effectiveness of encouraging self-reflection or self-evaluation in students to stimulate creativity (Soh, 2000; Treffinger et al., 2002). All these characteristics of a creative environment combined will help create an environment in which creativity is welcomed and stimulated.

Engineering Design Process and Creativity

Engineering can be described as an exercise in creative problem solving (Cropley, 2015a). To solve problems, engineers follow the engineering design process, which includes a series of steps guiding people through the process of designing creative solutions to problems. There are numerous variations of the engineering design process. In this study, we used the engineering design process, as described by the Boston Museum of Science (2009), which has five steps. The first step is to *ask*, which involves defining the problem and constraints; the second step is to *imagine* or brainstorm possible solutions; step three is to *plan* the steps and materials needed to create the final product; step four, *create*, involves creating the product (e.g., building a machine); and the final step is to *improve* and reflect on the final product and think of what worked well, what did not work, and what can be improved (Engineering is Elementary [EiE] Project, Boston Museum of Science, 2009). The engineering design process requires creative thinking skills during each step of the process.

As creativity is defined by the production of something novel and useful, creative thinking plays a vital role in the engineering design process. It is through creative design and creative thinking processes that engineers are able to come up with novel and useful solutions for problems (Charyton & Merrill, 2009; Cropley, 2015a; Daly et al., 2014). Essentially, engineers combine convergent and divergent thinking skills in the creation of their products and ideas (Cropley, 2015b). The recent move toward Science, Technology, Engineering, Art, and Mathematics (STEAM) is one way to emphasize the need for creative problem-solving skills and interdisciplinary approaches in the STEM fields (Blashki et al., 2007). However, fostering creativity in engineering education is still not a priority due to the specialized nature of engineering degrees and the focus on convergent thinking and factual knowledge (Cropley, 2015b). Further, to prepare students for real-world engineering challenges, there is a need to ensure they have appropriate collaboration skills and the ability to perform in teams (Jordan et al., 2016; Juhl & Lindegaard, 2013) that involve collaborative ideation and communicating ideas within and across teams (Capobianco et al., 2011).

Collaborative Creativity

Creativity scholars highlighted the sociocultural and collective aspects of creativity (Sawyer, 2012; Sawyer & DeZutter, 2009). Miell and Littleton (2004) discussed a range of issues related to collaborative creativity, including the perception of creativity and creative problem solving as naturally social and communal processes and specific aspects affecting group work. O'Hear and Sefton-Green (2004) emphasized collaboration is crucial to creative achievements. In the same view, Ivinson (2004) suggested all creative endeavors involve some collaborative procedure that may include idea-extensions, the influence of role models, and the use of traditional skills in cultural systems. Wirtanen and Littleton (2004) emphasized creative behaviors need to be considered within the framework of relationships embedded within the social and cultural context. Collaborative relationships are vital when focusing on the creative process in particular (Miell & Littleton, 2004).

Relationships between and among members of a collaborative group and the context are important factors affecting the generation of novel ideas (Wirtanen & Littleton, 2004; Searle, 2004). Chan (2013) suggested a key factor in a supportive classroom atmosphere for creative knowledge co-construction is shifting the focus from task-based to idea-centered approaches and giving a central role to students' idea-generation. Bryan (2004) also suggested the process of creative collaborations necessitates modeling, practicing, and nurturing. Therefore, teachers may scaffold the idea-development processes, problem-centered collaborations, and productive queries to improve ideas and artifacts (Chan, 2013).

The Complex Instruction Approach is one of the instructional methods designed to promote collaborative creativity. The Complex Instruction Approach was initially developed to promote equity in cooperative learning classrooms (Cohen et al., 1994). This approach facilitates higher-order thinking in heterogeneous classrooms and advocates for multiple ability treatment and multidimensional activities; high cognitive demand; classroom environments that encourage hard-working and effort; and open-ended challenges (Boaler & Staples, 2008; Cohen & Lotan, 2014). Tomlinson (2018) stated that Complex Instruction Approach is appropriate for "(a) challenging advanced learners, (b) discovering and nurturing capacity in students who may not be readily identified as highly able, (c) supporting equity of access to excellence, (d) promoting complex thinking, (e) building community, and (f) engaging students with important ideas and skills" (p. 8). Additionally, university-based outreach and enrichment programs are one of the important settings to engage K-12 learners in these areas of collaborative creativity (Brophy et al., 2008; Subotnik et al., 2011).

University-based Enrichment Programs for Gifted Learners

Enrichment is an umbrella term used to characterize a category of educational programming that expands and enhances the general curricula and often focus on areas not typically covered in the standard curriculum and general education classrooms (Adams & Pierce, 2008; Coleman & Cross, 2005; Gavin & Adelson, 2008; Reis, 2008; Reis & Renzulli, 2010; Subotnik et al., 2011). The goal of enrichment courses is to provide students with opportunities to engage with a topic or an area of human endeavor in more depth than they probably would in a regular school setting (Kim, 2016). Enrichment is the most common programming strategy for high-ability students, and it could potentially benefit all students (National Association for Gifted Children, 2013; Olszewski-Kubilius, 2003; Robinson et al., 2007; Subotnik et al., 2011).

Many researchers have found that enrichment courses have positive cognitive, socioemotional, and attitudinal effects on students with gifts and talents (e.g., Gubbels et al., 2014; Hodges et al., 2017; Kim, 2016; Kulik & Kulik, 1984). Benefits of summer enrichment programs specifically include social support for learning and achievement; differentiation and suitable level of challenge and pace; familiarity with university programs; development of independence and life skills (in residential programs); increased academic and social risk-taking; improved self-concept and self-esteem; and improved openness and cultural awareness (Davis et al., 2011; Olszewski-Kubilius, 2003). Jen et al. (2017) also provided evidence that a diverse, university-based summer residential enrichment program was beneficial to high-ability students in terms of their short- and long-term social and emotional development. Through content analysis of qualitative data from a university-based enrichment program, Altan and Tan (2020) revealed middle-school learners' creative ideas were influenced by several factors, including exposure to other students' ideas, prior knowledge of the design-based learning process, and creating prototypes of their ideas. Aranda et al. (2020) suggested working in design teams requires creative thinking to harmoniously balance several design components, such as design limitations, requirements, individual experiences, and content knowledge.

Conceptual Framework: IPO Model of Collaboration

The Input-Process-Output (IPO) framework has attracted considerable attention and has been applied in several knowledge domains such as computer science, business management, engineering, and mathematics. For example, through a bibliometric review of a decade of research (2002-2015) on collaborative networks, Appio et al. (2017) explored the application of the IPO framework. They found 83 articles from different disciplines, including computer science; business management and accounting; engineering; mathematics; arts and humanities; economics and finance; psychology; and social sciences, that have been systematically included an Input-Process-Output (IPO) framework in their studies.

In Education, one of the most-cited works on the IPO model is Webb and Palincsar's (1996) theoretical framework, in which they developed and proposed an IPO model to represent factors for consideration in collaborative group activities. In this framework, the input characteristics "…suggest the great variety of ways in which structuring groups and group work have influenced group processes" (p. 851). Webb and Palincsar included several input factors in their model, such as a reward structure, group composition, group size, preparation for group work, and structuring teachers' role. They also included four sub-categories of group processes: conflict and controversy; co-construction of ideas; giving and receiving help; and socioemotional processes. These processes influence a variety of outcomes in teamwork, such as achievement, conceptual development, and socio-emotional variables. Finally, their model also included the mediating processes, which indirectly affect how group processes operate in the classroom.

Hülsheger et al. (2009) applied a general IPO framework to examine 15 group-level variables and their relation to creativity. Regarding *input* variables, they found task-relevant diversity, task interdependence, goal interdependence, group size, and group longevity were positively related to creativity, whereas, background diversity (including non-task-related differences such as age, gender, or ethnicity) was negatively related to creativity. For group *process* variables, Hülsheger et al. (2009) found that vision, participative safety, support for innovation, task orientation, cohesion, internal communication, external communication, and task conflict were positively related to creativity; whereas, relationship conflict was negatively related to creativity. Their results suggest that group *Process* variables of support for creativity, vision, task orientation, and external communication demonstrated the strongest relationships with creativity.

The IPO framework has been the dominant theoretical framework applied in inquiries on co-located team activities (Hoch & Kozlowski, 2014), and it provides a tool for categorizing and integrating characteristics of group-level factors. Thus, in this study, we adopted Webb and Palincsar's (1996) theoretical framework, to develop an IPO model of collaborative engineering for K-12 students' creative endeavors in their enrichment courses.

Purpose

In this inquiry, we examined students' experiences with the creative process in two engineering courses offered in a university-based summer enrichment program. The purpose of this study was to develop an IPO model to conceptualize collaborative creativity. This study was part of a larger longitudinal research project focusing on creativity-development strategies in university-based engineering enrichment courses.

Method

Semi-structured interview data form the empirical backbone of much qualitative research in the social sciences (Campbell et al., 2013; Saldaña, 2013). I explored high-ability, middle- and high-school students' experiences with the collaborative creative process in two engineering enrichment courses using interview data. Through content analysis, we examined interview transcripts. As Patton (2015) defined, "…more generally, content analysis refers to any qualitative data reduction and sense-making effort that takes a volume of qualitative material to identify core consistencies and meanings" (p. 541). The following research question guided this inquiry: What are the components of an IPO model to represent students' experiences with engineering enrichment courses, regarding group-level indicators of creative-thinking processes in teamwork activities?

Context

This study took place at a residential summer enrichment program for students with gifts and talents at a Midwestern university in July 2017. Students come from across the U.S., typically 25 states and four Native American reservations, and from around the world (e.g., China, Colombia, Kingdom of Saudi Arabia, South Korea). To ensure international students had no problem understanding the instruction, university students frequently served as interpreters.

Students who had completed grades 5 through 12 lived in campus residence halls and took challenging courses in areas of their interest. A typical daily schedule during the program included morning and afternoon classes, recreational activities, small-group affective discussions, recreational evening activities, and personal time. Our study focused on the STEAM Labs and Toy Design courses, which emphasized engineering design and building. These courses included a series of instructional units integrating STEM topics, including understanding energy concepts and electronics; engineering design; storytelling; and calculating probabilities. Classroom activities mirrored processes used by engineers to design and iterate in the real world, requiring the use of creativity in their day-to-day tasks, such as finding innovative solutions within the constraints provided by customers. Thus, the curriculum provided an authentic context for participants to learn about and apply the engineering design process and reinforced physics concepts previously learned at their schools, such as force, Newton's laws of motion, gravity, conservation of energy, and potential-kinetic energy conversions.

The *STEAM Labs* course included an introduction to the engineering design process and modules on a variety of science, physics, and mathematics topics, such as simple machines, energy transfer, and probability. Students in that course designed and built chain reaction machines. The *Toy Design* course included several modules related to engineering and physics and engineering design challenges, such as creating robots from recyclable materials.

Participants

Sixteen students (grades 7-11; including nine boys and seven girls) from diverse ethnic backgrounds, who were enrolled in the two courses, agreed to participate in this study. The participants' demographic information is presented in Table 1. These students provided two types of evidence of talent in their area of intended study (e.g., transcript with a grade point average at or above 3.5/4.0; minimum ability test score; achievement or aptitude test result at or above the 90th percentile; recommendation letters, awards, or certificates of involvement in the talent area) as part of their application materials. Additionally, all camp applicants submitted an essay or an alternative media statement addressing their desire and motivation to participate in the summer program and take their selected course. Participants selected the courses when they registered for the summer program.

Table 1 Participants' Demographic Information

Pseudonyms	Gender	Grade	Ethnicity
Aaron	Male	7th	Black
Alex	Male	7th	Latinx
Fiona	Female	7th	White
Henry	Male	8th	White
Kai	Male	7th	White
Kate	Female	7th	Latinx
Kian	Male	7th	White
Natalie	Female	8th	Latinx
Owen	Male	7th	Latinx
Rose	Female	10th	White
Rowan	Male	7th	[no answer]
Sarah	Female	11th	Latinx
Sarina	Female	7th	White
Sophia	Female	8th	White
Timon	Male	7th	Black
Yusef	Male	7th	[no answer]

Interview Protocol Development

To develop our interview protocol, we followed Patton's (2015) recommendations on a qualitative interview, including (a) establish trust and rapport; (b) ask meaningful, open-ended questions; (c) ask clear, neutral, singular, and focused questions; (d) begin with noncontroversial easy-to-answer questions; (e) and provide the interviewee with an opportunity to have the final say in the closing question. As suggested by Creswell (2012), we used probes and follow-up questions to obtain response clarity and additional information. Additionally, as Patton (2015) suggested, we included role-playing and simulation questions to engage interviewees, such as *Suppose I was a new student in this course, and I did not know anything about what goes on around here. What would you tell me?*

Before the first interview, the research team had meetings to discuss and finalize the interview protocol (see Appendix A). The research team included 10 questions. As Patton (2015) suggested, all questions that were included in the interview protocol are open-ended questions. Additionally, follow-up questions were included to probe incomplete responses. The first question in the interview protocol and its follow-ups included as a noncontroversial easy-to-answer question to establish trust and rapport. The following questions were included to explore interviewees' experience regarding their enrichment engineering courses and the development of creativity in their design-oriented hands-on activities. Additionally, as suggested by Patton (2015), these questions were in the form of *presupposition questions* that, "…creates rapport by assuming shared knowledge and assumptions […] and bypasses initial step by asking directly for description rather than asking for an affirmation of the existence of the phenomenon in question" (p. 459-460). For example, we used this presupposition format in the fourth question: *What aspects of this course have had the greatest impacts?* See other questions in Appendix A.

Moreover, Patton (2015) introduced six types of qualitative interview questions, including Experience and Behavior; Opinion and Values; Feeling; Knowledge; Sensory; and Background and Demographic questions. In finalizing the interview protocol, the research team attempted to cover these question types, except for the last one. The background and demographic information were gathered in the course registration process. For example, the follow-up question that *If I had been in this course with you, what would I have seen you doing?* was included to address Sensory experience. The last three questions (8, 9, and 10) were included to specifically probe interviewees' perceptions of creativity and engineering and their relationship. Finally, a closing question was included as an opportunity to add further comments. The research team checked the wording of the questions to make sure the questions are appropriate and clear for this age group. The interview protocol is presented in Appendix A.

Data Collection

We conducted one-on-one qualitative interviews, applying a standardized open-ended approach (Johnson & Christensen, 2012), in which all interviewees were asked the same basic questions with the same words in the same order (Creswell, 2012). As Patton (2015) mentioned, "In team research, standardized interviews ensure consistency across interviewers" (p. 440). We collected consent and assent forms before the camp started. The interviews took place in the residence hall, where the students resided while at the camp. The research team scheduled the interviews in collaboration with the camp counselors. Three members of the research team interviewed the sixteen participants, who were randomly assigned to one of the three interviewers. The interviews were recorded, and the third author transcribed them. The interviews required from 12 to 21 minutes, with an average of 18 minutes.

Data Analyses

Following Creswell's (2012) description of the inter-coder agreement process, we sought to develop a codebook that would be appropriate for data analysis. To achieve this, we examined the literature to explore previous research on developing creative behavior and assessing the creativity-fostering curriculum. Specifically, we focused on peer-reviewed journals in the fields of creativity and gifted and talented studies (i.e., *Journal of Creative Behavior, Creativity Research Journal*, *Gifted Child Quarterly*, *Gifted and Talented International*, *Roeper Review*, and *Journal for Advanced Academics*). We read through several peer-reviewed articles and examined different theoretical frameworks of creativity. We adopted the definition of creativity proposed by Plucker et al. (2004) for the characteristics that we planned to assess: "…the interaction among aptitude, process, and environment by which an individual or group produces a perceptible product that is both novel and useful as defined within a social context" (p. 90). We also adapted the framework developed by Treffinger et al. (2013) to create our initial codebook. We chose components and characteristics based on their appropriateness for the definition and the setting in a summer enrichment program with STEM-related courses. This initial codebook served as a start list for our provisional coding (Saldaña, 2013) of the interview transcripts. This initial codebook is presented in Table 2. We modified this codebook to develop our IPO model.

Table 2 List of Provisional Coding

Categories of Creativity Indicators	**Codes**			
Generating Ideas	Fluency	Flexibility	Originality/Novelty	Elaboration
Digging Deeper into Ideas	Analyzing	Synthesizing	Evaluating	Seeing Relationships
Openness and Courage to Explore Ideas	Problem Sensitivity	Aesthetic Sensitivity	Fantasy & Imagination	Open-ended Question/Project
Resolution	Adequate & Appropriate	Complexity		
Potential Evidence of Curriculum Effectiveness	Challenging Environment	Motivation and Engagement	Encouraging Environment	Self-reflection

Coding procedure and Inter-coder Reliability

We used NVivo 12 Pro software and followed Creswell's (2012) guidelines for establishing inter-coder reliability (ICR). As Creswell (2012) suggested, we sought to establish an inter-coding agreement of 80%. We used Cohen's kappa for ICR, which attempts to measure agreement between coders accounting for chance agreement (MacPhail et al., 2016). Burla et al.

(2008) suggested kappa values of 0.40–0.60 as satisfactory agreement and values greater than 0.80 as excellent agreement.

For the first round of coding, two of the authors independently coded the same three transcripts (approximately 19% of the data), using provisional coding. Provisional coding is an exploratory method that begins with a *start list* of researcher-generated codes based on what preliminary inquiry suggests might appear in the data before they are examined (Saldaña, 2013). Additionally, we applied open coding in the first round of coding to remain open to new patterns in the data (Charmaz, 2006). The coders agreed to use a sentence as the smallest unit of analysis for the coding process (Campbell et al., 2013).

After the first round of coding, we met to check for agreement and to discuss new categories of codes identified during the open coding but did not reach an appropriate level of agreement. Thus, we completed the second round of coding on the same subset of data following a similar approach, after which we revised the initial codes, removing ten codes, merging four codes, and adding three categories (Engagement, Learning, and Reason for Choosing the Class), based on the emergent codes. For the third round of coding, we applied revised codes to the three transcribed interviews. After the third round of coding, we discussed coded pieces of the transcripts with kappa values less than 0.70 to establish an appropriate ICR agreement. Our ICR agreement ranged from 81% to 100%. Thus, we finalized our codebook for the interview data, and the first author then used the final codebook to code all 16 interview transcripts.

Results and Discussion

Results are presented first by introducing the Input-Process-Outcome Model of Collaborative Creativity. Then, we detail our coding and the four major areas in this IPO model, including Inputs, Group Processes, Outcomes, and Mediating Factors, derived from our data.

Input-Process-Outcome Model of Collaborative Creativity: IPOCC Model

Through content analysis of the interview transcripts, we explored group-level features, processes, and predictors of innovation and creativity in the students' experiences. Applying a general input–process–output (IPO) model, we examined different group-level variables and their relation to collective creativity in these learners' experiences in the context of enrichment courses. Figure 1 illustrates our proposed IPOCC model in the context of pre-college engineering practices. Our initial codebook was an adaption of Treffinger et al.'s (2013) framework (Table 2), which gradually evolved during the process of open coding. After coding all of the transcripts and initial analysis of the data, we decided that applying an IPO model would be an appropriate way to present the results.

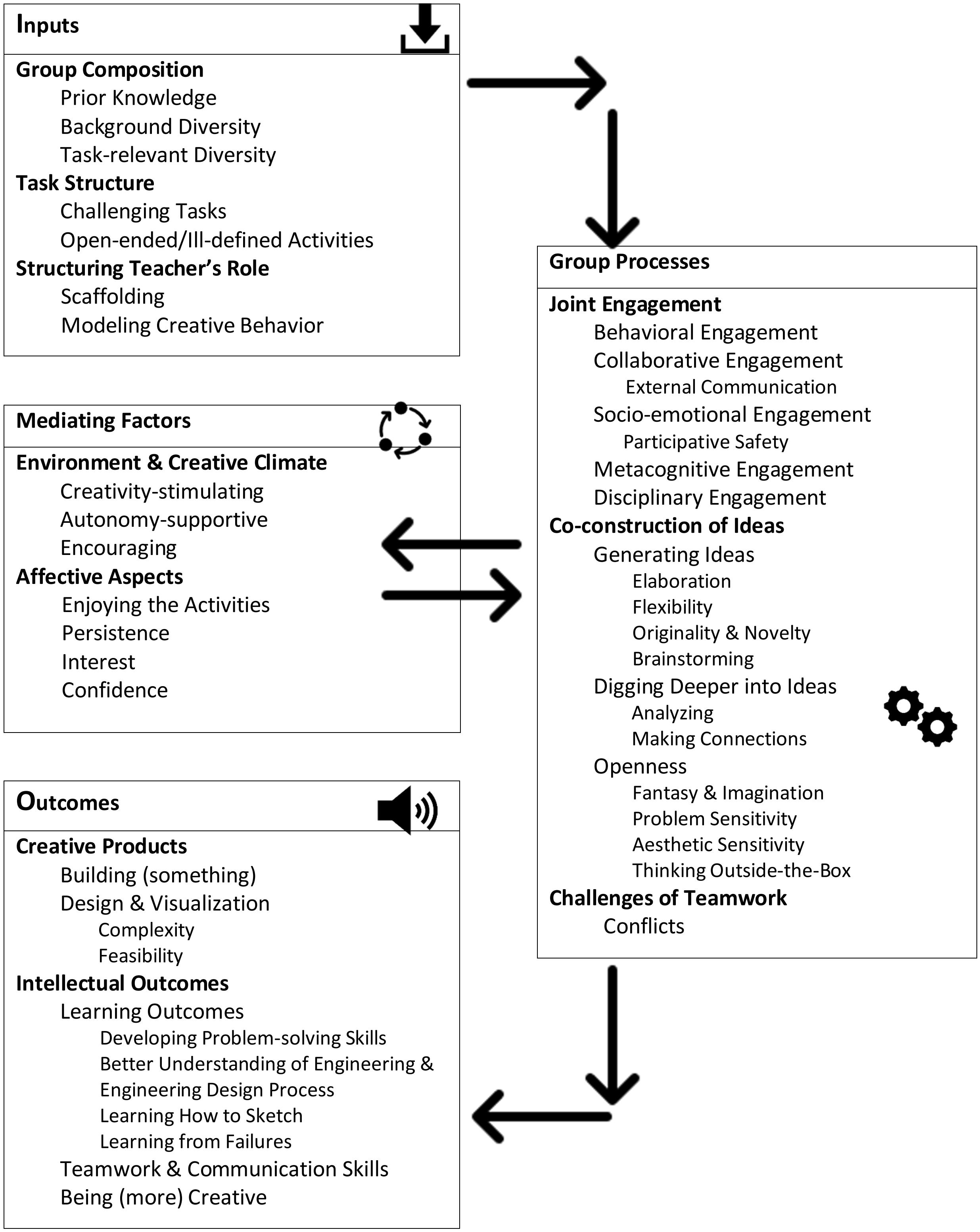

Figure 1 Input-Process-Outcome Model of Collaborative Creativity (IPOCC model) Representing Students' Experience Regarding Development of Creativity in Enrichment Engineering Courses

In this proposed IPOCC model, we adopted the framework suggested by Webb and Palincsar (1996) and grouped our findings under Inputs, Group Processes, Outcomes, and Mediating Factors. Under each of these areas, we found and categorized different components of this model. We grouped three categories under the Inputs for joint creative engineering practice, including Group Composition, Task Structure, and Structuring Teacher's Role. Under the Group Processes, the IPOCC model has three categories, including Joint Engagement, Co-construction of Ideas, and Challenges of Teamwork. We grouped two categories under the Outcomes for co-creative engineering practice, including Creative Products and Intellectual Outcomes. Finally, Environment & Creative Climate and Affective Aspects were categorized under the Mediating Factors. In the following sections, we present this IPOCC model in additional detail.

Inputs

In this IPOCC model, input components that influence the group processes and other outcomes are grouped into three categories: Group Composition, Task Structure, and Structuring Teacher's Role. Table 3 presents these Inputs categories, sample excerpts from interviews supporting these categories, and ICR agreement for the codes included in these three categories.

Table 3 Inputs—Sample Quotes from Students' Interviews Supporting Codes and Categories

NVivo Codes	Exemplar(s)/representative Interview Excerpts	ICR Agreement	Intrv.[a]	Freq.[b]
	Category 1: Group Composition			
Prior Knowledge	*Sophia*: "No, I think it was a little bit difficult because a lot of the kids that took the class already had extensive engineering and building backgrounds."	.95	7	11
Background Diversity	*Rose*: "Well definitely forced us all to work together, I remember the first couple of days it was weird before we got comfortable around one another and in my class there is native English speakers, I think there is like two maybe, one other girl and me, yeah I think that's it. And then there is some [Students from South America], two or three who speak really good English and then some who didn't speak any English at all and then there were three [students from East Asia] kids, but there English was pretty good. Like getting through that all together and like communicating, that was just such a weird experience in a good way."	.96	4	4
Task-relevant Diversity	*Natalie*: "My team consists of three other people, one who is very Artistic, another who is very mechanically inclined and then another who just has like ideas that we can put it back, so I think we all complement each other."	1	2	3
	Category 2: Task Structure			
Challenging Tasks	*Aaron*: "Some advice is be ready for challenge, is not going to be easy, but it will be fun."	.92	15	47
Open-ended Activities	*Yusef*: "I like the way that we could use our creative minds. It wasn't like do this do that; it wasn't so structured; we got to be free and creative with it."	.89	7	14
	Category 3: Structuring Teacher's Role			
Scaffolding	*Rose*: "They were really independent. Like the teacher he would, he helps you, but mostly is what you want to do. Like he'll let you try, but then he'll help you if it fails."	.96	6	7
Modeling Creative Behavior	*Sarah*: "I really like how the teacher is like a really good teacher like he really challenges our ideas usually after every class before we leave he tells us stuff he notices in other groups that are happening, and he offers like solutions that could happen in the groups that could like work together, so he's always there to be like to make sure the teams are working and get ideas flowing."	1	3	6

[a] The number of interviewees who mentioned the code; [b] The frequency of the code across all interview transcripts

Group Composition

This category addresses the issue of how instructors should assign learners to collaborative groups. Many collaborative-learning approaches recommend heterogeneous grouping in terms of task-relevant abilities (Cen et al., 2016), gender, and ethnic background (Mouw et al., 2019), to maximize peer-learning opportunities (Webb & Palincsar, 1996); to improve cross-race connections and cross-gender relations; to make groups comparable; and to improve group performance (Anderman & Dawson, 2011; Kagan, 1989; Slavin, 2011; Watanabe, 2012). The benefits of diversity in teams are evident in our interviews. For example, Natalie mentioned, “My team consists of three other people: one who is very artistic, another who is very mechanically inclined and then another who just has like ideas that we can put it back, so I think we all complement each other” (personal communication, July 12, 2017).

Task Structure

Task-related features fall into two sub-categories: Challenging Tasks, and Open-ended/Ill-defined Activities. Fifteen out of sixteen participants mentioned challenges as a central feature of the activities. For example, Kian mentioned, “At first, when I started like building stuff out of recycled materials, and the Nerf Blaster taken apart, like the first few maybe like the first 20 minutes of that I kind no this not going to work, I’m going to destroy everything and I’m not going to be able to put it back together, and I got better at it” (personal communication, July 13, 2017). Kai mentioned that “For example, when we were using the CAD software we had, we could build a bike, but it was really open-ended. For example, we had to make penguins, and a lot of us did different kinds of making a penguin” (personal communication, July 12, 2017).

Structuring the Teacher's Role

Although only six participants addressed Structuring the Teacher's Role category, this is a critical Inputs component in creative collaboration (Jadallah et al., 2011; Rogat et al., 2014; Webb et al., 2006). Sarah mentioned, "The teacher …he really likes challenges our ideas, he's always there to be like to make sure the teams are working and get ideas flowing" (personal communication, July 12, 2017). Hmelo-Silver and Chinn (2016) mentioned that teachers who model the practice of providing an appropriate level of descriptions and require learners to do the same can promote better learning environments.

Group Processes

In the IPOCC model, processes that influence learning and other outcomes are classified into three categories: Joint Engagement, Co-construction of Ideas, and Challenges of Teamwork. Table 4 presents these categories, sample excerpts from interviews supporting these categories, and ICR agreement for the codes included in these categories.

Joint Engagement

Gresalfi et al. (2009) suggested that different facets of engagement are central to and inseparable from learning. All 16 participants in this study addressed different facets of engagement, and this concept was one of the high-frequency codes in the interview transcripts. For this category, the Productive Disciplinary Engagement (PDE) framework was applied (Fredricks et al., 2004; Rogat et al., 2019; Sinatra et al., 2015) as a meta-construct encompassing five facets: behavioral, collaborative, social-emotional, metacognitive, and disciplinary engagement.

In the PDE framework, behavioral engagement refers to indicators of being on-task, investing mutual effort, attentive and persistent mutual on-task engagement, even in the face of conflict and teamwork challenges, and students' awareness of its importance. For example, Natalie mentioned, "…my group was very helpful in like doing things that there were supposed to and staying on task, so I think it was good" (personal communication, July 12, 2017).

Collaborative engagement refers to evidence of students' attempts to be involved in coordinated teamwork activities and processes, including the elaboration of and building on each other's ideas. For instance, Kate mentioned, "I would say the teamwork aspect [of this course had the greatest impact] because before this I kind of liked to work individually alone without anyone, but now I don't really mind working in a group because it was really helpful to have other people's ideas shared" (personal communication, July 13, 2017).

Socio-emotional engagement addressed the group climate regarding respectful interaction, emotional reactions, and psychological safety. Metacognitive engagement referred to the shared regulation, in terms of planning, monitoring, evaluating, and reflecting on the task progress, indicating socially shared-metacognition evident in group discourse. Disciplinary engagement referred to indicators of domain-specific content and hands-on disciplinary activities as resources to make intellectual progress in facing meaningful design challenges. See Table 4 for sample student quotes supporting these sub-categories.

Table 4 Group Processes—Sample Quotes from Students' Interviews Supporting Codes and Categories

NVivo Codes	**Exemplar(s)/representative Interview Excerpts**	**ICR Agreement**	**Intrv.**[a]	**Freq.**[b]
	Category 1: Joint Engagement			
Behavioral Engagement	*Yusef*: "My participation, I understand better now that when you participate, you have to give a hundred percent, or the job just won't get done."	.95	12	20
Collaborative Engagement	*Rowan*: "Lots of teamwork [coughs] one of the simple machines and lots of creativity!"	.81	14	71
External Communication	*Kate*: "We had to like to communicate with pretty much everyone in the room."	1	6	11
Socio-emotional Engagement	*Natalie*: "You have to be very delicate with the people you work with because some of them take it much harder than others when you say well we probably shouldn't do that because of this and some people take that as offensive, but you kind of have to like say it slower and like more gentle."	.94	7	14
Participative Safety	*Aaron*: "I feel like my classmates felt like I was there friends my teammates felt like I was their friend yeah we felt cool with each other we didn't feel threatened or anything."	.97	5	8
Metacognitive Engagement	*Kate*: "Well we had to come up with our own like limitations that we had to follow as a group so we had to keep it on one table which ended up being a huge issue for some groups and we had to modify that and also we had to do it within time limits which were certainly difficult."	.96	11	25
Disciplinary Engagement	*Rowan*: "They were really good because we had to build a machine of course, so we had to do hammer stuff or hammering nails into the wood to attach it use the screws to attach a ninety-degree angle bracket."	.77	16	149
	Category 2: Co-construction of Ideas			
Generating Ideas	*Kate*: "Almost every time the equipment failed, or we had to rethink anything after the design phase because everyone was just bringing up ideas and so we all had to like pick out of which ones were the best."	.90	16	105
Elaboration	*Aaron*: "It was real; it was pretty important cause you have to visualize it because you have to sketch it, so you have to visualize your sketch. Sketch it, annotate the sketch and make it real."	.94	11	25
Flexibility	*Sarina*: "A lot of the time! Instead of doing the two pulleys, we used only one, and we shortened our pipe and made a smaller funnel, so that the marble would work to jug the next machine."	.94	11	14
Originality & Novelty	*Sophia*: "I think to be an engineer, you have to be creative because of coming up with new ideas, things like that. If everyone was engineering the same thing, then there would be like one thing."	.94	7	13

Table 4 continued

NVivo Codes	Exemplar(s)/representative Interview Excerpts	ICR Agreement	Intrv.[a]	Freq.[b]
Brainstorming	*Kate*: "We had a whole bunch of materials to choose from, so we had to like pick out which ones work the best for the situation, and we would share ideas with each other which kind of like helped out with the design process."	1	5	11
Digging Deeper into Ideas	*Kai*: "[After taking this course] I don't like to rush into ideas and stick to them. I kind of like go from one to another."	1	12	21
Analyzing	*Kian*: "I look at some objects, like you know, analyze them more, like what they have […] I should take it apart and play around with it and see what I can do with it."	1	6	8
Making Connections	*Sophia*: "One girl is totally completely one hundred percent not interested in it at first and then […] she realizes how similar this is like it's just building and kind of figuring out what works together. A lot of people are starting to see how it connects to the real world."	.93	11	30
Openness	*Sarah*: "I guess the advice is that always be open for ideas and be able to par- like do present new ideas you have and be creative about them."	1	16	107
Fantasy & Imagination	*Owen*: "Like for the animation thing right now. We're making like it's kind of like where it's like these three people are like trying to save their city from monsters!"	.89	15	36
Problem Sensitivity	*Kate*: "We had to visualize what the machine would look like individual parts and overall so it would all function correctly, especially the part where it's like the ending meets with the beginning cause if they were on two separate spots then it would never work."	.98	13	29
Aesthetic Sensitivity	*Alex*: "Well, I guess it helped me like be more creative because like I'd say I'm more of a machinist than an artist because you just give me something to do and then I can do it fairly easily, but I can't come up with how to do it and like how to make it look good."	.89	10	20
Thinking Outside-the-Box	*Henry*: "[The course] Makes me …helps me think outside the box."	.97	5	10
	Category 3: Challenges of Teamwork			
Conflicts	*Alex*: "I would've been building and doing my work most of the time, and then when not doing my work, it's because my help was being rejected! Like I offer, I offer up my help to them, and then my group members would be like 'Okay! No!'"	.96	10	25

[a] The number of interviewees who mentioned the code; [b] The frequency of the code across all interview transcripts

Co-construction of Ideas

Collaborative knowledge-building often refers to the group processes that promote a shared understanding of the challenging situation. Hämäläinen and Vähäsantanen (2011) stated, "…there is congruence between successful collaborative knowledge construction and creative collaboration" (p. 173). Treffinger and his colleagues (2002, 2013) identified several categories of characteristics of the creative processes, including (a) generating ideas; (b) digging deeper into ideas; and (c) openness and courage to explore ideas. We applied these three categories while coding the interviews.

Within the context of the engineering design process, the first category, Generating Ideas, is a crucial step. Therefore, this is an important skill to stimulate in the classroom (Daly et al., 2012). All participants addressed idea generation. For example, Rose mentioned, "All of us had different ideas on how it could work, and you know sometimes we'll go with only persons' ideas, and sometimes we can put two together" (personal communication, July 12, 2017). Regarding Generating Ideas, we found evidence of four sub-categories in these student's interview transcripts, including Elaboration, Flexibility, Originality & Novelty, and Brainstorming. For example, regarding what he learned in the class, Kian indicated, "…just how to really be an engineer type person. How to have an engineering mindset. And like you know, always look for a different approach beyond the obvious" (personal communication, July 13, 2017). Kai added that,

> Creativity is thinking of a basic idea, and what it would do, and engineering is doing that in a successful and organized way…like when we were looking at an object to use for our story, and we had a bunch of ideas on what it would do, and then we went from one idea to another, and then spread like spread it out in different varieties. (personal communication, July 12, 2017)

The second category, Digging Deeper into Ideas, encompasses convergent and critical thinking (Treffinger et al., 2002, 2013). This category included two sub-categories: Analyzing and Making Connections/Seeing Relationships. Digging deeper into ideas is an inherent part of several steps in the engineering design process, as engineers are constantly analyzing and evaluating their ideas to create a fitting solution for the problem at hand. For instance, Sarina indicated,

> Engineers have to have a plan, and they have to draw it out, and usually, they have to state the plan, state anything that could go wrong, any requirements, anything they could do to fix the problems, any way to add, any advantages they have of the program. (personal communication, July 13, 2017)

Yusef mentioned, “I learned better engineering. I learned how to create things with different systems and how to use math to help better built my structures, and I learned how to sketch before I do anything” (personal communication, July 12, 2017).

The third category, Openness, included four sub-categories: Fantasy & Imagination, Problem Sensitivity, Aesthetic Sensitivity, and Thinking Outside-the-Box (Treffinger et al., 2002, 2013). For example, Rose described, “…the first time I was kind of annoyed like ‘no it was a perfect plan, why didn’t it work’ but now like we are on to our second machine, but it is bigger and like and I’m more accepting of trying new things” (personal communication, July 12, 2017). Sarah mentioned, “…on your team there are always other people that have other ideas and other ways of approaching so make sure you try everyone’s ideas and make sure you can like participate and have like creative ways to try to overcome obstacles” (personal communication, July 12, 2017). These categories are commonly associated with creative-thinking processes (Csikszentmihalyi, 1996; Daniels-McGhee & Davis, 1994; Davis et al., 2011; Gregerson et al., 2012; Selby et al., 2005; Starko, 2010; Sternberg, 2000).

Challenges of Teamwork

Ten out of sixteen participants addressed the challenges of collaboration. For example, in response to the question regarding her teamwork experience, Sarina mentioned, “Sometimes me and one of my teammates would always fight like because we were the ones that were always like fighting for like what was right and we would always fight” (personal communication, July 13, 2017). In their examining interactions among disagreeing partners, Darnon, Doll, and Butera (2007) distinguished and proposed two types of conflicts. First, in a situation in which self-competence is not threatened, the conflict can be epistemic. In this case, conflict is focused on the task, ideas, or question of knowledge. “However, if self-competence is under threat, individuals focus their attention on the question of self-competence protection instead of learning, and the benefits of the conflict are lost” (p. 229). Darnon, Doll, and Butera (2007) qualified this second type as relational conflict, in which the perceived contribution of the partners reduced. In the elaboration of the conflicting situations, only two of these ten students described a relational conflict. Additionally, participants addressed some other challenges of teamwork, such as social-loafing, language barriers, and leadership issues. For example, Timon mentioned, “Compromise, because I'm a very bossy person, so I like things my way, so I had to learn how to compromise” (personal communication, July 28, 2017).

Table 5 Outcome—Sample Quotes from Students' Interviews Supporting Codes and Categories

NVivo Codes	Exemplar(s)/representative Interview Excerpts	ICR Agreement	Intrv.[a]	Freq.[b]
	Category 1: Creative Products			
Building (something)	*Alex*: "Well, you have to be creative to design a bridge that won't collapse! So, I'd say that!"	.84	14	77
Design and Visualization	*Fiona*: "Well you definitely need to be able to be like think creatively to be able to like design certain things or like put stuff together."	.91	13	47
Complexity	*Rowan*: "The course is basically building a Rube Goldberg machine. It's a machine that's designed to do a lot of simple tasks or a simple task making it as long and complicated as possible so you can have pulleys you can activate pulleys have leavers things like that to make the thing the machine more complicated."	1	6	7
Feasibility	*Timon*: "You have to create something, and then you have to engineer it, but our creativity can be very unrealistic to the point where you cannot engineer it."	.95	7	11
	Category 2: Intellectual Outcomes			
Learning Outcomes	*Kai*: "I got better at planning. I had learned to use some CAD software, computer-aided design software that they gave us."	.91	16	236
Developing Problem-solving Skills	*Rose*: "I think it definitely helps a lot with problem-solving skills and planning and everything I mean you should plan most of what you do not like day to day things, but like in your career you're going to have to plan, so I think this was a good exposure to that."	.91	15	45
Better Understanding of Engineering	*Sarina*: "Engineers have to have a plan, and they have to draw it out, and usually they have to state the plan, state anything that could go wrong, any requirements, anything they could do to fix the problems, any advantages they have of the program, or like things they are doing."	.94	13	51
Learning How to Sketch	*Timon*: "Uh, I prepare like if I'm going to design something, I sketch it out first versus just going into it and just start writing stuff down I mean start uh putting stuff together."	.93	9	19
Learning from Failures	*Henry*: [The most important part of the engineering was] "Learning from your mistakes."	1	5	10
Teamwork & Communication Skills	*Yusef*: "I would say I would say again with my confidence. This really helped me be more outgoing and ready to meet other people. I think that before the class, before the class, I think that I didn't really talk in groups as much, but now I feel again that I'm contributing more. I'm giving more ideas."	.91	9	19

Table 5 continued

NVivo Codes	Exemplar(s)/representative Interview Excerpts	ICR Agreement	Intrv.[a]	Freq.[b]
Being (more) Creative	*Kian*: "Learning how to be more creative in their approaches to problems, so even if they weren't interested in STEAM or engineering, maybe they're interested in teaching or something, like take a new approach to teach then something or whatever, new activities."	.81	6	15

[a] The number of interviewees who mentioned the code; [b] The frequency of the code across all interview transcripts

Outcomes

Students mentioned a range of different outcomes of co-creative engineering. We grouped these outcomes into two categories: Creative Products and Intellectual Outcomes. Table 5 presents the Outcomes in the IPOCC model, sample excerpts from interviews supporting these two categories, and ICR agreement for the codes included in these categories.

Creative Products

We grouped evidence supporting the Creative Products category into two sub-categories: Building (something) and Design & Visualization. Additionally, Complexity and Feasibility were mentioned by nine interviewees as two essential characteristics of a creative product. Creativity involves developing a perceptibly creative product (Plucker et al., 2004; Rhodes, 1961). Therefore, it seems reasonable to include objectives for creative products when evaluating how creativity is addressed in engineering curricula. Timon asserted, “I feel like creativity was like something that you think of in your head and you might draw it, but you won't actually make it, but when I think of the classroom it taught me that you can possibly make it if you try” (personal communication, July 28, 2017).

However, there was evidence of conceptual change in the students’ perceptions of engineering. This change is the shift from an extremely product-oriented view of engineering to a more process-oriented conception of its iterative nature. For instance, Sarina stated, “I used to think that engineering was more like just building something not that you had to write it out, draw it out, build it, write it out again, draw it out again, build it again, to help fix it” (personal communication, July 13, 2017). Aaron stated, “Engineering is really fun. It's not only about building; it’s about designing how to build” (personal communication, July 14, 2017).

Intellectual Outcomes

In addition to a concrete product as an outcome of the creative process, participants mentioned a range of learning-related outcomes as a result of the joint creative process, including a better understanding of engineering and the engineering design process, developing problem-solving skills, learning how to sketch, and learning from failure. Regarding the engineering design process, nine out of sixteen students addressed learning idea-sketching and drawing abilities, as an important skill in the design visualization. For example, Aaron mentioned, “It was pretty important cause you have to visualize, because you have to sketch it, so you have to visualize your sketch. Sketch it, annotate the sketch and make it real” (personal communication, July 14, 2017). Yusef stated, “I learned how to sketch before I do anything so I can have something to work off of and to plan ahead my structure or my creation (personal communication, July 12, 2017).

In response to the question regarding the most important part of the engineering process, Henry responded, “Learning from your mistakes” (personal communication, July 14, 2017). Responding to the same question, Natalie mentioned, “…failure isn't bad… I constantly failed on my robot, and I never truly succeeded at making it, but I understood some of the flaws that I had.” Additionally, regarding the engineering design process, she continued, “…basically it just takes a lot of failures, and you have to have a general idea of what you're going to do before you try to accomplish it” (Natalie, personal communication, July 12, 2017). “Learning is always a creative process” (Sawyer, 2012, p. 395). Sawyer (2010, 2012) suggested creativity and learning encompass the same mental processes and noted important products are almost always the result of complex collaborations (Sawyer & DeZutter, 2009). Beghetto (2016) asserted that the outcome of creativity-in-learning is a change in a learner’s personal understanding.

Further, Teamwork & Communication Skills and Being (more) Creative were two other sub-categories in these students' responses. Regarding how the course affected students, Rose said, "Well [the course] definitely forced us all to work together; I remember the first couple of days it was weird before we got comfortable around one another" (personal communication, July 12, 2017). Sarah indicated, "I learned how working in a team can be beneficial and what are the obstacles in working in a team…you have to learn that in teams everyone has to make a contribution and don't feel like one or two people have to do all the work" (personal communication, July 12, 2017). Timon mentioned, "Well the teamwork helps me compromise so I won't always get frustrated when somebody wants to do something that I don't want to do" (Timon, personal communication, July 28, 2017).

Six out of sixteen students stated that participating in these courses helped them with being more creative. For example Fiona, in response to the question on how participation in this class influenced her problem-solving abilities, mentioned "It definitely helped because made us think like kind of more creatively like more to be able to say instead of this we can do this (personal communication, July 12, 2017). As another example, responding to the question how do you think participation in the course affects students who do not have an interest in engineering or STEM, Kian said, "…learning how to be more creative in their approaches to problems so even if they weren't interested in STEAM or engineering" (personal communication, July 13, 2017). Other noteworthy changes in participants' perceptions of engineering were increased openness to imagination and aesthetic sensitivity. For example, Kate stated, "I think a lot of students think it's just math and science. I think this would show everyone that it involves our creativity as well, and the creation of machines does not happen without an artist or an imaginative person" (personal communication, July 13, 2017). Rose mentioned, "I didn’t think that engineers were quite artistic in a way, but art is really important actually to engineering” (personal communication, July 12, 2017).

Mediating Factors

In this IPOCC model, factors mediating group processes, learning, and other outcomes are grouped into two categories: Environment & Creative Climate and Affective Aspects. Table 6 presents the Mediating Factors, sample excerpts from interviews supporting these categories, and ICR agreement for the codes included in these categories.

Table 6 Mediating Factors—Sample Quotes from Students' Interviews Supporting Codes and Categories

NVivo Codes	Exemplar(s)/representative Interview Excerpts	ICR Agreement	Intrv.[a]	Freq.[b]
	Category 1: Environment & Creative Climate			
Creativity-stimulating	*Sophia*: "I remember at one point we were designing bikes with the co3Deator, and instead of making my wheels a circle, I made them hands! I thought it was really cool because they let me do what I wanted with it, and I could just create it how I wanted."	.88	10	36
Autonomy-supportive	*Aaron*: "The most important [experience I had in this course was], I think the end where we got to create the storytelling stuff. Cause we got to make our own like we got to make it like we didn't have any help or anything it was like on us, which is pretty cool because we got to do every the story could be about whatever you want so we were free to make the story."	.90	10	26
Encouraging	*Yusef*: "With the 3-D, with the CAD system, they told us how to do it at first, and then they let us do it, and then they let us print it out, and build it instead of just teaching us how to do it, and we could see it on the computer they actually took it a step further to help us understand how it worked better with actually printing it out and letting us work with it."	.96	4	4
	Category 2: Affective Aspects			
Enjoying the Activities	*Fiona:* "I thought it would be like really interesting, and fun and it really is, and I'm really enjoying it."	.90	14	57
Persistence	*Natalie*: "It kind of showed me that things are not going to be perfect the first seven times that you do them and it takes a lot more energy, and effort than you put into everyday life to accomplish something."	.90	11	21
Interest	*Sarah*: "Well, I chose the STEAM Labs class because of before I was already interested in engineering and that field of science and math […] And then although if you are interested in STEM, you have to be really interested in like doing every step of the way and more creative ideas."	1	11	16
Confidence	*Sophia*: "At first it is really hard to get some of them involved and like they wouldn't understand it, and now they really do, and that's cool, and I think a lot some of them are a lot more confident with the materials."	.88	4	8

[a] The number of interviewees who mentioned the code; [b] The frequency of the code across all interview transcripts

Environment and Creative Climate

Participants described the classroom environment as Creativity-stimulating, Autonomy-supportive, and Encouraging. Fourteen out of 16 participants addressed these categories in their descriptions of their course and classroom atmosphere. For example, Sophia described,

> …taking apart a nerf gun and putting it back together like I've never played with those really, and I kind of doubted myself but I got it back together, and things like using a computer program to build things were like kind of crazy cause I had never done that and then I was probably one of the best in my group. (personal communication, July 12, 2017)

Yusef mentioned, "I like the way that we could use our creative minds; it wasn't like do this do that; it wasn't so structured. We got to be free and creative with it" (personal communication, July 12, 2017). This notion needs to be highlighted that less-structured and more open-ended activities serve as essential features (Cohen & Lotan, 2014; Tomlinson, 2018), not only for a creative climate but also for Task Structure in the Inputs area.

Davis et al. (2011) stated, "…a creative atmosphere rewards creative thinking and helps it become habitual" (p. 224). Learning environments that support student creativity are almost as important as the input components or group processes through which the creative outcome is formed (Beghetto & Kaufman, 2014; Rhodes, 1961; Richardson & Mishra, 2018; Rubenstein et al., 2018). Autonomy-supportive teaching style and environment enhance creativity (Liu et al., 2011; Wang & Dong, 2019). According to Starko (2014) and Nickerson (2000), a learning environment that supports creativity development should include open-ended learning activities that focus on the skills and attitudes of creativity, modeling the creative process, and creative methods/strategies of disciplines.

Affective Aspects

In the interviews, 14 out of 16 students addressed Affective Aspects, such as Enjoying the Activities, Persistence, Interest, and Confidence. For example, Natalie mentioned,

> It kind of showed me that things are not going to be perfect the first seven times that you do them, and it takes a lot more energy and effort than you put into everyday life to accomplish something**…**You have to have like a very good tolerance level of like failing, but other than that, it is absolutely amazing. [This course] showed me that I can build things whether or not they work in the end. I can build them; I just have to keep trying. (personal communication, July 12, 2017)

Davis et al. (2011) mentioned that creative performance requires "creative traits" such as humor, playfulness, interest, and confidence, "…that can be enhanced by a creativity-conscious teacher" (p. 209). Poon et al. (2014) suggested that some students might possess the knowledge but do not have the confidence to try out their creative potential" (p. 38). Further, these affective factors contribute to the creation of social capital and leadership skills in young people, as these areas interact with and give rise to cognitive development (Renzulli, 2012), while also playing a role in the formation of beliefs, attitudes, values, and the development of an action orientation (Renzulli & D'Souza, 2014).

Some of the important factors described in the literature on collaborative creativity did not appear in our analysis of the interviews, including preparation for teamwork such as co-construction of group norms; coordination and leadership issues; and mechanisms of giving and receiving help among co-learners. Future research could investigate these group-level processes in co-creative group activities.

From a Classic 4P View to an IPO Model of Collaborative Creativity

Our examination of students' creativity and teamwork experience in engineering courses resulted in developing our IPOCC model. The IPOCC model mirrors Plucker et al.'s (2004) definition of creative thinking as "…aptitude, process, and environment by which an individual or group produces a perceptible product" (p. 90), that is original and valuable within a context. As Lubart (2018) mentioned, the Western perspective on creativity is "… relatively individual-oriented and product-oriented" (p. 139). The IPOCC model can be considered part of contemporary inquiries toward developing theories of process-oriented group creativity. Additionally, this model provides initial steps to extend the 4P model of creativity (Rhodes, 1961) to include group-level components of collaborative creativity.

As Gruszka and Tang (2017) suggested, research on creativity has widely applied the classic 4P model (Rhodes, 1961), investigating four facets of creativity: *Person* (characteristics of creative individuals), *Process* (procedure to generate new ideas), *Product* (feasible and useful outcomes), and *Press* (an environment that is inspiring creative behavior). Doyle (2019) stated, "The 4P framework originated in a definition of creativity as encompassing four interconnected strands—taking place when a Person goes through a Process to produce a novel Product in the context of environmental Press" (p. 41). Many scholars have conceptualized creativity in terms of one, two, three, or all four components of this model to assess, nurture, and stimulate creative behaviors. The IPOCC model expands the 4P model of creativity to incorporate collaborative contexts. In the IPOCC model it is suggested that in the context of K-12 collaborative practice, creativity involves group-level considerations in addition to individual-level components.

In the 4P model, *Person* refers to the characteristics of a creative individual. Numerous studies have focused on describing personality and individual-level qualities related to a creative person (e.g., Jankowska et al., 2019; Karwowski et al., 2013; Plucker et al., 2009; Runco et al., 2017). For example, Treffinger et al. (2013) listed several "personal creativity characteristics" such as "desire to resolve ambiguity", "preferring complexity", "integrates personal dichotomies (selfish/unselfish; extroverted/introverted)", "self-disciplined", and "argumentative" (p. 63-64). However, there are indications that the creativity of individual members may not be the only and the most important factors in small group activities (Doyle, 2019; Hülsheger et al., 2009). For instance, the results of teamwork tend to be more creative if the group members represent a diversity of perspectives (Page, 2008).

The IPOCC model broadens the idea of *Person*, as Inputs, including group-level components in Group Composition, such as Background Diversity and Task-relevant Diversity of group members. In addition to Group Composition, Task Structure and Structuring Teachers' Role are two other input categories that are brought to the table, which can exert significant influence on group processes and creative outcomes. As the IPOCC model is mainly developed for classroom creativity and K-12 settings, the teacher is one of the crucial input factors in this model, as a more knowledgeable person and also as a mentor modeling creative behavior (Jadallah et al., 2011; Rogat et al., 2014; Webb et al., 2006).

Moreover, in the 4P model, *Process* refers to (a) practical methods and strategies used or (b) underlying cognitive processes that occur when an individual is engaged in creative thinking (Doyle, 2019; Gruszka & Tang, 2017). For example, Piirto (2005) suggested seven "I's" of the creative process, including Inspiration, Imagery, Imagination, Intuition, Insight, Incubation, and Improvisation. Analogical thinking, visualization, aesthetic thinking, divergent thinking, and critical thinking are some of the creative processes mentioned in the literature as well (Davis et al., 2011). The IPOCC model widens the notion of *Process* to capture Group Processes, incorporating Joint Engagement and Co-construction of Ideas and including collective aspects of creativity and the perception of creativity as social and communal processes (Miell & Littleton, 2004; Sawyer, 2012; Sawyer & DeZutter, 2009).

Similar to what Hülsheger et al. (2009) found, the IPOCC model includes group-level processes such as communication, support for creativity, participative safety, and task conflict as important elements in group creativity. Operational aspects of the practical strategies used when a group is engaged in collaborative creative thinking are different from the practical strategies an individual uses in creative thinking. Group-level interactions add another layer of complexity to collaborative creativity. For example, mechanisms of idea-generation in group-level creativity involve different processes compared to individual-level creative thinking. Idea-generation in group-level creativity involves challenges such as conflict over ideas. Under Group Processes, we included the Challenges of Teamwork as relationships between members of a collaborative group, which are vital when focusing on the co-creative processes (Miell & Littleton, 2004). These relationships affect the generation of innovative ideas (Wirtanen & Littleton, 2004; Searle, 2004).

Further, in the 4P model, *Press* refers to the relationship between creative individuals and their environment (Rhodes, 1961) and surrounding conditions under which creative behaviors are likely to exhibit (Csikszentmihalyi, 2014). For instance, Runco and Pagnani (2011) listed "…six levels of socialization as press factors: physical surroundings, family upbringing, schooling experiences, workplace environments, cultural traditions, and the historical milieu in which we happen to have been born" (p. 67). As Gruszka and Tang (2017) mentioned, individual creative contribution at the group level is generally considered and discussed under the *Press* facet of the 4P model.

The idea of *Press* in the 4P model is reflected in the Mediating Factors of IPOCC model, including the most immediate environmental surroundings and creative climates in the classroom, such as Creativity-stimulating, Autonomy-supportive, and Encouraging environment.

Additionally, Mediating Factors in the IPOCC model also include Affective Aspects such as Enjoying the Activities, Persistence, Interest, and Confidence as significant contributors that mediate group processes, learning, and other outcomes of collaborative creativity. As Davis et al. (2011) suggested, creativity requires affective attributes such as humor, playfulness, interest, and confidence. Mediating Factors in the IPOCC model do not directly shape the creative outcomes of teamwork, but either mediate or moderate it by affecting variables related to the Inputs and specifically Group Processes.

Finally, in the 4P model, a creative *Product* plays a dominant role among the 4P's of creativity (Gruszka & Tang, 2017), and the Western perspective on creativity is relatively product-oriented (Lubart, 2018). Therefore, in the product-oriented view, creativity assessments are generally focused on evaluating the final product, and person, process, and environment are considered creative if they are associated with a creative product. Researchers have developed different criteria to evaluate the creativity of a product, such as originality and usefulness (Plucker et al., 2004), which considered as standard criteria of creativity (Runco & Jaeger, 2012). Many researchers assumed that there must be a concrete product when they developed theories of creativity; however, in K-12 settings, the results of students' efforts are rarely comparable to eminent creative people (Runco & Pagnani, 2011).

Additionally, the result of students' group creativity frequently manifests itself in the learning process without a tangible product. As Runco and Pagnani (2011) stated, "Not all creative efforts result in a product" (p. 66). Accordingly, the IPOCC model expands on the idea of a concrete product to Outcomes, including not only Creative Products but also Intellectual Outcomes such as Learning-related Outcomes, Developing Problem-solving Skills, as well as improving Teamwork and Communication Skills. For example, Learning from Failures is a sub-category in the Outcomes, which addresses and implies situations in which group efforts did not result in a tangible product. However, in these situations, students' teamwork endeavors and interaction with a challenging task can help them to develop and improve their collaborative problem-solving skills, and therefore can result in a productive failure (Kapur, 2008, 2014).

Implications

As Chan (2013) stated, "Helping students to engage in collaborative inquiry and work creatively with ideas is now a major educational goal" (p. 437). The results of this study can help teachers to pursue this educational goal. The findings of this study offer valuable insights for educators in terms of input components, group processes, and mediating factors that can facilitate learners' engagement in creative teamwork and affect outcomes of group creativity. Implementing a teaching approach that directly addresses the various areas of the IPOCC model may improve collaborative creativity among students and could stimulate positive conceptual changes in students' perceptions of engineering and creativity.

The IPOCC model can inform learners' preparations in terms of increasing students' ability to regulate collaborative interactions. Creative and productive peer-collaboration in educational settings requires preparation for teamwork (Borge & White, 2016; Chan, 2013). The IPOCC model can help to prepare students to establish and maintain an atmosphere of encouragement, participative safety, and risk-taking exploration is a necessary part of any creativity-supporting climate (Beghetto & Kaufman, 2014; Rubenstein et al., 2018; Sullivan, 2011). For example, one of the strategies to promote effective collaboration is assigning roles to the group members (Borge & White, 2016). Based on the four areas in the IPOCC model (Inputs, Group Processes, Mediating Factors, and Outcomes), we can envision teachers assigning four different roles to students accordingly, such as Diversity Manager, Idea-generation Manager, Mediation Manager, and Productivity Manager.

In a collaborative environment such as the engineering enrichment courses used in this study, assigning this set of socio-metacognitive roles (i.e., Diversity Manager, Idea-generation Manager, Mediation Manager, and Productivity Manager) can help improving learners' abilities to regulate and understand collaborative creativity. Teachers can assign students to these four roles to monitor and regulate group interactions and activities, regarding four areas of the IPOCC model. For example, the Idea-generation Manager can help create an appropriate group dynamic to facilitate Joint Engagement. The Idea-generation Manager can be responsible for making sure that everyone verbally participates in the co-construction of ideas, carefully listens, builds on each other's ideas, and comes to a shared understanding of the plan.

In this study, we grouped our findings under Inputs, Group Processes, Outcomes, and Mediating Factors. Any curriculum designed to support co-creative behaviors in the context of engineering education can potentially benefit from considering these four areas and different categories addressed under each area in the IPOCC model, to provide learners with creativity-fostering experiences in their classrooms. Particularly, to scaffold co-creative endeavors in collaborative groups, our findings emphasized the importance of non-authoritative instructional strategies (Sullivan, 2011), such as the Complex Instruction Approach (Cohen et al., 1994).

Several components of the IPOCC model are aligned with the Complex Instruction Approach, including Challenging Tasks and Open-ended/Ill-defined Activities, Structuring Teacher's Role, Joint Engagement, and Co-construction of Ideas. As Cohen and Lotan (2014) and Tomlinson (2018) suggested, our findings indicated that less-structured activities serve as a critical element to provide students with a creativity-supporting environment. Delegating agency and authority to the learners facilitates peer-collaboration (Tomlinson, 2018). A combination of challenging tasks, open-ended problems, and student teamwork provides learners with a rich environment that promotes thinking creatively and critically. Indeed, collaboration is increasingly of value to creative endeavors in the workforce, so development of the mindset and dispositions likely to foster collaborative creativity is critical in education (Hinrichs, 2004).

Limitations

The participants and context of this study limit the generalizability of the results to other K-12 educational settings. Regarding the participants, all of them were from the United States. Although they came from various ethnic backgrounds, potentially, it would be beneficial to include students from different countries to investigate international participants' experiences with these university-based enrichment courses. Moreover, we had multiple participants; however, they were all students. Thus, the present study is limited in that it is based solely on one source of data. Regarding the context, we developed and proposed this IPOCC model in the context of university-based enrichment engineering courses held during one university program for youth with gifts and talents.

Another limitation was the interview time. Because of the students' busy schedule during the enrichment program, these interviews took place in the evening and between program activities, when the students potentially had less energy. As a result, students might have been eager to finish the interview as soon as possible. As Patton (2015) mentioned, one of the challenges in interviewing youth is keeping their interest and attention. For some students, this issue of interview time might affect their interest and attention, and therefore, the level of their elaboration on the responses and explanation of their experiences.

Future Research

Although this model can theoretically be applied to other areas of joint creative endeavors, future research is needed to provide evidence of this model's applicability to other contexts and settings. Future studies are necessary to evaluate, confirm, or extend this IPOCC model and its implications. More specifically, we will conduct mixed-method inquiries to collect different forms of data. In future research, we will apply triangulation design (Patton, 2015), especially to use different sources of data, such as interviews with teachers and observational data, to provide more evidence of the credibility and trustworthiness of these findings (Johnson & Christensen, 2012). Future researchers should focus on examining the relationships among different categories in the IPOCC model and collective creativity in the classroom environments. In the future, we plan to use a mixed-method intervention design (Creswell, 2015), to explore conceptual changes in the learners' perceptions of engineering and its connection to creativity. Finally, as Sawyer (2018) suggested, more research is necessary to investigate relationships between individual-level creativity and group-level creativity, especially in terms of sources of challenges and obstacles that learners and teachers encounter in the process of collaborative creativity.

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Appendix A: Interview Protocol

Interviewee's name: ______________________ Date: __________ Location: _________

Start time: __________ End time: __________ Interviewer's name: ____________

Interview Questions

1. Why did you choose this class?
   Follow-up questions: What did you do in this course? Describe the course activities! If I had been in this course with you, what would I have seen you doing?
2. What was the most important experience that you had in this course?
   Follow-up questions: What did you especially like about the activities in this class? Was there anything you dislike? What were some of the challenges, if any?
3. What were some things you learned in this class?
   Follow-up questions: (ask about the engineering process if students don't mention it.) Based on your experience in this course, what was the most interesting/important part of the engineering process?
4. What aspects of this course have had the greatest impacts? (What did you get out of participating in this course?)
5. What is your opinion about hands-on activities used in this class? How do you feel? Give me an example.
6. What has changed in your understanding/perception of engineering as a result of participation in this course?
   Follow-up questions: What, if anything, do you do now that you didn't do before taking this course?
7. What advice would you give to someone thinking about taking this class?
   Follow-up questions: Suppose I was a new student in this course, and I didn't know anything about what goes on around here, what would you tell me?
8. How did participation in this course influence your problem-solving abilities?
9. How often did you use your problem-solving abilities in this class?
   Follow-up questions: How often did you use your imagination in this class? How often did you generate new ideas in this class? How important was visualization? How often did you take different approaches to a problem?
10. In your understanding, how creativity and engineering affect each other?
    Follow-up questions: Has participation in this GERI course changed your understanding?

Do you have any further comments that you want to add? Do you want to share anything else about the course?

CHAPTER THREE A SYSTEMATIC LITERATURE REVIEW OF NOVICE/K-12 VISUAL REPRESENTATIONS OF DESIGN IDEAS: A THREE-PRONGED DESIGN SKETCHING FRAMEWORK

Abstract

The purpose of this study was to systematically investigate how novice/K-12 students' visual representation of design ideas has been operationalized, measured, or assessed in the research literature. In the different phases of screening in this systematic review, inclusion, exclusion, and quality criteria were applied. From an initial sample of 958 articles, 40 studies were included in the final step of the coding process and qualitative synthesis. Applying provisional and open coding, three broad themes, and 23 characteristics were identified that have been used by researchers to conceptualize sketching of ideas, in novice/K-12 design activities: Communicating Ideas, Visual-Spatial Characteristics, and Design Creativity. We propose this Three-pronged Design Sketching (3-pDS) framework to examine K-12 design sketches.

Introduction

Based on perceived needs of a nation, societies may value and endorse specific areas of giftedness at particular times (Subotnik et al., 2011)—for example, the contemporary emphasis on STEM talent that has been reignited in the United States, most likely in response to *A Nation at Risk* (National Commission on Excellence in Education, 1983), to remain viable and competitive in a growing global economy (Robinson, 2017). Thus, engineering and design are considered a part of the contemporary K-12 education curricula and standards, in which collaborative design-thinking and creative problem solving gradually become significant educational goals. For example, the *Framework for K–12 Science Education* (National Research Council, 2012), the *Next Generation Science Standards* (NGSS Lead States, 2013), and *STEM*

Integration in K-12 Education (National Academy of Engineering, 2014) include engineering design in K–12 science instruction. However, little empirical research exists on how students learn to apply their knowledge and abilities through design (Purzer et al., 2015). Purzer et al. (2015), in their exploratory study of informed engineering design behaviors of high school students, suggested that researchers should probe patterns of design behavior with a more diverse group of students and conceptualize these patterns with middle and high school students. In this systematic review, we investigated patterns of sketching characteristics in novice/K-12 learners and proposed a three-pronged conceptual framework to examine design sketches.

STEM Programming for Students with Gifts and Talents

STEM enrichment programs are defined as "…a program outside of the regular school curriculum that offered additional opportunities for students to explore STEM-related concepts after school, on Saturdays, and in the summer" (Mun & Hertzog, 2018, p. 122). STEM project-based learning has been employed in K-12 classrooms to encourage students' participation in interdisciplinary and collaborative activities (Han et al., 2015). Having STEM project-based experiences is positively related to academic achievements, attitudes toward learning, and collaborative behavior (Dominguez & Jaime, 2010; Kaldi et al., 2011). For example, Han et al. (2015) provided evidence that participating in STEM project-based learning activities positively affected high school students' mathematics achievement. Olszewski-Kubilius (2010) outlined the benefits of special STEM schools for students with gifts and talents, including providing high-potential learners with intellectual peers, modeling authentic scientific inquiry, improving motivation, providing students with academic challenge, developing study habits and stress-management methods, and fostering other important intellectual and social skills.

In their 25-year longitudinal study, Wai et al. (2010) examined the relationship between educational experiences of pre-collegiate STEM enrichment programs and adult accomplishments in science, technology, engineering, and mathematics. The results indicated accomplishments in STEM disciplines are related to the amount of "…advanced pre-collegiate educational opportunities in STEM" and "…a higher STEM educational dose" (Wai et al., 2010, p. 860) and intellectually challenging opportunities. Exploring STEM high school teachers' beliefs regarding STEM student giftedness, Tofel-Grehl and Callahan's (2017) findings illustrated robust views among these teachers that high-ability students in STEM courses require a high-workload environment including ample inquiry-based learning with minimal structured support to learn independently and keep the students challenged and engaged. Early identification of high-potential learners and providing them with enriched programming in content-specific domains is an effective strategy to balance opportunities for STEM education and career success (Robinson, 2017), especially among economically underprivileged, high-potential, rural students (Assouline et al., 2017; Plucker et al., 2010; Robinson et al., 2018). With the increasing prominence and prevalence of STEM professions across the globe, nurturing environments to improve individuals' motivation and passion is vital to developing a STEM pipeline (Makel et al., 2015). Thus, STEM enrichment programs for students with gifts and talents usually involve engineering design practice.

Engineering Design Practice

The several required characteristics of design-based engineering practice are a natural fit for many students with gifts and talents (Mann et al., 2011; Robinson, 2017). Engineering design-based challenges can provide excellent opportunities for encouraging student creativity, which has long been associated with gifted education (Hathcock & Dickerson, 2017). Creativity is one of the central components of giftedness and talent development (Dai, 2010; Davis et al., 2011; Callahan & Hertberg-Davis, 2013; Sternberg et al., 2011). Engineering design is a recent addition to the *Framework for K–12 Science Education* (NRC, 2012), the *Next Generation Science Standards* (NGSS Leads States, 2013), and *STEM Integration in K-12 Education* (National Academy of Engineering, 2014). Engineering design activities are suitable and effective ways to infuse innovation and creative thinking into the curriculum, as design-based challenges inherently allow for creativity (Darbellay et al., 2018; Cropley, 2015; Hathcock & Dickerson, 2017).

The engineering design process emphasizes the importance of problem-identification and problem-solving strategies (Mann et al., 2011; Robinson, 2017). Engineering design is an iterative process that provides gifted students with intellectual challenges, reflective decision-making, problem-solving situations, motivated peer groups, skilled teachers, and educational contexts for the learning of mathematical, scientific, and technological concepts while encouraging and developing higher-order thinking abilities (Fan & Yu, 2017; Jonassen, 2014; Mann et al., 2011; Mun & Hertzog, 2018; Wendell et al., 2017). Hathcock and Dickerson (2017) argued that the ill-structured nature of engineering design-based challenges make them open-ended, multifaceted, and more like real-world problems. These challenges require design-thinking strategies, including understanding the challenge, build knowledge, generating ideas, representing ideas, weighing options and making decisions, conducting experiments, troubleshooting, revising/iterating, and reflecting on the process (Crismond & Adams 2012). As "…the engagement of learning in science and the creativity in engineering design are enviable matches to the characteristics and needs of talented children in the early years of school"

(Robinson, 2017, p. 28), it is important to provide STEM-talented students with interdisciplinary design-based activities.

Brophy et al., (2008) stated that K-12 design-based instruction in science and mathematics can develop learners' competencies to evaluate and explain the configuration and function of complex systems, to develop cognitive models of working systems, to design and conduct experiments to inform decision making, to communicate ideas, to utilize geometric and visual-spatial reasoning, to represent and manage the complexity of a system, to elaborate on ideas and results with mathematics, and to synthesize ideas toward an appropriate solution that meets goals. As described in the *Informed Design Teaching and Learning Matrix* (Crismond & Adams, 2012), idea-generating and visual representation are an integral part of the design-thinking process (Buxton, 2007; Goldschmidt, 1991; McKim, 1980), which is the focus of this systematic review.

Idea-Sketching in the Design-Thinking Process

During ideation, free-hand sketching supports designers to visualize different levels of abstraction, think through problems, understand ill-defined problems, extend short-term memory for problem-solving, and aid communication and team building (Booth et al., 2016). Wendell and Lee (2010) emphasized the importance of student engagement in drawing tasks before constructing a physical prototype. Free-hand sketching has been used and taught in the field of architecture and industrial design as a method for problem solving, idea generation, and concept generation (Bilda et al., 2006; Booth et al., 2016; Eissen & Steur, 2011). According to Jonassen et al. (2006), the most common method of problem representation is drawing. Sketches are an essential approach for engineers to embody their ideas (Ullman et al., 1990), especially for idea communication (Cardella et al., 2006; Jordan et al., 2016; Römer et al., 2001).

Design thinking and visual reasoning can be supported through sketching in a number of ways, including (a) making internal thinking explicit, (b) envisioning more complex systems, (c) enhancing collaboration and communication, and (d) supporting the designers' self-reflection on their imagined solutions (Cardella et al., 2006; Crismond & Adams, 2012; Uziak & Fang, 2018). Purzer et al. (2015), in their exploratory study of informed engineering design behaviors, suggested researchers should probe patterns of design behavior and conceptualize these patterns with a more diverse group of students. In an engineering context, Ferguson (1992) classified sketches into three categories: (a) *thinking* sketches, which focus and guide non-verbal thinking; (b) *prescriptive* sketches, which help develop the finished drawing and direct a designer in making a finished drawing; and (c) *talking* sketches to communicate and exchange ideas among technical people to clarify possibly confusing parts of the drawing. The purpose of this study is to systematically investigate how novice/K-12 students' visual representation of an engineering design idea has been operationalized, measured, or assessed in the research literature.

Method

Intellectual contributions of scholars must be situated in the context of prior studies and knowledge-construction endeavor; however, the number of published papers each year is rapidly growing. Different disciplines are developing methods of systematic review approaches to synthesize previous studies (Borrego et al., 2014). For example, in areas such as social sciences (Petticrew & Roberts, 2008), education (Gough et al., 2017), and engineering education (Hynes et al., 2017) systematic reviews are used to critically evaluate, summarize, and try to "…reconcile the evidence in order to inform policy and practice" (Petticrew & Roberts, 2008, p. 15). In this study, we attempted to follow precise, methodical, and repeatable procedures aiming at (a) selection of an appropriate collection of studies that would address the review questions and (b) extraction of trends, patterns, relationships, and the overall picture of the research topic from the collected studies. Consistent with the purpose of systematic reviews, our goals were to describe and explore the state of knowledge or practice on novice/K-12 free-hand idea-sketching.

Procedure

In this systematic review of the novice/K-12 design studies, we consider articles within three disciplines suggested by expert librarians: Education, Mechanical Engineering, and Engineering Education. These three disciplines are more closely related to education in general and sketching in particular. Additionally, people in the Mechanical Engineering sketch more frequently than other fields of engineering. We followed steps suggested by Borrego et al. (2014) for systematic reviews in engineering education and other developing interdisciplinary fields. This approach is aligned with Evans and Benefield's (2001) key features of a systematic review in educational research, as well as Petticrew and Roberts' (2008) practical guide for systematic reviews in the social sciences.

First Step: Deciding to Conduct a Systematic Review

Based on our initial review of design studies, there is no reliable measure for evaluating novice/K-12 student-level idea-sketching activities in the context of STEM disciplines. The purpose of this systematic review is to explore trends, patterns, relationships, and the overall picture of K-12 visual representations of ideas, from the collected studies. This systematic review serves as the first stage of scale-development design, following guidelines that DeVellis (2017) and McCoach et al., (2013) provided on the development of closed-form multi-item measures. This study was part of a larger longitudinal research project focusing on implementing creativity development strategies in university-based summer enrichment engineering courses.

Second Step: Identifying the Scope and Research Questions

Employing a qualitative systematic review method, the purpose of this study is to explore how novice/K-12 students' visual representation of a design idea (e.g., sketches) has been operationalized, measured, or assessed. In other words, the research question guided this study was *what research and evaluation methods, coding protocol, or criteria had been used to study novice/K-12 visual representation of a design (e.g., sketches)?* How are sketching and visual representation of a design conceptualized in novice/K-12 formal and informal education? This qualitative systematic review attempted to select, categorize, and provide an age-appropriate set of criteria and standards to inform and evaluate novice/K-12 idea-sketching activities in response to a design-based practice.

Third Step: Defining Inclusion/Exclusion Criteria

Given the above scope and research question, we defined a set of criteria for inclusion in the systematic review. These criteria and their description are presented in Table 7.

Table 7 Systematic Review Inclusion Criteria

Criteria	Description
Publication type	Scholarly peer-reviewed journal publications
Paper type	Research (including empirical studies and theoretical/non-empirical articles)
Publication date	January 1989-August 2019
Context of research	K-12 design studies and STEM education including sketching and drawing activities (this may include research on K-12 teachers, informal settings involving K-12 students such as enrichment and extra-curricular activities, as well as formal classroom settings)
	First-year college students who were described as novice designers in the studies
Language	English

Publication Type. We included peer-reviewed journal articles, which are generally assumed to have higher quality than other types of publications. Additionally, by limiting our search to peer-reviewed papers, we intended to eliminate conference papers reporting on novice/K-12 STEM education research because of the highly variable quality of these papers.

Paper Type. All included papers were expected to report original research. Further, in assessing the quality of the studies, only research papers were considered, including empirical and non-empirical papers, which are articles that did not use any types of data (qualitative or quantitative) such as theoretical papers.

Publication Date. Because we were not able to find any systematic review on K-12 idea-sketching, we used a long range of years in our search. Thus, papers published between January 1989 through August 2019 were considered to include articles from 30 years.

Context of the Research. Papers reporting on research on novice/K-12 design studies and STEM education that included student sketches or drawing activities in any setting were selected. This may include research in K-12 settings, including formal classroom settings and informal settings, such as extra-curricular enrichment activities. Notable exclusion criteria were:

- EC1. Entirely focused on adults, graduate or university students, or early childhood. (First-year college students who were described as novice designers in the studies were included.)
- EC2. Exclusively used computer-assisted visualizations and sketching software.
- EC3. Entirely focused on technology, art, or architecture.

Language. We included research articles that were published in English, as this is the authors' common language.

Fourth Step: Finding and Cataloging Sources

The primary search was conducted across five large databases, as shown in Table 8. We consulted three university librarians to select the most appropriate databases to search for the purposes of this review. Two of the authors met with an expert librarian faculty who had experience with systematic review in Engineering Education (ENE), to check our initial systematic review protocol. Also, the two authors had a training session with another expert librarian in the field of education on the guides for working with the EBSCO*host* databases. Finally, the two authors had a meeting with a full professor of Library Sciences (Science and Engineering Data Librarian) to finalize our systematic review protocol. The two authors also had a training session provided by the full professor, on how to work with the Engineering Village database. So, based on these three meetings and these experts' recommendations, using our initial keywords, we created a list of search *terms* (Browsing ERIC, Thesaurus for Relevancy Ranked) in the EBSCO*host* educational databases (ERIC, Education Source, and Education Full Text), and also *controlled terms* (Brose Indexes) to be used in the engineering databases (Engineering Village and ProQuest Technology Collection).

Table 8 Five Periodical Databases and Our Boolean Search Terms Used to Identify Potential Articles in The Initial Step

Subjects	Databases (Description)	Combination of Search Terms and Word Strings
Education	ERIC (EBSCO Interface—Bibliographic database sponsored by the US Department of Education, is the premier source for education-related research, documents, and journal articles.) Education Full Text (This search platform includes articles in the area of education. This full-text source of education scholarship provides coverage for a wide range of topics, including adult education, continuing education, literacy standards, multicultural/ethnic education, secondary education, and teaching methods.) Education Source (The complete collection of full-text education journals, monographs, yearbooks, and more, covering scholarly research and information to meet the needs of education students, professionals, and policymakers. It covers all levels of education—from early childhood to higher education—as well as all educational specialties, such as multilingual education, health education, and testing.)	***Area 1 (Discipline):*** (((((((DE “Science Education”) OR (DE “Engineering Education”)) OR (DE “Mathematical Concepts” OR DE “Mathematical Enrichment” OR DE “Mathematics” OR DE “Mathematics Activities”)) OR (DE “Physics”)) OR (DE “Science Teachers”)) OR (DE “Science Instruction” OR DE “Science Projects”)) OR (DE “Biology”)) OR (DE “STEM Education”) OR “science education” OR “engineering education” OR “math education” OR “physics education” OR “chemistry education” OR “biology education” OR “stem education” AND ***Area 2 (Our focus)*:** (((((((DE “Freehand Drawing” OR DE “Drafting”) OR (DE “Visual Measures” OR DE “Visual Perception” OR DE “Visualization”)) OR (DE “Knowledge Representation”)) OR (DE “Brainstorming”)) OR (DE “Design Crafts”)) OR (DE “Design Requirements”)) sketching OR “freehand sketch*” OR “freehand drafting” OR “visual representation” OR “idea representation” OR “visual reasoning” OR “visual-spatial reasoning” OR “design representation” OR “design graphics” OR “engineering drawing” OR “engineering drafting” OR “engineering sketch*” OR “visual model” OR “drawing ideas” OR “idea visualization” OR “document* ideas” OR “drawing ideas” OR “design representation” OR “design visualization” OR “design studies” OR “graphical representation” AND ***Area 3 (Educational level)*:** ELEMENTARY EDUCATION, ELEMENTARY SECONDARY EDUCATION, GRADE 1, […], GRADE 12, HIGH SCHOOLS, INTERMEDIATE GRADES, JUNIOR HIGH SCHOOLS, MIDDLE SCHOOLS, PRIMARY EDUCATION, SECONDARY EDUCATION

Table 8 continued

Engineering	Engineering Village (Compendex and INSPEC Combined—Engineering Village is the information discovery platform to search across both Compendex and INSPEC databases. This search platform includes engineering related articles. Link: https://www.engineeringvillage.com/search/quick.url) ProQuest Technology Collection (Technology Research Database—This database is the total technology research solution, combining full-text journals with indexing of global literature on technology and applied science. This search platform is a collection of technology research in the areas of engineering and education. Link: https://search.proquest.com/technology1)	***Area 1 (Discipline):***: MAINSUBJECT.EXACT("Science education") OR MAINSUBJECT.EXACT("STEM education") OR MAINSUBJECT.EXACT("Technology education") OR MAINSUBJECT.EXACT("Physics") OR MAINSUBJECT.EXACT("Mathematics teachers") OR MAINSUBJECT.EXACT("Mathematics") OR MAINSUBJECT.EXACT("Biology") OR MAINSUBJECT.EXACT("Chemistry") AND ***Area 2 (Our focus)*****:** MAINSUBJECT.EXACT("Mechanical drawing") OR MAINSUBJECT.EXACT("Scale and proportion") OR MAINSUBJECT.EXACT("Universal design") OR MAINSUBJECT.EXACT("Design specifications") OR MAINSUBJECT.EXACT("Drawing") OR MAINSUBJECT.EXACT("Engineering drawings") OR MAINSUBJECT.EXACT("Sketches") OR MAINSUBJECT.EXACT("Drafting") OR MAINSUBJECT.EXACT("Pens & pencils") OR MAINSUBJECT.EXACT("Industrial design") OR MAINSUBJECT.EXACT("Design engineering") OR MAINSUBJECT.EXACT("Creativity") OR MAINSUBJECT.EXACT("Pilots") OR sketching OR "freehand drawing" OR "freehand sketching" OR "freehand drafting" OR "visual representation" OR "engineering drawing" OR "engineering drafting" OR "engineering sketches" AND ***Area 3 (Educational level)*****:** MAINSUBJECT.EXACT("Students") OR MAINSUBJECT.EXACT("Middle school students") OR MAINSUBJECT.EXACT("Middle schools") OR MAINSUBJECT.EXACT("Middle school education") OR MAINSUBJECT.EXACT("Beginning teachers") OR "middle school students" OR "high School students" OR "K-12 students" OR "Pre-college students" OR "Naïve Designers" OR "Novice Designers" OR "secondary education"

As shown in Table 8, in our initial search, we used a relatively broad set of terms, to avoid eliminating potential papers. We used Boolean operators to connect our search words to either narrow or broaden our set of results in the three different target areas. EBSCO*host* databases (ERIC, Education Source, and Education Full Text) have almost similar methods for searching, and we used the same search terms (see Table 8) for these three databases, to search the titles, subjects, and abstracts of articles. For engineering databases, the controlled terms were slightly different from the ones used in EBSCO*host*; however, both engineering databases (Engineering Village and ProQuest) use the same control terms with a slightly different method for searching. Table 8 provides search terms that were used for ProQuest.

Furthermore, we used controllers to limit our search to peer-reviewed journal publications, published from January 1, 1989, through August 15, 2019. We downloaded the Research Information System (RIS) file of the resulting sets of publications, which is a bibliographic citation file saved in a format developed by Research Information Systems. This initial search resulted in 885 articles. Mendeley citation manager was used to eliminate duplicated articles. We applied several elimination rounds to remove false-positive results. For example, the STEM search term commonly returns studies on the stem-cell subject matter in biology.

In addition to database searching, we considered three additional search approaches and sources: contacting experts, citation searching, and hand searching (Papaioannou et al., 2010). Contacting experts involved selecting specific experts and professional organizations to request articles for inclusion regarding the research questions and criteria (Borrego et al., 2014). The first author contacted ten professors in a School of Engineering Education. Citation searching involved reviewing (a) cited references in previously identified articles, and (b) citing references which include articles that cite the sources already identified (Borrego et al., 2014). Finally, hand searching consisted of searching for articles published in specific journals (National Institute for Health and Clinical Excellence, 2009), including the *Journal of Pre-College Engineering Education Research*, *Journal of Engineering Education*, *International Journal of Engineering Education*, and *Design Studies*.

Abstract Screening. After identifying potential articles using the search approaches described in the previous section, article abstracts were checked to further eliminate studies that did not match the inclusion criteria listed in Table 7. We started the abstract-screening phase with the Engineering Village database. Our search in the Engineering Village database returned 268 articles. Two of the authors reviewed 163 together in six 2-hour meetings to determine the inclusion or exclusion of these articles. Then, the two authors reviewed 38 articles separately and checked for the inter-coder reliability (ICR) agreement. The ICR agreement for the first round of abstract reviews was 75.67%. The two coders discussed the areas of disagreements, before the next round of inter-coder reliability agreement. Then, in the second round, 68 articles were separately coded. For the second round, the ICR was 85.29%. Having this level of agreement, we continued our abstract screening separately. We completed the abstract-screening phase, in which 843 (in total) articles were examined against the inclusion/exclusion criteria. As Petticrew and Roberts (2008) mentioned, after the irrelevant studies were excluded, full copies of the rest of the papers were retrieved and scanned to determine whether they met inclusion and exclusion criteria.

Further, we included consideration of fit to our systematic review question, as part of our overall inclusion/exclusion assessment of the individual studies (Borrego et al., 2014). Therefore, in addition to our inclusion/exclusion criteria, we examined the full text of 189 articles to check that to what extent the studies (a) focused on exploring or analyzing sketching, drafting, drawing, or visual representations of ideas; (b) included and elaborated on a systematic analysis of the sketches, drawing, or visual representation; and (c) to what extent the articles could be beneficial in developing a measure for exploring K-12 student idea-sketching activities. In this final screening step, 51 articles were excluded as they did not focus on design sketching (*n*=33) and did not include criteria, metrics, or coding protocols for exploring or evaluating sketches (*n*=18). Our PRISMA flowchart in Figure 2 represents the number of sources included and excluded at different phases of this systematic review. This left 138 articles for the fifth step, checking for the quality of articles.

Fifth Step: Critique and Appraisal

After the primary sources had been carefully selected, identified, and organized (*n* = 138), the next step was to systematically evaluate the quality of each primary source. Our criteria for the quality-check phase are presented in Table 9. In the existing literature on systematic reviews, quality is discussed as "…fit, transparency, and appropriateness" (Borrego et al., 2014, p. 58). In other words, as Petticrew and Roberts (2008) elaborated, the theoretical framework, procedures, and decisions need to be clearly stated. We employed the same criteria and procedures that Garcia et al., (2019) applied for quality checks in their systematic review. We responded to each criterion measure question in Table 9 using a 2-point scale, with 0 = No and 1 = Yes. Before checking the quality of all chosen articles, ten articles were randomly selected for the inter-rater reliability agreement. Reviewing and rating these ten studies, the first and third authors established an appropriate range of ICR agreement of 83% to 100%. Then, each rater independently checked the quality of randomly assigned articles.

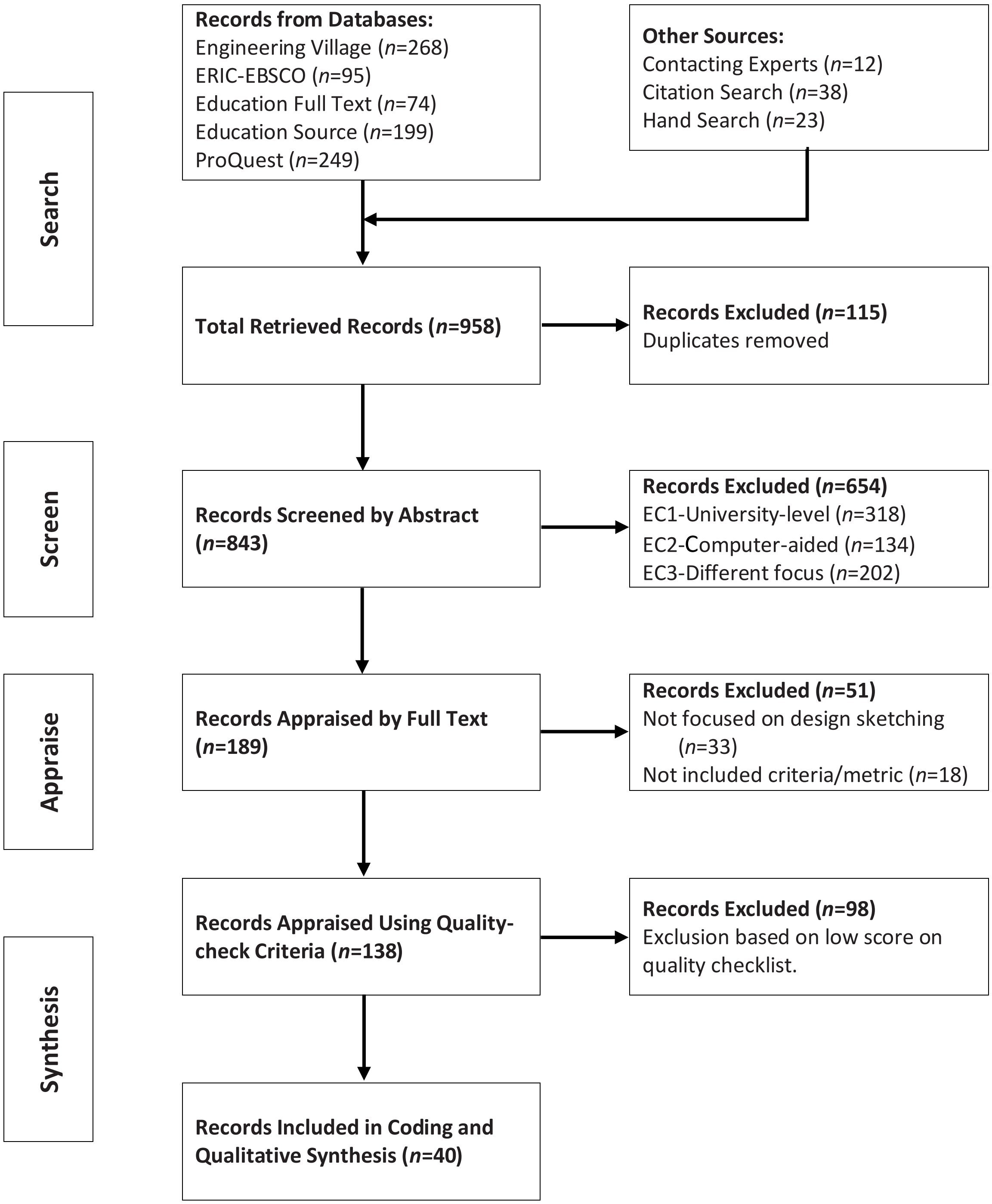

Figure 2 PRISMA Flowchart Representing Detailed Search and Screening Procedures

Table 9 Criteria to Evaluate Quality of Articles

Categories	Criteria Questions*
Empirical Studies	1. Is the article empirical?
	2. Is the research purpose or objective clear?
	3. Is the literature review, conceptual, or theoretical framework appropriate, driving the research questions and/or methods?
	4. Is the appropriate method used for addressing the purpose or objectives?
	5. Is there sufficient sample/data to address the purpose or objective?
	6. Is the research context adequately described?
	7. Is the analysis adequate or appropriate for addressing the purpose/objectives?
	8. Are the results and findings clearly presented and connected to the data?
	9. Are the methodological limitations or trustworthiness stated?
	10. Are the conclusions drawn from or connected to the data and empirical evidence?
Non-empirical Studies	1. Is the article nonempirical (descriptive or theoretical or program evaluation)?
	2. Is the research purpose or objectives clear?
	3. Is the problem statement, introduction, literature review, conceptual or theoretical framework appropriate and connected to the purpose?
	4. Is the description or theoretical argument or evaluation methods sufficient for responding to the purpose?
	5. Is the context adequately described?
	6. Are the conclusions drawn from the description or theoretical analysis or evaluation?

* All criteria are adopted from Garcia et al. (2019).

Studies that did not meet quality criteria (i.e., sum of the quality-score below 7 for empirical studies or below 4 for nonempirical studies) were excluded from the final review. After completing this quality check procedure, 96 articles were removed. This left a total of 40 articles included for our systematic review. Figure 2 illustrates the entire search, screening, and critique and appraisal process. Provisionally, during this fifth step of critique and appraisal, the first author developed the initial codebook and *start list* (Saldaña, 2013), for the purpose of the next step, coding, and qualitative synthesis.

Sixth Step: Coding Process and Qualitative Synthesis

For this step, we started coding selected records/studies, using Provisional Coding. Provisional Coding is an exploratory method, that begins with a *start list* of researcher-generated codes based on what preliminary inquiry suggests might appear in the data before they are examined (Saldaña, 2013). Additionally, we applied open coding in the first round of coding as well, to remain open to additional themes in the data (Charmaz, 2006). The NVivo software (QSR International Pty Ltd., 2018) was used as an organizing software program, and we followed Creswell's (2012) guidelines for establishing inter-coder reliability (ICR) agreement. For the first round of coding, 6 articles (~14% of the data) were randomly selected for the inter-coder reliability agreement process.

Inter-coder Reliability Process. After developing initial codebook as a *start list* of researcher-generated codes (Saldaña, 2013), two coders met to discuss these NVivo codes/nodes and to become familiar with their definition. Then, in the second meeting, the coders used the NVivo software, coding one article together. Then, the coders separately coded six randomly selected articles. After the first round of coding, the coders met to check for agreement and to discuss potentially new categories of nodes that emerged during the open coding process. The range of inter-coder reliability (ICR) agreement was between 92.9 and 100%. Therefore, based on this appropriate level of ICR agreement (Creswell, 2012), the coders continued coding the rest. Table 10 depicts the final codebook, descriptions of the nodes applied to code the articles, frequencies, and ICR agreement. The results and synthesis of the qualitative content analysis is discussed in the following section.

Table 10 Nodes, Descriptions, Frequencies, And Inter-Coder Reliability (ICR) Agreements of the Coding Process

NVivo Nodes	**Description**	**Frequencies**		**ICR* (%) Agreement**
		Files (#of Articles)	**References**	
Aesthetic Sensitivity	Comprised evidence of aesthetic sensitivity (such as use of color, pattern, or other visually appealing elements) to make pleasing presentation of ideas.	**17**	**59**	**96.9**
Annotations	Incorporated annotations to clarify elements in the sketch. (Sketches may have no annotations, one type, or multiple types of annotations.)	**31**	**167**	**92.9**
Cause-Effect Relationships	Included visual signs, labels, or annotations to presented casual relationships between/among different elements of the design.	**7**	**21**	**
Complexity	Showed adequate level(s) of complexity for the age-level group (e.g., number of steps represented in the design).	**20**	**61**	**99.6**
Configuration	Precisely represented position, distance, and arrangements of its elements to perform the intended plan.	**20**	**82**	**
Connections	Contained functional indicators (e.g., arrows, numbers, letters, or symbols) to make relationships between different parts or steps clear, the degree of interconnectedness.	**23**	**64**	**99.6**
Context	Included familiar object(s) or elements that indicate context or environment where it will be used or how it will be used.	**15**	**54**	**94.3**
Feasibility	Involved enough elaborations and details that makes the design feasible to build a prototype. (How close it comes to meet the design specifications and degree of manufacturability.)	**20**	**67**	**99.3**
Flexibility	Involved evidence of flexible thinking such as considering different types of design ideas or use of materials in different ways.	**8**	**14**	**99.7**
Forces	Employed arrows or other visual elements to indicate forces.	**9**	**68**	**99.8**
Functionality	Used enough visual components (e.g., words, symbols, drawings, callouts) to illustrate the intended functional aspects/mechanisms of the design.	**20**	**72**	**98.7**
Imagination	Included imaginative ideas or document imaginary story and creation of the mind.	**8**	**28**	**96.3**
Labels & Symbols	Used labeling parts to help the reader identify parts or determine prototyping materials, using symbols, signs, or texts.	**34**	**177**	**96.2**

Table 10 continued

NVivo Nodes	Description	Frequencies: Files (#of Articles)	Frequencies: References	ICR* (%) Agreement
Materials	Indicated each component of the design by its material or provided list of materials.	**20**	**69**	**
Motion	Accurately indicated anticipating motion and its direction, and expressed dynamics of moving parts or objects, such as using arrows, axes of rotation, steps through time, or other means. (Signals the presence of arrows or directional lines that are show movement on a static plane of paper.)	**20**	**75**	**98.3**
Numerical Elaboration	Included numbers or quantities to elaborate and add information, developing ideas in further details.	**18**	**87**	**99.2**
Originality	Included relatively original ideas.	**14**	**60**	**99.5**
Purpose	Clearly communicated purpose(s) of the design. Answer enough of the needs/purposes of the given task.	**15**	**56**	**98.4**
Scale	Included familiar object(s) or dimension that indicate the relative size of the concept depicted in the sketch.	**25**	**91**	**96.5**
Sequence	Incorporated visual signs or labeling to help the reader to understand sequence of events.	**18**	**43**	**98.4**
Shape Accuracy	Accurately illustrated geometric elements (such as lines, circle, triangular, oval, etc.) faithful to the intended shape.	**22**	**91**	**97.7**
Size of the Sketch	Covered the paper page that have been used for drawing.	**13**	**29**	**96.5**
Views	Used different views (such as isometric, top, front, back, or zoom-in) of the design. (use of shading to suggest three-dimensionality, juxtaposing multiple views)	**25**	**108**	**98**

***** NVivo-reported inter-coder reliability agreements
****** Added after ICR agreement, in the Open Coding process

Table 11 General Characteristics of the Qualifying Papers

Published Year	Before 2001	2001-2005	2006-2010	2011-2015	2016-2019
	2	4	3	16	15
Discipline of Journal	Design Studies	Engineering Education	Technology and Design	Science Education	Others**
	10	8	11	8	3
Major Focus of the Article	Eng. Design Process	Visual Representations	Sketching/Drawing	Design Thinking	Design Creativity
	8	8	16	3	5
Type of Study	Empirical	Non-empirical			
	34	6			
Methods	Quantitative	Qualitative	Mixed Methods		
	7	16	11		
Target Population*	Elementary	Middle School	High School	Novice/First-year College	General (N/A)
	10	5	13	8	7

***** Some of studies included more than one category, regarding targeted population in their research. The total number of the student sample sizes for the 40 selected papers is approximately 2075.

****** Mathematics Education, Creative Behavior, and Gifted Education

Synthesis

Following the procedures shown in Figure 2, our systematic review yielded 40 peer-reviewed journal publications on novice/K-12 idea sketching. Appendix A includes the summary of the articles based on their categories. The general characteristics extracted during the preliminary analysis to summarize the articles were (a) authors and year of publication, (b) type of article, (c) main research questions/purpose (target population), (d) main outcome/conclusions, (e) coded criteria for idea-sketching, and (f) whether the articles included a clear description of the applied sketching criteria (marked as yes, partially, or no). We need to mention that for almost all of the articles, the coded items (using our codebook for this study) were a larger set of features, rather than the criteria, metrics, standards, rubric, or coding protocol that were mentioned in the articles. In fact, some of researchers reviewed several features of sketching, but they did not include all the features they mentioned in their literature review in their coding protocol and analyses. Further, several of the articles did not include a clear description of the sketching criteria applied in data analysis. The majority (n = 34) of the included papers were empirical studies published after 2000 that appeared in technology and design journals. Table 11 summarizes general characteristics of the qualifying articles.

Themes in Conceptualizing Design Sketches

Our qualitative systematic review revealed three broad themes used by researchers to conceptualize sketching and visual representation of a design, in novice/K-12 formal and informal settings. These three themes include Communicating Ideas, Visual-Spatial Characteristics, and Design Creativity. In this section, we provide a summary of each of these three themes and discuss how they characterized sketching in the studies reviewed. A concept map of these categories and themes is presented in Figure 3.

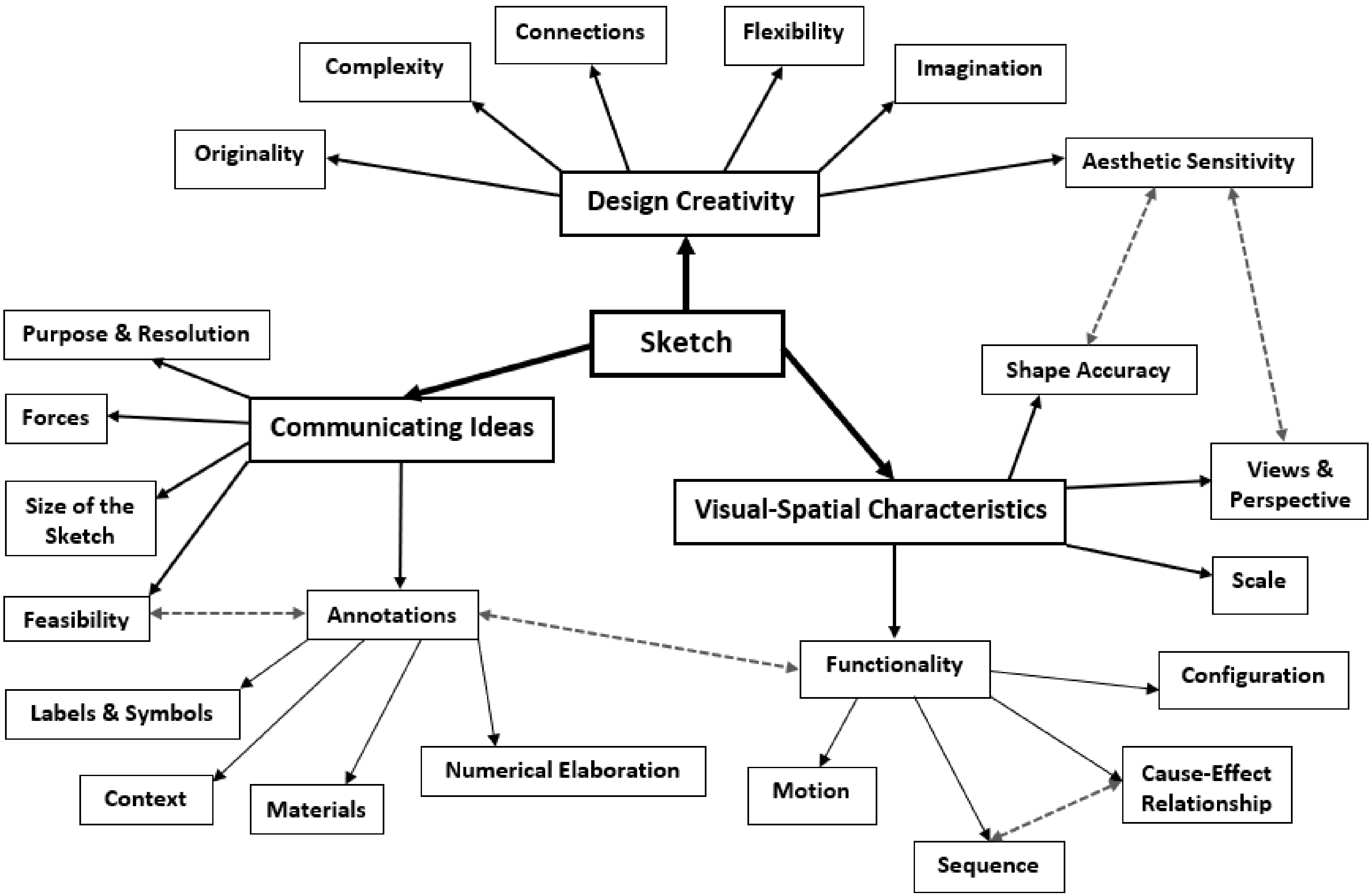

Figure 3 Concept Map of the Categories and Themes (3-pDS Conceptual Framework)

Communicating Ideas

Design challenges engage learners in a collaborative exercise that develops logical thinking and communication skills (Crismond & Adams, 2012; Sadler et al., 2000). Free-hand sketching is among the most common tools applied by engineers to express and communicate ideas, specifically during ideation (Galil et al., 2017; Pei et al., 2011). We found and categorized nine characteristics of sketching in this theme, including Annotations, Context, Feasibility, Forces, Labels, Materials, Numerical Elaboration, Purpose, and Size of the Sketch (see Table 10 for descriptions and frequencies of these codes). Based on our understanding from this systematic review, four of these subcategories (Labels & Symbols, Numerical Elaboration, Materials, and Context) can be grouped under the Annotations category, as elaborated in the following parts.

This theme and its subcategories, especially subcategories of Annotations were well-represented in approximately 85% (*n* = 34) of the 40 articles selected for our review. There were a few *Other* characteristics related to this theme, that were not included because of extremely low frequencies. For example, two of the articles mentioned cost and a bill of materials list as additional information can be included in the design specifications.

Technical drawing as a planning document is essential to support the development of a designer's ideas and to formulate, express, and communicate design ideas to others (Brophy et al., 2008; Capobianco et al., 2011; Charyton & Merrill, 2009; Lammi & Becker 2013) to co-construct shared knowledge. "The sketches and other forms of drawing are languages for handling design ideas. The actual process of creating design ideas is usually envisaged as going on in the mind's eye and the drawings as attempts to reproduce the designer's mental images" (Tovey et al., 2003, p. 137). Idea-sketching is highly recommended to carefully support the development phase of design, to help students understand the importance of drawing a model to communicate their design plans (Bamberger & Cahill, 2013; English, 2019). Kelley and Sung (2017) stated, "When students come to realize sketching as a journey of design thinking, sketching becomes a vehicle to communicate design ideas to other as well as self-communicating and refining the individuals' design ideas; it becomes a cognitive skill" (p. 367). Team-generated, handwritten sketches of their prototype design enable students to freely communicate their thoughts with one another (McFadden & Roehrig, 2019). Pei et al. (2011) recommended that communication among interdisciplinary members can be facilitated by having a shared understanding of visual representations, such as sketches. Martínez-Peña and Gil-Quílez (2014) mentioned the need to teach drawing as a communication tool in science classes as well.

In examining design cognition coding schemes for P-12 engineering/technology education, Grubbs et al., (2018) reviewed several coding schemes of design studies. In several of those design studies, communicating ideas is one of the common themes and categories (e.g., Atman et al. 2007; Hill & Wicklein 1999; Mentzer, 2014: Wicklein & Rojewski, 1999). As another example, Kelley and Sung (2017) provided evidence that design instruction treatment did improve student's design and communication practices, "…moving from using sketching as a container of ideas to the use of sketching as a form of design communication and to refine design ideas." (p. 363) Their treatment included presentations of sample sketches that contained symbols and labels students could identify. They showed Edison's and Rube Goldberg's sketches to the students to illustrate the power of using symbols, annotations, and labels, to communicate ideas, and a designer's ability to communicate the function of a design, motion of devices, sequence, and cause-effect relationships. Kelley and Sung (2017) mentioned, "…students were impressed that Edison's sketch could still communicate to us over 100 years after he created it"

(p. 370). Further, in the development of their Complexity scale, McGown et al., (1998) assessed each sketch based on the information that is communicated to the observer.

Several researchers elaborated on different cases of using sketching to communicate designs in groups of high school students. Sketching is most effective when combined with other forms of communication, such as annotations (Booth et al., 2016; Mentzer et al., 2014; Yang & Cham, 2007). Informed designers use gestures, words, and artifacts to explore and communicate their design plans (Crismond & Adams, 2012). Crismond and Adams (2012) stated that previous research showed skilled and beginner designers frequently use verbal descriptions when communicating early design ideas. For example, Galil et al., (2017), in their study of cognitive chunking during free-hand sketching of design ideas in engineering, asked their participants to annotate their drawing(s) with leaders and labels, as detailed as necessary for communicating their ideas to their team members. Student sketches are used throughout the design process, typically for communication purposes or idea generation, which may potentially be an unfamiliar practice for some students (Lammi & Becker 2013). McFadden and Roehrig (2019) presented the challenge of promoting drawn designs as a mean to communicate design ideas during problem-solving scenarios for elementary-aged learners. They provided examples of how the teams did not know how to effectively communicate their drawn design ideas, such as failing to incorporate labels. As Pei et al. (2011) stated, "…information sketches aim to quickly and effectively communicate features through the use of annotation and supporting graphics" (p. 73).

Visual-Spatial Characteristics

A second theme identified was the inclusion of indicators of visual-spatial reasoning in the drawn designs. Spatial reasoning concerns "…shapes, locations, paths, relations among entities and relations between entities and frames of reference" (Newcombe & Shipley, 2015, p.

180). Developing visual-spatial reasoning in combining design components is highly associated with the conceptual tasks involved in conceiving design ideas (Brophy et al., 2008; Sadler et al., 2000). Therefore, as Brophy et al. (2008) stated, pre-college engineering education may employ various hands-on activities to develop learners' competencies to apply geometric and spatial thinking and to acquire a qualitative sense for visual-spatial reasoning. We categorized eight characteristics of sketches in this theme: Shape Accuracy, Scale, Views, Configuration, Functionality, Cause-Effect Relationships, Motion, and Sequence (see Table 10 for descriptions and frequencies of these characteristics). Based on our understanding from this systematic review, four of these subcategories (Configuration, Cause-Effect Relationships, Motion, and Sequence) can be grouped in the Functionality category, as elaborated in the following parts. This theme and its subcategories are signified in 24 (60%) of our 40 selected articles, specifically subcategories of Functionality such as Scale and Views.

Learning many scientific concepts demands visual and spatial skills and understanding of the location of objects, their shapes, their relation to each other, and the paths they take as they move. For example, Cheng & Gilbert (2014) mentioned this notion in chemical ideas of the spatial distribution of particles (e.g., electrons) at different states of matter, and spatial rearrangement of atoms regarding the malleability of metals. In the context of engineering design, visual thinking is one of the techniques to help people achieve divergent thinking (Crismond & Adams, 2012), and different potential solutions to the design task could be developed through visual thinking (MacDonald & Gustafson, 2004). For instance, Juhl and Lindegaard (2013) explored representations and visual synthesis in first-year engineering design students. They described the addition of a third spatial dimension (three-dimensionality) as an improvement in learners' sketching, which helped to better understand the functionality of their design and relate the presented subfunctions to the product's internal architecture. This revealed the connection between Views and Functionality and how the changes in spatial representation (from a 2D drawing to isometric view) better illustrated the functional relations among the internal parts.

Visual-spatial reasoning can be supported by sketching, and sketches provide visual cues that can be helpful in problem-solving (Do et al., 2000; Goldschmidt, 1994; Jordan et al., 2016; Suwa & Tversky, 1997). As another example, in their analysis of spatial concepts, spatial skills and spatial representations in New York State Regents Earth science examinations, Kastens et al. (2014) applied subcategories such as Position, Configuration, Distance, Direction, Motion, Speed, Trajectory, and Shape in their Spatial Concepts category. They concluded that students, on average, scored lower on items coded as spatial than on items coded as nonspatial.

Visual-spatial skills are considered an essential component of the design process in general, and idea-sketching in particular (Brophy et al., 2008; Crismond & Adams, 2012; English, 2019; MacDonald & Gustafson, 2004). Goldschmidt (1991) discussed sketching as a dialectical process in which the role of design sketches is to facilitate spatial reasoning and analogy. Sketching has been considered as an important practice in the cognitive development of visual-spatial abilities and spatial visualization skills (Lane et al., 2010; McKim, 1980; Sorby & Baartmans, 1996; Strimel et al., 2019).

Design Creativity

Sketching has been closely linked with promoting design thinking and creativity (Daly et al., 2016; Galil et al., 2017; Joshi & Summers, 2012; Kelley & Sung, 2017; McGown et al., 1998; Oxman & Oxman, 1992; Römer et al., 2000; Suwa & Tversky, 1997). Engineering design practices involve open-ended, problem-based challenges that leave ample opportunity to support learners' creative behavior (Bamberger & Cahill, 2013; Lewis, 2009). Creative behaviors and hands-on activities are perceived as highly connected areas in the context of engineering design (Lasky & Yoon, 2011). Galil et al. (2017) mentioned, "Systematic study of sketching could provide insight into the cognitive and computational aspects of engineering creativity" (p. 115). Sketching shows the potential to function as both mediator and recorder of creative actions (McGown et al., 1998; Yang & Cham, 2007). We categorized six characteristics of sketching in this theme, including Aesthetic Sensitivity, Complexity, Connections, Flexibility, Imagination, and Originality (see Table 10 for descriptions and frequencies of these characteristics). This theme and its subcategories were found in 20 (50%) of our qualifying articles. We coded a few *Other* characteristics related to this theme that we did not include them because of our specific focus on the outcome of sketching activity, not the developmental processes. For instance, four out of the 40 studies mentioned fluency and quantity as a metric to evaluate the sketching (Daly et al., 2016; Joshi & Summers, 2012; Kelley & Sung, 2017; McGown et al., 1998).

A number of researchers in studies out of our selected list stated that the role of drawing in communicating ideas is overemphasized, and its role in creating and developing ideas is undervalued (e.g., Garner, 1992, 1994; Anning, 1997; Hope, 2000; MacDonald & Gustafson, 2004; Smith, 2001). Goel (1995) stated that free-hand sketching plays a vital role in the creative, explorative, open-ended phase of problem-solving. Purcell and Gero (1998) indicated that designers emphasize the sketching often because it is thought to be connected with innovation and creativity. While sketching is important in the design process, researchers in several studies have mentioned that students are reluctant to sketch. Booth et al. (2016) defined this reluctance as inhibition and summarized those factors that inhibit sketching in eight categories, including social loafing and comparative inhibition. These factors tend to cause a high cognitive load, which is correlated with the lower creative product. Bamberger and Cahill (2013) discussed an instructional strategy to balance the use of scaffolding with encouraging creative behavior with middle-school students, which supported learners in developing a metacognitive understanding of the design process.

Among the 40 articles we selected for inclusion in this systematic review were eleven studies in which the researchers tried to quantify subcategories of the Design Creativity theme (i.e., Bamberger & Cahill, 2013; Booth et al., 2016; Charyton & Merrill, 2009; Daly et al., 2016; Jordan et al., 2016; Kelley, 2017; McGown et al., 1998; Oman et al., 2013; Schwartz et al., 2011; Trebell, 2013; Yang & Cham, 2007). Comparing ideation techniques for beginning designers, Daly et al. (2016) assessed all of the concepts generated for creativity, elaboration, and practicality. Charyton and Merrill (2009) assessed general creativity and creative engineering design in first-year college students. They tried to develop their Creative Engineering Design Assessment (CEDA) measure, in which participants were asked to sketch ideas in response to specific functional goals that combine one or several three-dimensional components, list possible users of their design (people), generate other uses for their design, and perform problem finding. The measure involves five design problems to assess the ability to formulate and express design ideas through sketching. In their investigation of the influence of sketch quality on perceptions of product-idea creativity, Kudrowitz et al. (2012) concluded that ideas represented through high-quality sketches are much more likely to be perceived as creative. However, Pei et al. (2011) stated that the ambiguity of sketches can be beneficial for fostering creativity.

Some of the scholars in our selected studies (16 out of the 40) applied a qualitative approach to explore learners' visual representations, using different metrics, classifications, and coding protocols. Some studies in our selected list employed mixed methods (n = 11) or a quantitative approach (n = 7) to quantify some of the sketching characteristics, specifically for the creative characteristics. In this systematic review, we could not find any scholarly validated scale or rubric to evaluate K-12 student-generated sketches. Our goal in completing this qualitative systematic review was to select, categorize, and provide an age-appropriate set of criteria and standards to inform the development of an appropriate measure to evaluate K-12 idea-sketching activities. Based on our systematic review, 23 characteristics were proposed and categorized into three themes.

Limitations

We acknowledge some limitations to our systematic review. First, the scope of this systematic review is limited to the three disciplines (Education, Mechanical Engineering, and Engineering Education). Investigation of other domains in engineering is needed to address the applicability of the 3p-DS framework to other disciplines. Second, the selection process delineated in this paper excluded any book chapters and almost all conference proceedings reporting on K-12 sketching research. Additionally, we omitted a number of highly cited works explicitly focused on university-level sketching because our focus was on K-12 students. Therefore, information from chapters and studies of university students is not included in this review. It is possible if we had included it, our results may have been different.

Third, because the number of studies on K-12 sketching activities was limited, we included articles that targeted first-year novice college students. There may be relevant studies or scholarly articles that we did not find because of the limitations in the search terms and strings we used to identify potential articles (see Table 10). Articles that did not have the word "sketch" in the title or abstract may have been missed. Fourth, limiting our search to five databases may have led to some articles that would have met our inclusion criteria being missed. Some studies may have been published in journals or conference proceedings not indexed in these databases we used in our search. We tried to counteract these limitations by consulting three skilled librarians with expertise in systematic reviews in the field of education and engineering education and expanding our search terms to include more alternative words using *controlled terms* and *thesaurus* options. Finally, as Borrego et al. (2014) mentioned, different forms of bias associated with publishing add to limitations of systematic reviews in general, and these could have contributed to the limitations of this review. For example, publication bias and citation bias may have decreased the probability that studies with negative or uncertain results were published.

Future Directions

In K-12 settings, assessment is one of the major challenges in researching the effect of engineering education programs and curricula. There is a need for developing effective and reliable assessment methods to evaluate students' design activities. In future research, we will apply the Three-pronged Design Sketching (3-pDS) as a theoretical framework to develop a measure for evaluating pre-college learners' freehand sketches in response to a design task. The 3-pDS framework can serve as a skeleton for teaching how to generate a high-quality sketch of design ideas. It also can facilitate and guide the research agenda in K-12 engineering design and to explore students' engineering thinking and learning through sketching. Moreover, the role of group-level variables in communication and social interactions in design practices in general, and in idea-sketching, has not been investigated in the K-12 settings (Crismond & Adams, 2012). Whether it is within or across teams, disciplines, or cultures, there is a need to know more about how students apply the language of sketching when they try to communicate their ideas (Martínez-Peña & Gil-Quílez, 2014). Finally, the absence of specific research about visual-spatial creativity versus other dimensions of creativity leads to the need for comprehensive research agenda to examine visual-spatial creativity and how it compares and contrasts with all other types and dimensions of creativity.

Conclusion

Based on the findings from this systematic review, we conclude that there are indeed components common and necessary for high-quality design sketching. First, Communicating Ideas refers to the degree to which a student's sketch clearly communicates the design idea(s) and effectively represents the design information. Second, Visual-Spatial Characteristics refers to the degree to which a student's sketch properly involves visual cues related to the spatial characteristics of the design and combination of the parts. Third, Design Creativity refers to the degree to which a student's sketch presents indicators of creative design, such as producing a perceptible design that is both original and valuable as defined within the design context. In fact, these three components seem to form the basis of effective sketching for early engineering design practices. We, researchers of this study propose this Three-pronged Design Sketching (3-pDS) framework as a theoretical framework for future examination of novice/K-12 design sketches.

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Appendix A General Characteristics of the Qualifying Studies

Authors (Year)	**Type and approach of study**	**Main research questions/purpose**	**Target population (sample size)**	**Main outcome/conclusion**	**Coded items using our codebook for idea-sketching**	**Description for the criteria***
Abe & Starr (2003)	Empirical Qualitative	Describing an approach to teach how to create design specifications	1^{st} and 2^{nd} year engineering students	Appropriateness of the take-apart exercise for writing design specifications	Annotation, Forces, Connection, Functionality, Context, Motion, Labels & Symbols, Numerical Elaboration	No
Bamberger & Cahill (2013)	Empirical Mixed methods	Teaching engineering design and helping teachers in terms of scaffolding strategies	Middle-school level, summer camp (*n*=38)	Discussing, revising, and proposing two scaffolding strategies that can address teachers' concerns	Annotation, Connection, Imagination, Flexibility, Functionality, Scale, Labels & Symbols, Materials, Numerical Elaboration, Purpose, Views	Yes
Booth et al. (2016)	Empirical Mixed methods	Exploring improvement in sketching abilities and reducing the inhibition to sketch with a sketching intervention	Novice student designers (*n*=66)	Provided evidence that "use of tools, indicating motion, the sketch size and, shape accuracy enhanced after the intervention" (p. 19)	Annotation, Complexity, Flexibility, Context, Motion, Scale, Sequence, Originality, Shape Accuracy, Size, Views	Yes

Appendix A continued

Authors (Year)	Type and approach of study	Main research questions/purpose	Target population (sample size)	Main outcome/conclusion	Coded items using our codebook for idea-sketching	Description for the criteria*
Brophy et al. (2008)	Non-empirical Theoretical	Exploring how engineering education can support achievement of a wide range of knowledge and abilities associated with comprehending and using STEM knowledge to accomplish real world problem solving through design, troubleshooting, and analysis activities (*P-12*)	N/A	Considered "issues regarding teacher knowledge and professional development, and institutional challenges such as curricular standards and high-stakes assessments, providing direction for future research and development on engineering" (p. 369)	Aesthetic Sensitivity, Cause-effect Relationships, Complexity, Configuration, Imagination, Feasibility, Flexibility, Materials, Purpose, Views	No
Capobianco, Diefes-dux, Mena, & Weller (2011)	Empirical Qualitative	Investigating students' conceptions about engineers and how might students' conceptions vary by grade level, gender, and community setting	Elementary students (*n*=396)	"A framework for organizing and interpreting students' conceptions is presented. Students conceptualized an engineer as a mechanic, laborer, and technician. More than half of the students who drew a person drew male engineers" (p. 304)	Annotation, Context, Scale, Labels & Symbols, Materials, Shape Accuracy	No

Appendix A continued

Authors (Year)	**Type and approach of study**	**Main research questions/purpose**	**Target population (sample size)**	**Main outcome/conclusion**	**Coded items using our codebook for idea-sketching**	**Description for the criteria***
Charyton & Merrill (2009)	Empirical Quantitative	Developing and validating a measure—the Creative Engineering Design Assessment	First-year engineering students (*n*=63)	The CEDA offers a tool of assessment to measure the challenging construct of creativity in engineering design, which is a necessary skill for innovation.	Annotation, Flexibility, Labels & Symbols, Materials, Originality, Purpose, Shape Accuracy	Partially
Cheng & Gilbert (2014).	Empirical Qualitative case study	Investigating 10-graders students' visualization of metallic bonding and the malleability of metals	High-school students (*n*=3)	The study suggests that a clearer understanding of the electrostatic force involved can be attained when students experience visual and verbal representations simultaneously, a conclusion supported by dual coding theory.	Annotations, Forces, Configuration, Connections, Context, Motion, Scale, Sequence, Labels & Symbols	No

Appendix A continued

Authors (Year)	**Type and approach of study**	**Main research questions/purpose**	**Target population (sample size)**	**Main outcome/conclusion**	**Coded items using our codebook for idea-sketching**	**Description for the criteria***
Crismond & Adams (2012)	Non-empirical Theoretical	Connecting and simplifying disparate findings from research on design cognition and presenting a robust framework for a scholarship of P-16 design teaching and learning (*P-16*)	N/A	This paper's theoretical contribution is an "emergent educational theory of informed design that identifies key performance dimensions relevant to K–16 engineering and STEM educational contexts. Practical contributions include the Informed Design Teaching and Learning Matrix" (p. 738).	Aesthetic Sensitivity, Annotation, Complexity, Configuration, Connections, Imagination, Feasibility, Functionality, Sequence, Labels & Symbols, Originality, Purpose	No

Appendix A continued

Authors (Year)	Type and approach of study	Main research questions/purpose	Target population (sample size)	Main outcome/conclusion	Coded items using our codebook for idea-sketching	Description for the criteria*
Daly et al. (2016)	Empirical Mixed methods	Comparing ideation techniques for beginning designers	First-year college students/Novice (*n*=102)	"Brainstorming led to the most concepts within the short ideation session. The elaboration of the concepts was significantly higher with design heuristics and morphological analysis techniques, and the practicality was significantly higher using design heuristics" (p. 101108)	Aesthetic Sensitivity, Annotations, Complexity, Configuration, Connections, Imagination, Feasibility, Flexibility, Functionality, Context, Motion, Scale, Sequence, Labels & Symbols, Originality, Shape Accuracy, Size, Views	Yes
English, Hudson, & Dawes (2012)	Empirical Mixed methods	Reporting on some findings from the longitudinal study, designing and implementing engineering-based problem-solving activities	Middle-school students (*n*=58)	"Identification of six, increasingly sophisticated levels of illustrated bridge designs, with designs improving between the classroom and homework activities of two focus groups of students" (p. 736)	Annotations, Forces, Complexity, Configuration, Connections, Feasibility, Labels & Symbols, Materials, Numerical Elaboration, Shape Accuracy, Views	Partially

Appendix A continued

Authors (Year)	**Type and approach of study**	**Main research questions/purpose**	**Target populatio n (sample size)**	**Main outcome/conclusion**	**Coded items using our codebook for idea-sketching**	**Description for the criteria***
English (2019)	Empirical Mixed methods	Reporting on a 4-year longitudinal, design research study across grades 3–6, proposing a conceptual framework towards informed design	Elementar y students (*n*=34)	"Students' increased satisfaction with their redesigns, displaying knowledge of material properties, measurement and spatial skills, and design processes indicated progress towards informed design" (p. 1011).	Aesthetic Sensitivity, Annotations, Configuration, Connections, Feasibility, Functionality, Scale, Labels & Symbols, Materials, Numerical Elaboration, Purpose, Views	Partially
Galil, Martusevich, & Sen (2017).	Empirical Mixed methods	Reporting a "human-subject protocol study aimed to study cognitive chunking during free-hand sketching of design ideas in engineering" (p. 115)	Novice undergrad students (*n*=9)	"The physical structure of the design solution is perceived by the designer in small chunks, rather than in continuous streams" (p. 115).	Annotations, Complexity, Connections, Functionality, Motion, Scale, Sequence, Labels & Symbols, Purpose, Shape Accuracy, Views	Yes
Grubbs, Strimel, & Kim (2018)	Empirical Qualitative content analysis	"Examining design cognition coding schemes for P-12 engineering/technology education to aid others in choosing an appropriate coding scheme" (p. 899-900)	P-12 Coding protocols (*n*=16)	"This article presents an examination of recent P-12 design cognition coding schemes with the purpose of providing a background for selecting and applying a scheme for a specific outcome" (pp. 899-900)	Feasibility, Views	No

Appendix A continued

Authors (Year)	**Type and approach of study**	**Main research questions/purpose**	**Target population (sample size)**	**Main outcome/conclusion**	**Coded items using our codebook for idea-sketching**	**Description for the criteria***
Jordan, Pereira, & Dalrymple, (2016)	Empirical Quantitative	Exploring the implementation of design swapping to encourage middle and high school students to better document their designs	Middle- and high-school students (*n*=136)	"Results showed that students who were notified prior to a design review of an imminent design swap generated higher-quality design sketches than those who were not notified or notified after a design review" (p. 1984).	Annotations, Complexity, Configuration, Connections, Feasibility, Flexibility, Functionality, Motion, Scale, Sequence, Labels & Symbols, Materials, Numerical Elaboration, Shape Accuracy, Views	Yes
Joshi & Summers (2012)	Empirical Qualitative	Exploring generic trends in reviewing the metrics currently used to analyze sketches (*General*)	Metrics currently used by researchers for analyzing sketches (*n*=13)	"This paper presents a review of the metrics currently used by researchers for analyzing sketches as a foundation for a more systematic approach to evaluating engineering design sketches through critical selection of metrics" (p. 781).	Aesthetic Sensitivity, Annotations, Forces, Complexity, Configuration, Connections, Imagination, Feasibility, Functionality, Context, Motion, Scale, Sequence, Labels & Symbols, Materials, Originality, Shape Accuracy, Size, Views	Yes

Appendix A continued

Authors (Year)	**Type and approach of study**	**Main research questions/purpose**	**Target population (sample size)**	**Main outcome/conclusion**	**Coded items using our codebook for idea-sketching**	**Description for the criteria***
Juhl & Lindegaard (2013)	Empirical Qualitative	Investigating how students engage with engineering design challenges and use visual representations to develop and integrate recognitions	First-year engineeri ng design students (*n*=5)	"Representations not only communicate findings but also incorporate analysis in their creation and facilitate what we call collaborative design synthesis" (p. 20).	Annotations, Forces, Complexity, Configuration, Connections, Feasibility, Functionality, Context, Motion, Scale, Sequence, Labels & Symbols, Materials, Numerical Elaboration, Originality, Purpose, Shape Accuracy, Size, Views	No
Kastens, Pistolesi & Passow (2014)	Empirical Mixed methods	Analyzing, categorizing, and quantifying the spatial concepts, spatial skills and spatial representations on New York State's end-of-course Earth Science exam	All items across 12 exams for high-school students (1,016 items total)	"Students on average scored lower on items that were coded as spatial than on items were coded as nonspatial" (p. 278).	Annotations, Configuration, Context, Motion, Scale, Sequence, Labels & Symbols, Shape Accuracy, Views	Yes
Kelley & Sung (2017)	Empirical Mixed methods	Exploring how students (grade 3-6) "learn and use design sketching to support their learning of science and design practices" (p. 363)	Elementa ry students (*n*=91)	"Design instruction treatment did improve student's design and communication practices, moving from using sketching as a container of ideas to the use of sketching as a form of design communication and to refine design ideas" (p. 363)	Annotations, Cause-Effect Relationships, Forces, Complexity, Configuration, Connections, Feasibility, Functionality, Motion, Scale, Sequence, Labels & Symbols, Materials, Numerical Elaboration, Originality, Views	Partially

Appendix A continued

Authors (Year)	**Type and approach of study**	**Main research questions/purpose**	**Target population (sample size)**	**Main outcome/conclusion**	**Coded items using our codebook for idea-sketching**	**Description for the criteria***
Kelley (2017)	Non-empirical Theoretical	Teaching K-12 student design sketching beyond traditional sketching exercises (*elementary*)	N/A	Proposing general design sketching fundamentals and scaffolding strategies to help students refine sketches	Annotations, Connections, Feasibility, Functionality, Motion, Scale, Sequence, Labels & Symbols, Materials, Views	Yes
LaDue, Libarkin, & Thomas (2015)	Empirical Qualitative	Evaluating the similarities and differences of visuals used to assess students' knowledge of chemistry, earth science, living environment (biology), and physics on the New York State Regents examination	Analysis of distinct visual representation categorized across the four content examinations of high-school students (*n*=266)	"This study identifies which representations are most critical for training students across the science disciplines in anticipation of the implementation and eventual assessment of the NGSS" (p. 818).	Annotations, Connections, Motion, Scale, Sequence, Labels & Symbols, Numerical Elaboration, Shape Accuracy, Views	Partially

Appendix A continued

Authors (Year)	Type and approach of study	Main research questions/purpose	Target population (sample size)	Main outcome/conclusion	Coded items using our codebook for idea-sketching	Description for the criteria*
MacDonald & Gustafson (2004)	Empirical Qualitative	Investigating characteristics of children's (ages 11-13) design technology drawings and how an analytic scheme, derived from professional drawing practice, be used to analyze children's design technology drawing (p. 55)	Middle-school students (*n*=27)	Proposing integrated drawing/design technology problem-solving model	Annotations, Connections, Feasibility, Scale, Labels & Symbols, Materials, Numerical Elaboration, Views	Partially
Martínez-Peña & Gil-Quílez (2014)	Empirical Qualitative	Analyzing graphic representations of landscapes, produced by 46 Spanish 10th-grade secondary students and 92 teacher-training students (p. 701)	High-school students (*n*=46) and teacher-training students (*n*=92)	Causal relationships are hardly shown in either the drawings or the descriptions. This study uses a tool to analyze students' drawings that can be used to promote the learning of models by producing drawings.	Aesthetic Sensitivity, Annotations, Complexity, Configuration, Connections, Cause-Effect Relationships, Context, Scale, Motion, Sequence, Labels & Symbols, Materials, Numerical Elaboration, Purpose, Shape Accuracy, Size, Views	Yes

Appendix A continued

Authors (Year)	Type and approach of study	Main research questions/purpose	Target population (sample size)	Main outcome/conclusion	Coded items using our codebook for idea-sketching	Description for the criteria*
Marušić & Slisko (2018)	Empirical Qualitative	Investigating visual representations of situation in a partially defined Physics problem to explore kinds of drawings students generate	High-school students (*n*=50) and first-year college students (*n*=75)	"Numerical exercises, formulated in standard way mostly used in the teaching process, cannot develop the ability of visual representation of physics problem in a satisfying way" (p. 1).	Annotations, Forces, Configuration, Labels & Symbols, Numerical Elaboration, Views	Yes
McFadden & Roehrig (2019)	Empirical Qualitative	Exploratory case study examining "how various instructional strategies can influence student discourse patterns during an engineering design challenge" (p. 231)	Elementary students (*n*=4) and their teacher	"The study's findings illustrate the importance of designing and implementing pedagogical supports capable of ensuring students understand how their drawn designs can be used" (p. 231).	Cause-Effect Relationships, Labels & Symbols, Materials	No
McGown, Green, & Rodgers (1998)	Empirical Mixed methods	Investigating "designers at work in the early stages of design, concentrating on the visible sketching component of the design activity" (p. 431)	Students in Product Design Engineering course (*n*=4)	Developing a Complexity scale, quantifying qualities sketches for a measure of the information it communicated to the observer (p. 445)	Aesthetic Sensitivity, Annotations, Forces, Complexity, Configuration, Connections, Feasibility, Functionality, Cause-Effect Relationships, Context, Motion, Scale, Sequence, Labels & Symbols, Materials, Numerical Elaboration, Purpose, Shape Accuracy, Size, Views	Yes

Appendix A continued

Authors (Year)	**Type and approach of study**	**Main research questions/purpose**	**Target population (sample size)**	**Main outcome/conclusion**	**Coded items using our codebook for idea-sketching**	**Description for the criteria***
Mentzer, Huffman, & Thayer (2014)	Empirical Mixed methods	Identifying how high-school students allocate their time across different types of graphical and mathematical modeling	High-school students (*n*=20)	"Implications for the classroom include encouraging students to transfer understanding of science and mathematics into technology and engineering contexts through different types of modeling, such as mathematical, graphical, and physical" (p. 293).	Aesthetic Sensitivity, Annotations, Configuration, Feasibility, Context, Scale, Labels & Symbols, Materials, Numerical Elaboration, Shape Accuracy, Size, Views	Partially
Nemiro, Larriva, & Jawaharlal (2017)	Empirical Qualitative	Examining how the School Robotics Initiative fosters student creative behavior through designing a robot with a preplanned approach	Elementary students, 4^{th}-6^{th} grade (*n*=194)	The authors "propose a componential model for developing creative behavior in the students through robotics" (p. 70).	Annotation, Cause-Effect Relationships, Motion, Sequence, Materials, Numerical Elaboration, Originality	No
Oman, Tumer, Wood, & Seepersad, (2013)	Empirical Quantitative	Introducing a new perspective/ direction on assessing and encouraging creativity in concept design for application in engineering design education and industry (p. 65)	Students in an engineering design course (*n*=29 design teams)	"The paper details the creation of the two creativity assessment methods followed by an application of the CCA and MPCA to two case studies drawn from engineering design classes" (p. 65).	Complexity. Feasibility, Flexibility, Functionality, Context, Labels & Symbols, Originality, Size	Yes

Appendix A continued

Authors (Year)	Type and approach of study	Main research questions/purpose	Target population (sample size)	Main outcome/conclusion	Coded items using our codebook for idea-sketching	Description for the criteria*
Pei, Campbell, & Evans (2011)	Non-empirical Theoretical	Identifying the "representations employed by industrial designers and engineering designers during NPD" (p. 64) (*General*)	N/A	Categorized visual design representations in the form of a taxonomy "that is a systematic organization of VDRs that are presently dispersed in the literature" (p. 65)	Aesthetic Sensitivity, Annotation, Feasibility, Functionality, Context, Labels & Symbols, Scale, Material, Numerical	Yes
Purcell & Gero (1998)	Non-empirical Theoretical	Collecting and reviewing the results of previous research the sketch and its role in design, "and to relate it to similar research that has looked at the role of drawings in problem solving in other disciplines" (p. 389)	(*General*) N/A	"This work provides theoretical frameworks, experimental methodologies and a considerable body of research results that are of great potential importance to design research" (p. 389).	Complexity, Configuration, Connections, Feasibility, Functionality, Scale, Materials, Originality, Size	No
Rellensmann, Schukajlow, & Leopold (2017)	Empirical Mixed methods	Investigating how do "strategic drawing knowledge, drawing accuracy, and type of drawing (situational and mathematical drawings) relate to students' modelling performance" (p. 58)	High-school students (*n*=61)	"Strategic knowledge about drawing was positively related to students' modelling performance, mediated by the type and accuracy of the drawings that were generated. The accuracy of situational drawing was related only indirectly to performance. The accuracy of mathematical drawings, however, was strongly related to students' performance" (p. 70).	Labels & Symbols, Numerical Elaboration, Shape Accuracy	Yes

Appendix A continued

Authors (Year)	Type and approach of study	Main research questions/purpose	Target population (sample size)	Main outcome/conclusion	Coded items using our codebook for idea-sketching	Description for the criteria*
Schwartz, Thomas-Hilburn, & Haverland (2011)	Empirical Quantitative	Examining student responses to different forms of assessment, including drawing prompts	Elementary students (*n*=165)	"Students who are able to answer objective questions about groundwater are not necessarily able to demonstrate their knowledge" (p. 139).	Complexity, Connections, Labels & Symbols, Motion, Purpose, Size	Yes
Shively, Stith, & Rubenstein (2018)	Non-empirical Theoretical	Providing sample rubrics to assess creative and critical thinking skills independently within the Design Thinking Model (*K-12*)	N/A	This article provided "many criteria for teachers to assess thinking process skills in any given project, but particularly highlighted the natural intersections of creative and critical thinking in the DTM" (p. 155).	Flexibility, Originality, Purpose	Yes
Smith & Bermea (2012)	Empirical Qualitative	Exploring student sketches of plate boundaries with required annotations	First-year college students (*n*=149)	"Analysis of the sketches revealed that most students lack an explanatory mental model that links the locations of earthquakes, volcanoes, and magma generation to plate-boundary processes" (p. 350).	Annotations, Connections, Configuration, Forces, Labels & Symbols, Motion, Scale, Sequence, Shape Accuracy	Yes

Appendix A continued

Authors (Year)	**Type and approach of study**	**Main research questions/purpose**	**Target population (sample size)**	**Main outcome/conclusion**	**Coded items using our codebook for idea-sketching**	**Description for the criteria***
Song & Agogino (2004)	Empirical Quantitative	Describing designers' sketching activities in new product design teams	First-year college students (*n*=57) and conceptual design sketches (*n*=260)	"There is a statistically significant correlation between the total number of individual journal sketches created during the design process and an individual student's class grade" (p. 1).	Aesthetic Sensitivity, Annotations, Complexity, Configuration, Connections, Context, Feasibility, Functionality, Labels & Symbols, Materials, Motion, Numerical Elaboration, Originality, Scale, Sequence, Shape Accuracy, Size, Views	Yes
Strimel, Kim, Grubbs, & Huffman (2019)	Empirical Qualitative meta-analysis	Examining the design cognition studies identified and "synthesized both the findings and discussions according to the three coding scheme themes" (p. 1)	Design cognition studies (*n*=16)	"The results of this investigation can provide deeper insights into primary and secondary students' design thinking and can help inform design pedagogy" (p. 3).	Feasibility, Functionality, Labels & Symbols, Purpose	No
Tovey, Porter, & Newman (2003)	Empirical Qualitative	Presenting a brief summary of work in the general field of concept sketching and visual thinking	Design students (*n*=6)	"The design of CAD systems to support concept development must take account of the importance of sketching activity" (p. 135).	Aesthetic Sensitivity, Annotations, Complexity, Functionality, Imagination, Labels & Symbols, Originality, Scale Shape Accuracy, Size, View & Perspectives	Yes

Appendix A continued

Authors (Year)	Type and approach of study	Main research questions/purpose	Target population (sample size)	Main outcome/conclusion	Coded items using our codebook for idea-sketching	Description for the criteria*
Trebell (2013)	Empirical Qualitative	Investigating the effectiveness of a conceptual design unit as part of the Design and Technology curriculum for 14 years old pupils in England (p. 23)	High-school students (n=18)	Findings indicate that the "pupils' designing was highly iterative, creative, involved making a wide range of design decisions and revealed understanding of technological concepts" (p. 23).	Aesthetic Sensitivity, Annotations, Complexity, Connections, Imagination, Feasibility, Functionality, Context, Motion, Scale, Labels, Numerical Elaboration, Originality, Purpose, Shape Accuracy, Views	Yes
Yang & Cham (2007)	Empirical Quantitative	Investigating "the role of designer's sketching ability and to examine the potential link between sketching skill and measures of engineering design performance" (p. 476)	Undergraduate novice students (*n*=32)	"Negative correlation was found between sketch quantity and a skill related to mechanism visualization. No conclusive correlations were found between the sketching skills and design outcome and reviewer ranking" (p. 476).	Annotations, Complexity, Configuration, Functionality, Labels & Symbols, Originality, Scale, Shape Accuracy, Views	Yes
Zheng, Yao, Zhao, & Wang (2017)	Empirical Quantitative	Proposing a weak supervised approach to discover the most discriminative patches for different categories of sketches, which perhaps grasp the key to a good free-hand sketch	TU-Berlin sketch benchmark dataset (*n*=20,000 sketch images	The experimental results on the TU-Berlin sketch benchmark dataset (dataset of sketch open to the public) demonstrate the effectiveness of the proposed method, as compared to other available approaches.	Aesthetic Sensitivity, Annotations, Complexity, Labels & Symbols, Motion, Purpose	Partially

* For almost all of the articles, the coded items (using our codebook for this study) were a larger set of features, rather than the criteria, metrics, standards, or coding protocol that have been mentioned in the article.

CHAPTER FOUR TOWARD INFORMED DESIGN SKETCHING: DEVELOPING THE IDEA-SKETCHING EARLY ENGINEERING DESIGN (I-SEED) SCALE

Abstract

In K-12 settings, one major challenge of conducting research on the influence of engineering education programs and curricula involves assessment. There is a need for developing alternative, effective, and reliable assessment measures to evaluate students' design activities. This study aimed to address this need by developing the idea-Sketching Early Engineering Design (i-SEED) Scale to assess pre-college learners' freehand sketches in response to a design task. Applying the Three-pronged Design Sketching (3-pDS) as a theoretical framework, the purpose of this study was to examine evidence of content validity, construct validity, and internal consistency of the i-SEED Scale data. The data collection took place in a residential summer enrichment program for students with gifts and talents at a Midwestern university. Following different stages of scale-development design, a sample of 113 design sketches were scored in this study, and the scores were used to provide evidence of the validity of the data for the i-SEED Scale. The sketches were generated by 120 middle- and high-school students in a collaborative design-oriented course. Exploratory factor analysis results supported a three-factor model for the i-SEED Scale, including Visual-Spatial Characteristics, Design Creativity, and Communicating Ideas.

Toward Informed Design Sketching: Developing the idea-Sketching Early Engineering Design (i-SEED) Scale

As many outreach programs have demonstrated, engineering education has enormous potential to increase conceptual understanding of Science, Technology, Engineering, and Mathematics (STEM) disciplines for students (Brophy et al., 2008; Crismond & Adams, 2012). It also has been promoted as pedagogical support for learning scientific content (McFadden & Roehrig, 2019). Specifically, engineering design is considered as a *central piece* (National Research Council, 2011) for K-12 learners, as it provides students with domain-specific disciplinary engagement intended to mirror engineering practice (Next Generation Science Standards [NGSS] Lead States, 2013). Design experiences play a substantial role in precollege students' STEM education and career preparation (Crismond & Adams, 2012; Kelley & Sung, 2017). Design-oriented practice activates higher-order thinking skills (McFadden & Roehrig, 2019) that enable learners to analyze, evaluate, and make decisions during the design process (Fan & Yu, 2017).

Idea-sketching is a fundamental area of design (Booth et al., 2016; Crismond & Adams, 2012) that includes brainstorming, documenting ideas, and communicating ideas to others (Cardella et al., 2006; Jordan et al., 2016; Kelley & Sung, 2017). Design-oriented practices can be supported through sketching in several ways, such as making internal thinking explicit; envisioning more complex systems; enhancing collaboration and communication; and supporting the designers' self-reflection on their imagined solutions (Cardella et al., 2006; Uziak & Fang, 2018). Thus, visual representations and sketching play a critical role in improving STEM learning (Rau, 2017).

Although design practices increasingly play a key role in engineering education within K–12 settings, there are few inquiries to purposefully link research findings on how pre-college students design and what educators need to improve K–12 learners' design skills (Crismond & Adams, 2012). In K-12 settings, one major challenge in researching the influence of engineering education programs and curricula involves assessment (Brophy et al., 2008; Crismond & Adams, 2012). As Brophy et al. (2008) emphasized, there is a need for developing alternative, effective, and reliable assessment measures to evaluate students' design activities, such as their ability to, "…generate external representations to make sense of a complex problem, … [and] creatively generate a number of viable ideas" (p. 380). Although K-12 teachers are becoming more interested in design-based instruction as a STEM pedagogical approach, more research is necessary to develop methods of evaluating students' design ability (Kelley, 2017). This study aimed to address this need through developing the idea-Sketching Early Engineering Design (i-SEED) Scale to assess precollege learners' freehand sketches in response to a design task.

Theoretical Framework: Three-pronged Design Sketching Framework

The Three-pronged Design Sketching (3-pDS) framework (Ghahremani et al., 2020) served as the theoretical framework of the i-SEED Scale development. This theoretical framework was developed through a systematic literature review, in which how novice and K-12 students' visual representation of design ideas has been operationalized, measured, or assessed was investigated. In the different phases of screening in this systematic review, we applied our inclusion, exclusion, and quality criteria. From an initial sample of 958 articles we included 40 studies in the final step of the coding process and qualitative synthesis. Applying provisional and open coding, three broad themes were identified in this inquiry that have been used by researchers to conceptualize sketching of ideas, in novice and K-12 design activities: Visual-Spatial Characteristics, Design Creativity, and Communicating Ideas.

Visual-Spatial Characteristics

In general, visual-spatial characteristics are considered as an essential component of idea-sketching in the engineering design process (Brophy et al., 2008; Crismond & Adams, 2012; English, 2019; MacDonald & Gustafson, 2004). Developing visual-spatial reasoning is highly associated with the conceptual tasks involved in conceiving design ideas (Brophy et al., 2008; Sadler et al., 2000). Crismond and Adams (2012) stated that in the context of engineering design, visualization is one of the techniques to help learners achieve divergent thinking. Idea-sketching activities support visual-spatial reasoning and provide visual cues that can facilitate the problem-solving process (Do et al., 2000; Goldschmidt, 1994; Jordan et al., 2016; Suwa & Tversky, 1997). MacDonald and Gustafson (2004) emphasized that different potential solutions to the design task could be developed through visualization. Therefore, K-12 engineering education may engage students in various design challenges to develop visual-spatial competencies and to acquire a qualitative sense for visual-spatial reasoning (Brophy et al., 2008). Idea-sketching practices serve as one of the important strategies in the cognitive development of visual-spatial abilities (Lane et al., 2010; McKim, 1980; Sorby & Baartmans, 1996; Strimel et al., 2019).

Design Creativity

Idea-sketching can potentially serve as a mediator and a recorder of design creativity (McGown et al., 1998; Yang & Cham, 2007), as sketching has been strongly associated with promoting creativity in design thinking (Daly et al., 2016; Galil et al., 2017; Joshi & Summers, 2012; Kelley & Sung, 2017; McGown et al., 1998; Oxman & Oxman, 1992; Römer et al., 2000; Suwa & Tversky, 1997). As Bamberger and Cahill (2013) and Lewis (2009) stated, design challenges involve problem-based open-ended tasks that leave ample opportunities to support learners' creative behavior. Creative behaviors and open-ended design-based activities are perceived as highly interconnected in the context of engineering education (Lasky & Yoon, 2011). Galil et al. (2017) mentioned, "Systematic study of sketching could provide insight into the cognitive and computational aspects of engineering creativity" (p. 115). Kudrowitz et al. (2012) concluded that ideas represented through high-quality sketches are much more likely to be perceived as creative.

Communicating Ideas

Design challenges are among the instructional strategies that engage students in collaborative learning that facilitate the development of logical thinking and communication abilities (Crismond & Adams, 2012; Sadler et al., 2000). Especially during design ideation, freehand sketching is one of the common tools in engineering design used to articulate and communicate ideas, (Galil et al., 2017; Pei et al., 2011). McFadden and Roehrig (2019) stated team-generated, handwritten sketches of their prototype design enable students to easily communicate their thoughts with one another. Bamberger and Cahill (2013) and English (2019) recommended the use of idea-sketching to help students understand the importance of drawing a model to communicate their design plans. In addition to communicating design ideas to others, the idea-sketching process serves as a self-communicating metacognitive tool to enhance and refine individuals' ideas (Kelley & Sung, 2017).

Toward Informed Design

The Informed Design Learning and Teaching Matrix (IDLTM) developed by Crismond and Adams (2012) served as a conceptual foundation for this study. Through a meta-literature review, in this theoretical framework, Crismond and Adams characterized students' design performances with *appropriate* starting and endpoints, proposing key performance dimensions relevant to K–16 engineering practices. They introduced nine design strategies, including Understand the Challenge, Build Knowledge, Generate Ideas, Represent Ideas, Weight Options/Make Decisions, Conduct Experiments, Troubleshoot, Revise/Iterate, Reflect on Process. As described in this framework, idea-generating and visual representation are an integral part of the design-thinking process. Specifically, two of these strategies, Generate Ideas and Represent Ideas, involve idea-sketching and visual representation of design ideas. The focus of this study is on the design strategy of Represent Ideas.

Crismond and Adams (2012) linked the nine design strategies to design patterns, contrasting “beginning vs. informed”, stating how novice designers versus informed designers apply those nine strategies. One of the central ideas within the IDLTM framework is the notion of an *informed designer* who is, “…considered to have gained a level of competence that lies beyond that of a novice designer but not that of an expert” (English, 2019, p. 1014). In this framework, the starting point chosen to portray a baseline in design competence is the thinking and performance level of students with little or no skill and no formal training in designing. The endpoint in design competence is that of the informed designer, whose level of thinking and performance lies somewhere between novice and expert designers. As Moraes et al. (2019) mentioned, the notion of an informed designer has been discussed in the literature using different labels such as an “advanced novice” (Dreyfus & Dreyfus, 2005), “expertlike novice” (Bereiter & Scardamalia, 1993), or “expert student” (Sternberg, 1998).

In the IDLTM framework, for each design strategy, Crismond and Adams (2012) proposed and elaborated on start- and endpoint performance levels. Regarding the design strategy of Represent Ideas, for start-point patterns (*surface drawing*), they stated beginning designers, “…propose superficial ideas that do not support deep inquiry of a system, and that would not work if built”; and for the endpoint performance level (*deep drawing*), they stated informed designers, “…use multiple representations to explore and investigate design ideas and support deeper inquiry into how system works” (p. 748). For this strategy, IDLTM learning goals for students involve exploring and investigating different design ideas through sketching. Crismond and Adams (2012) suggested their proposed two-step progression requires further modification and adjustment through empirical validation studies, and additional research needs to differentiate the IDLTM’s current two-point performance levels. “Such work would require developing suites of psychometric instruments that can reliably measure students’ use of design strategies” (Crismond & Adams, 2012, p. 775). Focusing on the idea-representation strategy through sketching, this study aimed to address this need, developing an instrument to differentiate among different performance levels of design sketching.

Purpose and Research Questions

The purpose of this study was to develop the idea-Sketching Early Engineering Design (i-SEED) Scale—an instrument to evaluate pre-university engineering design sketches that can potentially be used for early identification of high-potential designers. Specifically, the goal was developing a measure to evaluate middle and high school students’ sketches of Rube Goldberg-like chain-reaction machines. Following research questions guided this research:

RQ1. What content validity evidence exists from the data used to develop the i-SEED Scale?

RQ2. What construct validity evidence exists from the data used to develop the i-SEED Scale?

RQ3. What internal consistency evidence exists from the data used to develop the i-SEED Scale?

Methods

Research Design and Procedure: Scale Development

We followed general guidelines that DeVellis (2017) and McCoach et al. (2013) suggested on the development of closed-form multi-item measures including generating an item pool, selecting a scaling format, obtaining expert review, conducting a pre-pilot study, analyzing data, and revising the instrument based on results. According to McCoach et al. (2013), the initial steps of instrument development involve specifying the purpose(s) of the instrument, making sure that no existing scale serves the same objective(s), describing the construct and its dimensions, and developing final conceptual definitions for each dimension through an extensive literature review. These initial steps of this scale-development study have been addressed through our systematic literature review of novice and K-12 freehand idea-sketching practices (Ghahremani et al., 2020), in which we investigated how novice and K-12 students' visual representation of an engineering design idea has been operationalized, measured, or assessed in the research literature. Based on our systematic review of literature, the 3-pDS framework was proposed, which served as the theoretical framework for the i-SEED Scale development.

Generating Initial Item Pool

In our systematic review (Ghahremani et al., 2020), we could not find any scholarly developed and research-based measure to assess K-12 student-generated sketches. Our goal in completing a qualitative systematic review was to select, categorize, and provide an age-appropriate set of criteria and standards to inform the development of an appropriate scale to assess K-12 idea-sketching activities. Based on our qualitative systematic review, three broad themes/constructs were identified that have been used to conceptualize sketching of ideas, in novice and K-12 design activities: Visual-Spatial Characteristics, Communicating Ideas, and Design Creativity. We generated our initial item pool based on this Three-pronged Design Sketching (3-pDS) framework, including 23 characteristics that were identified in the systematic review of design studies. See Appendix A for the initial item pool and 23 characteristics. Definitions of the three constructs are as follows: The Visual-Spatial Characteristics construct measures the degree to which a student's sketch properly involves visual cues related to the spatial characteristics of the design and combination of the parts. The Design Creativity construct measures the degree to which a student's sketch presents indicators of creative design, such as producing a perceptible design that is both novel and useful as defined within the design context. The Communicating Ideas construct measures the degree to which a student's sketch clearly communicates the design idea(s) and effectively represents the design information.

Scaling Technique

To evaluate sketching quality, among traditional scaling techniques that McCoach et al. (2013) described, we used a common 5-point Likert-type measure to develop a closed-form multi-item scale with the following response options: 1 (Not at all/Naïve level), 2 (To a small extent/Novice level), 3 (To a moderate extent/Intermediate level), 4 (To an appropriate extent/Informed level), 5 (To a great extent/Advanced level). For consistency, all items in the i-SEED Scale have similar formats: *To what extent does the student use/involve/represent [X characteristic] in the design sketch?* We chose the 5-point response format as it can usually be treated as a continuous scale (McCoach et al., 2013), providing an appropriate number of differential points and spanning the entire performance continuum. Using Likert-type scaling, we summed and then calculated the average of the ratings across the items to compute the scale scores for the three constructs. Table 12 includes a sample item from the i-SEED, including descriptions for the different performance levels and distinctions of criteria across the response scale.

Table 12 Sample 5-point Likert-type Item of the i-SEED Scale

Views. To what extent does the student use different viewpoints in the design sketch, such as from the top, frontal, back, or zoomed-in view, in the design?

Naïve level (1)	Novice level (2)	Intermediate level (3)	Informed level (4)	Advanced level (5)
Not at all The viewpoint is not clear, and it is confusing.	To a small extent Used only one viewpoint (frontal view, for example) for the drawings and visualizing design elements.	To a moderate extent Used only one viewpoint (frontal view, for example) for the drawings and visualizing design elements. AND Used shading, texture, or other features to visually suggest three-dimensionality or depth.	To an appropriate extent Included two different views, such as from the top, front, back, or zoomed-in the design. OR Used isometric view, *with no precision*, attempted to visually represent three-dimensional objects in two dimensions.	To a great extent Juxtaposed multiple views (more than two), such as from the top, front, back or zoomed-in to communicate more details of an object and better demonstrate design idea(s). OR Used isometric view, visually representing three-dimensional objects in two dimensions, *with precision*.

Expert Review and Establishing Content Validity

It is critical that the proposed items be reviewed by experts (DeVellis, 2017). McCoach et al. (2013) stated, "…validity evidence based on instrument content should receive the highest priority during the early stages of the instrument development process" (p. 94). Thus, to establish content validity, we contacted 15 well-known experts in the field of K-12 engineering education. These experts were identified in our systematic review (Ghahremani et al., 2020) based on their work and research on pre-university STEM education. For example, we included experts in the INSPIRE Research Institute for Pre-College Engineering, which is the world's first research center in the School of Engineering Education at Purdue University, focusing on pre-college engineering education research and integration with science, technology, mathematics, and literacy. The INSPIRE researchers investigate pre-college engineering experiences and environments to inform the development of curricula, assessment instruments, teacher and parent education, museum exhibits, afterschool programs, and STEM education policy within the full spectrum of P-12 engineering education.

We designed a Content Validity Form for our scale (Appendix A) and sent the form to these 15 experts to examine the validity evidence of the items' content. We received responses from seven experts. The content validation rating form involved three aspects: (a) category (indicates the construct that each item best fits into), (b) certainty (indicates how certain participants are about their placement of the item into the construct), and (c) relevance (indicates how relevant participants believe each item is to the construct). As McCoach et al. (2013) stated, gathering evidence of content validity involves measuring the degree to which items of the instrument are relevant to the targeted construct. In addition to the quantitative ratings, qualitative feedback was simultaneously collected, regarding suggestions for the definitions of the three constructs; the extent to which that items appear to cover the full range of content within each construct; suggestions for improving content coverage; the wording of the scale items; appropriateness of the wording for middle- and high-school educators; suggestions for improving the item stems; and suggestions for adding items. See Appendix A for the expert Content Validity Form.

After collecting the feedback from the experts, we included all items rated at 3 (Highly relevant) for the relevance to the construct and rated at 3 (Pretty sure) or 4 (Very sure) for certainty by at least five of the seven experts. Additionally, four experts suggested removing or combining some of the items because they were related. The original and revised items after experts' review are presented in Table 13.

Table 13 The Original and Revised Items After Expert Review Grouped by Hypothesized Construct

Original Items	**Revised Items (Reason for Elimination)**
	Visual-Spatial Characteristics
Scale. Incorporated visual or textual components that indicate the relative size of the concept depicted in the sketch.	Scale. *To what extent does the student incorporate* visual or textual components *in the design sketch* that indicate the relative size of the concept depicted in the sketch?
~~Configuration. Represented position, distance, and arrangements of elements with precision.~~	(Overlap with Other Items)
~~Motion. Indicated anticipating motion and its direction.~~	(Overlap with Other Items)
~~Cause-Effect Relationships. Included visual signs, labels, or annotations to indicate casual relationships between/among different parts of the design.~~	(Overlap with Other Items)
~~Sequence. Incorporated visual signs or labeling to show the sequence of events.~~	(Overlap with Other Items)
Shape Accuracy. Illustrated geometric elements ~~such as lines, circles, and triangles~~ with precision.	Shape Accuracy. *To what extent does the student illustrate objects and* geometric elements *in the design sketch* with precision?
Views. Used different viewpoints such as from the top, front, back or zoomed in the design.	Views. *To what extent does the student use* different viewpoints *in the design sketch*, such as from the top, front, back or zoomed-in, in the design?
	Design Creativity
Aesthetic Sensitivity. Comprised evidence of aesthetic sensitivity, such as use of color, pattern, ~~or other visually appealing elements.~~	Aesthetic Sensitivity. *To what extent does the student comprise* evidence of aesthetic sensitivity in the design sketch, *using elements of visual Arts*?
Complexity. Showed adequate level(s) of complexity for the age-level group.	Complexity *of Ideas*. *To what extent does the student show the* adequate level(s) of the complexity *of ideas* for the age-level group *in the design sketch*?
Flexibility. Involved evidence of flexible thinking, such as considering different types of design ideas or uses of materials.	Flexibility. *To what extent does the student involve* evidence of flexible thinking *in the design sketch,* such as considering different uses of materials, or different types of ideas?

Table 13 continue

~~Imagination. Included imaginative ideas, stories, or creations of the mind that are not real.~~	(Not Relevant to the Constructs)
Originality. Included relatively original ideas, compared to others in the same group or at the same level of experience.	Originality**.** *To what extent does the student include* relatively original ideas *in the design sketch*, compared to others in the same group or at the same level of experience?
Communicating Ideas	
Annotations. Incorporated annotations to clarify elements and their functions in the sketch.	Annotations. *To what extent does the student incorporate* annotations *in the design sketch* to clarify elements and their functions in the sketch?
Connections. Contained ~~functional indicators such as arrows, numbers, letters, or symbols~~ to show relationships between different parts or steps.	Connections. *To what extent does the student contain* indicators *in the design sketch* to show connections among different parts *of the design*?
~~Context. Included familiar object(s) or elements that indicate the context or environment in which the design will be used.~~	(Overlap with Other Items)
Feasibility. Involved elaborations and details that make building a prototype of the design feasible.	Feasibility. *To what extent does the student involve* elaborations and details *in the design sketch* that make building a prototype of the design feasible?
Functionality. Used visual components ~~such as words, symbols, drawings, and callouts~~ to ~~illustrate~~ the intended functional aspects~~/mechanisms~~ of the design.	Functionality. *To what extent does the student use* visual *or textual* components *in the design sketch* to *communicate* the intended functional aspects of the design?
~~Applied Forces. Employed arrows or other visual elements to indicate forces.~~	(Overlap with Other Items)
~~Labels & Symbols. Labeled components of the design using symbols, signs, or texts to identify different parts.~~	(Overlap with Other Items)
~~Materials. Indicated each component of the design by its material.~~	(Overlap with Other Items)
~~Numerical Elaboration. Included numbers or quantities to elaborate and add information.~~	(Overlap with Other Items)
~~Purpose. Clearly communicated purpose(s) of the design.~~	(Overlap with Other Items)
~~Size of the Sketch. Used the entire paper in making the drawing.~~	(Not Relevant to the Constructs)

Used ~~strike through~~ for items or words eliminated.
Used *italics* for words or items added.

Pre-pilot Study

After conducting judgmental reviews by experts, modifying our items, and creating semi-final version of our i-SEED Scale, as suggested by DeVellis (2017) and McCoach et al. (2013), we invited a seven respondents from the potential target group to pre-pilot this scale: Two sample student sketches with relatively different performance levels were chosen and seven colleagues from College of Education who had K-12 teaching experience in STEM were asked to evaluate these two sketches, using the 11-item scale. Specifically, we applied the think-aloud technique, which is a type of cognitive interview, to examine individual interactions with the i-SEED Scale, as an aspect of the response process (Padilla & Leighton, 2017). In these cognitive interviews (Leighton, 2017), participants were asked to say out loud what they were thinking about when scoring those two sketches using the 11-item measure. Additionally, they were asked to provide feedback on item wording, clarity of the directions, and the appropriateness of the performance levels. As McCoach et al. (2013) recommended for this step, the seven participants were asked to identify any confusing or unclear items and terms. Based on the feedback from our pre-piloting stage, we made revisions and added more descriptions to differentiate and elaborated on the different performance levels for each item.

The three scorers in this study were also involved in the pre-pilot stage. Based on their educational backgrounds and teaching experiences, they were also involved in adding and revising descriptions of different performance levels for each item of the i-SEED Scale. After revising our 11-item measure based on the expert review and pre-pilot stage, three researchers (first, third, and fourth authors) used the scale to evaluate 113 middle- and high-school students' design sketches. See Appendix B for the full version of the scale, including descriptions of different performance levels for each item.

Context and Description of the Sketch Data

Sketch data were collected in a residential summer enrichment program for students with gifts and talents at a Midwestern university. Students who have completed grades 5 through 12 come from across the U.S. and from around the world (e.g., China, Colombia, Kingdom of Saudi Arabia, South Korea) each summer to take challenging courses in areas of their interest. Our study focused on the *STEAM Labs* ™ course, which has been offered in this summer program since 2008 for students in grades 7 through 12. This course emphasized engineering design and included an introduction to the engineering design process and several modules on a variety of science, physics, and mathematics topics, such as simple machines, energy transfer, and probability. In this course, students designed and built chain reaction machines. As stated in the course description, one of the main goals in this course is to "Apply the engineering design process to construct STEAM Machines (i.e., chain-reaction machines that run on STEM and Art concepts) using everyday objects" (Institute, 2018). Chain reaction, Rube Goldberg-type machines are devices that complete a simple task, such as raising a flag, in overly complex ways. During the design activities, students were required to document their design ideas and use provided worksheets in the group Design Binder for idea-sketching. Table 14 contains demographic information of students (n = 120) whose sketches were used in this study. These sketches are from 2017 through 2019.

Table 14 Demographic Information of Students Whose Sketches Were Used in This Study

	Gender		Grades						Ethnicity				
Year	F	M	7	8	9	10	11	12	Asian	Black or African American	Hispanic or Latinx	Native American	White
2017	10	14	9	4	6	2	3	0	7	2	7	2	6
2018	24	43	17	16	14	10	7	3	29	3	10	12	13
2019	14	15	15	14	0	0	0	0	10	2	5	4	8
Total	48	72	41	34	20	12	10	3	46	7	22	18	27

Throughout the *STEAM Labs* ™ course, participants engaged in design-thinking processes such as iterative brainstorming, planning, building, and testing of sub-modules and prototypes of their STEAM machines (which are Rube-Goldberg-style chain-reaction machines). Throughout the course design activities, students learned about and used the engineering design process, which involves five steps: Ask, Imagine, Plan, Create, and Improve (Engineering is Elementary [EiE] Project, Boston Museum of Science, 2009). In this course, students were usually grouped in teams of four individuals, and each team was provided with a Design Binder to document their ideas and progress. In the Design Binder, students were provided with an introduction to the course; introducing the engineering design process, the definition of some terms in the chain-reaction machines (such as step, module, and machine); and several handouts and worksheets for the student design activities. Although teaching how to sketch is not part of this course, students were provided with an example of a detailed sketch in their Design Binder (Figure 4). In the next stage of this scale-development study, 113 of these pre-existing student-generated sketches in their group Design Binder (from 2017 to 2019) were scored, using the revised 11-item based on the expert review (Appendix B). The scoring team did not include seven sketches as they were only drawings of the materials, and not sketches of a chain-reaction machine.

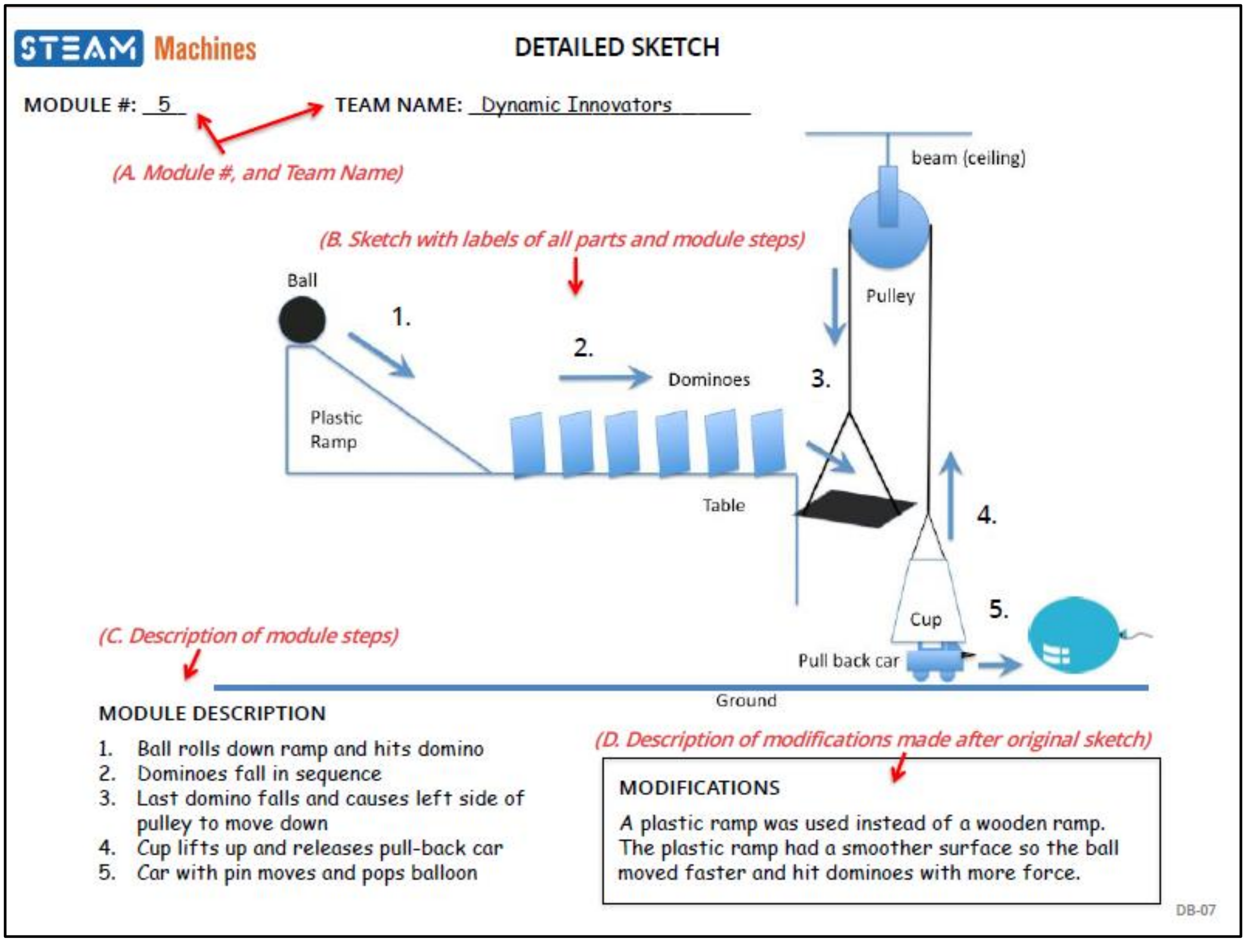

Figure 4 Detailed Sketch Example Provided in The Students' Group Design Binder (Jordan et al., 2016; © 2011-2014 Shawn Jordan, Odesma Dalrymple, & Nielsen Pereira)

Scoring Procedure

In the scoring phase, we evaluated sketches of the STEAM Machines from the *STEAM Labs* ™ courses, created by the students in their group Design Binder. Three graduate students in education, including two Ph.D. candidates, were involved in this scoring phase. Two of the raters had master's degrees in Physics, and the third one had an engineering background and teaching certificates in science and mathematics.

The first meeting to score sketches was face-to-face on March 16th, 2020. After the first meeting, because of the COVID-19 situation and stay-at-home orders, the rest of the meetings were held online, using the Office 365 Skype platform. Ratings were performed digitally, simultaneously using laptop computers connected to the Internet. The first author digitalized the Design Binders and shared sketches with the scoring team using Box a cloud-based data storage service for researchers. According to HRPP/IRB, the use of Box is an acceptable platform to store and share research data. The scoring team used a shared Excel spreadsheet on Office 365 OneDrive, with a separate sheet for each rater to record their scores. In this stage, we scored 113 sketches in 18 two-hour online sessions from March 16th through April 2nd, 2020, applying a modified version of the Consensual Assessment Technique (CAT: Amabile, 1982, 1983, 1996; Baer & Kaufman, 2019).

CAT was developed by Amabile (1982, 1983, 1996) to assess creativity aspects in a human product or performance, such as novelty, appropriateness, technicality, harmony, and artistic quality (Oman et al., 2013). This technique is widely used and well-validated in creativity research (Baer et al., 2004; Cheng, 2018). CAT is considered a gold standard of creativity assessment (Cseh & Jeffries, 2019). Baer and Kaufman (2019) suggested that this technique can be applied to any domain of human endeavor, including mathematical theories, dance performances, scientific theories, and experimental designs. Specifically, CAT is a common method in assessing engineering designs (e.g., Christiaans & Venselaar, 2005; Daly et al., 2016; Oman et al., 2013; Pektas, 2010). For example, similar to this study, Denson et al. (2015) reported adapting a web-based version of the CAT process for scoring student projects developed in a week-long engineering camp, using a series of Likert-type scales. As design creativity is one of the potential constructs in the i-SEED Scale development, the research team decided to use a modified version of the CAT for scoring sketches.

As suggested in the CAT, raters need to have domain experience, they should independently score the product (i.e., sketches), and they need to rate items relative to a specific sample and context (Cseh & Jeffries, 2019; Hennessey, 1994). For using this technique, Amabile (1996) also suggested that the raters need to rate products subjectively and only use their judgment, rather than using some standards in the domain. The highly subjective feature of rating in the original CAT is one of the issues challenging the CAT's credibility as a method (Cseh & Jeffries, 2019). Thus, in contrast to the Amabile's (1982, 1983) original suggestion, the raters in this study were provided with the i-SEED Scale to evaluate characteristics of the sketches.

Regarding the rating procedure, in the online meetings, for each sketch, the scoring team usually spent approximately 2-3 minutes to review the sketched design idea. Then, they separately scored the first item, recording their score in the separate individual Excel sheet on OneDrive. The scoring team repeated this procedure for all 113 sketches, using all 11 items in the i-SEED Scale. The average scoring time for each sketch was approximately 20 minutes.

Inter-rater Reliability Agreement

The scoring team reached an appropriate level of agreement in the fifth meeting, after scoring and discussing 30 sketches. During the fifth meeting, the team scored eight sketches and established an average of 82.25% pairwise inter-rater agreement (Creswell, 2012). For this set of scores, Fleiss' Kappa was .70 (Fleiss et al., 2003), and Krippendorff's alpha-reliability coefficient was .70, which can be considered as an acceptable level of inter-rater reliability (Hayes & Krippendorff, 2007; Krippendorff, 2004). The rating team applied the Consensual Assessment Technique, and three raters independently scored all of the sketches. To assess the CAT's reliability, Baer and Kaufman (2019) suggested calculating Cronbach's alpha as a measure of inter-rater reliability (Baer et al., 2004; Kaufman et al., 2008). Table 15 presents Cronbach's alpha coefficients for 11 items in the initial i-SEED Scale. These coefficients suggest high inter-rater reliability across all items.

Table 15 Cronbach's Alpha Coefficients For 11 Items Scored a By the Raters of this Study (n = 113)

Construct [b]	Item	Stem	C's α
Visual-Spatial Characteristics	Scale	To what extent does the student incorporate visual or textual components in the design sketch that indicate the relative size of the concept depicted in the sketch?	.90
	Shape Accuracy	To what extent does the student illustrate objects and geometric elements in design sketch with precision?	.93
	Views	To what extent does the student use different viewpoints in the design sketch such as from the top, frontal, back, or zoomed-in view?	.92
Design Creativity	Aesthetic Sensitivity	To what extent does the student comprise evidence of aesthetic sensitivity in the design sketch, using elements of visual Arts?	.94
	Complexity of Ideas	To what extent does the student show the adequate level(s) of the complexity of ideas in the design sketch for the age-level group?	.93
	Flexibility	To what extent does the student involve evidence of flexible thinking in the design sketch, such as considering different types of ideas, or different uses of materials?	.90
	Originality	To what extent does the student include relatively original ideas in the design sketch, compared to others in the same group or at the same level of experience?	.92
Communicating Ideas	Annotations	To what extent does the student incorporate annotations to clarify elements and their functions in the design sketch?	.96
	Connections	To what extent does the student contain indicators in the design sketch to show connections among different parts of the design?	.91
	Feasibility	To what extent does the student involve elaborations and details in the design sketch that make building a prototype of the design feasible?	.94
	Functionality	To what extent does the student use visual or textual components in the design sketch to communicate the intended functional aspects of the design?	.90

a. Scoring direction: For each item, please read descriptions for all the performance levels and choose the performance level that fits the sketch characteristics better, with the following options: 1 (Not at all/Naïve level), 2 (To a small extent/Novice level), 3 (To a moderate extent/Intermediate level), 4 (To an appropriate extent/Informed level), 5 (To a great extent/Advanced level).

b. Hypothesized construct.

Data Analyses and Results

For data analysis, similar to Chen et al. (2002), Cheng (2018), Daly et al. (2016), and Denson et al. (2015), average scores from three raters were used. After the rating phase, the scores were checked for the assumptions required of multivariate statistical techniques, specifically for exploratory factor analysis. The data were analyzed using SPSS software version 26 (IBM Corp., 2019).

Sample Size

Many authors have discussed issues surrounding adequate sample size for factor analysis, and different criteria exist (Beavers et al., 2013). The first category of criteria is related to the subjects-to-variables (STV) ratio. For example, Bryant and Yarnold (1995) recommended at least 10 cases for each item, and Suhr (2006) suggested at least 100 cases and an STV ratio of no less than 5. Our sample satisfied both these criteria as we scored 113 sketches, and the STV for this study is greater than 10. However, the ratio criterion may not provide an accurate guide, and the adequacy of a sample cannot be fully determined until the strength of the factors and the items have been analyzed. For example, Fabrigar et al. (1999) and MacCallum et al. (2001) indicated stable solutions can be reached with samples as low as 100 when three to four strong items (loadings of .70 or greater) comprise a factor.

As a different criterion, Fabrigar et al. (1999) recommended an inverse relationship between communalities of variables and sample size, in which strong communalities of 0.70 or greater indicate adequate factor saturation that a sample size as low as 60 could suffice. For communalities less than 0.50 sample sizes between 100 and 200 are recommended (MacCallum et al., 1999). Based on our data analysis, all item communalities for this sample are greater than .50, and six items have communalities greater than .70. Further, the Kaiser-Meyer-Olkin Test of

Sampling Adequacy (KMO) was conducted to assess the strength of the relationships and factorability of the variables and to check that a simple structure factor analysis model is likely to fit the correlation matrix (Kaiser, 1974). The KMO for the 113 scores was .81, which is considered Meritorious, based on the interpretation guidelines for this test (Beavers et al., 2013).

Item Analysis

Before conducting factor analyses, item frequencies, percentages, means, and standard deviations were examined, and correlation patterns of items within the scale were investigated to check for problematic items (McCoach et al., 2013). Table 16 presents descriptive statistics for the 11 items used for the rating.

Table 16 Descriptive Statistics for the 11 Items (n = 113)

	Mean			Response Percentages					Skewness		Kurtosis	
	Stat.	SE	SD	1	2	3	4	5	Stat.	SE	Stat.	SE
Annotations	2.89	.11	1.18	10.7	31.0	36.2	6.3	15.9	.44	.23	-.60	.45
Shape	2.21	.09	.92	22.1	45.9	17.1	7.9	1.8	.72	.23	.26	.45
Views	2.59	.07	.80	4.5	46.8	25.2	9.7	1.8	.65	.23	.46	.45
Connections	2.57	.07	.70	7.2	45.3	38.3	9.9	0.0	.40	.23	.02	.45
Scale	2.39	.08	.80	16.0	38.9	37.2	7.1	0.9	.36	.23	.35	.45
Functionality	2.60	.09	.99	13.3	33.7	31.0	18.6	3.6	.14	.23	-.66	.45
Complexity	2.41	.09	.94	18.6	35.4	33.7	8.8	3.6	.48	.23	.08	.45
Feasibility	2.81	.09	.99	13.2	22.1	37.2	26.5	0.9	-.26	.23	-.82	.45
Aesthetic	2.15	.09	.95	26.5	41.5	24.7	4.5	2.7	.83	.23	.63	.45
Flexibility	1.98	.08	.85	35.4	37.1	22.1	5.3	0.0	.61	.23	-.25	.45
Originality	2.30	.09	.93	21.2	31.9	32.8	14.1	0.0	.02	.23	-1.04	.43

Correlation Matrix and Multicollinearity

The intercorrelations among the 11 items are shown in Table 17. The next step in factor analysis is to evaluate the correlation matrix. As presented in Table 17, groups of variables significantly correlate with each other. For example, Shape and Aesthetic Sensitivity ($r = .85$, $p < .01$) and Shape Accuracy and Connections ($r = .79$, $p < .01$) were highly correlated. Two items, Shape Accuracy and Connections, were significantly correlated with most of the items and, as a result, might be problematic. However, none of the item correlations were greater than .85 (Bohrnstedt & Carter, 1971).

Table 17 Correlation Matrix For 11 Items Used in the Pilot Study

	Annotations	Shape	Views	Connections	Scale	Functionality	Complexity	Feasibility	Aesthetic	Flexibility	Originality
Annotations	1										
Shape	.23*	1									
Views	.08	.59**	1								
Connections	.69**	.79**	.68**	1							
Scale	.22*	.74**	.55**	.66**	1						
Functionality	.63**	.51**	.31**	.70**	.48**	1					
Complexity	.38**	.36**	.20*	.45**	.34**	.50**	1				
Feasibility	.51**	.60**	.39**	.69**	.59**	.79**	.30**	1			
Aesthetic	.11	.85**	.65**	.68**	.75**	.42**	.25**	.49**	1		
Flexibility	.37**	.46**	.30**	.52**	.33**	.51**	.78**	.38**	.35**	1	
Originality	.25**	.27**	.22*	.34**	.26**	.35**	.68**	.27**	.23*	.77**	1

*. Correlation is significant at the 0.05 level (2-tailed).
**. Correlation is significant at the 0.01 level (2-tailed).

We decided not to remove items at this point to check more empirical evidence about which items to retain through factor analysis. Although large correlations imply multicollinearity, examining the correlation matrix is not sufficient to detect multicollinearity (Alin, 2010). Thus, we checked the Variance Inflation Factor (VIF) and Tolerance values. For these items, no VIF values exceed 5.0, and all Tolerance values were greater than 0.2, which indicates there was no problem regarding multicollinearity (Hair et al., 2010).

Normality

Visual inspection of items' histogram, Q-Q plots, and box plots suggested that the scores were not normally distributed. Table 16 presents values and standard errors for skewness and kurtosis of the 11 items. The values of skewness for four items and the value of kurtosis for five items were greater than .50 (Doane & Seward, 2011). Finally, as shown in Table 18, the Kolmogorov-Smirnov and Shapiro-Wilk's tests of normality suggested for 10 items of the scale, the scores are not normally distributed (Razali & Wah, 2011; Shapiro & Wilk, 1965). Non-normal distribution of the scores led us to use the Unweighted Least Squares (ULS) extraction method for exploratory factor analysis of these data (Zygmont & Smith, 2014).

Table 18 Tests of Normality

	Kolmogorov-Smirnov			Shapiro-Wilk		
Items	Statistic	df	Sig.	Statistic	df	Sig.
Annotations	.145	113	<.001	.917	113	<.001
Shape Accuracy	.185	113	<.001	.928	113	<.001
Views	.195	113	<.001	.926	113	<.001
Connections	.081	113	.064	.984	113	.199
Scale	.125	113	<.001	.960	113	.002
Functionality	.089	113	.027	.967	113	.006
Complexity	.146	113	<.001	.944	113	<.001
Feasibility	.142	113	<.001	.948	113	<.001
Aesthetic	.146	113	<.001	.912	113	<.001
Flexibility	.133	113	<.001	.911	113	<.001
Originality	.117	113	.001	.940	113	<.001

Exploratory Factor Analysis

Bartlett's Test of Sphericity was used to confirm that the correlation matrix was factorable. The null hypothesis of Bartlett's test states that the observed correlation matrix is equal to the identity matrix (Pett et al., 2003). In our data, Bartlett's test produced a significant test result (χ^2 (45) = 799.82, p < .001), rejecting the null hypothesis, which provides evidence for a factorable correlation matrix, confirming linear combinations. Thus, we proceeded to conduct exploratory factor analysis (EFA) to provide evidence of the construct validity and the initial factor structure of the data used in developing the i-SEED Scale. Using EFA, we empirically examined the interrelationships among the items and identified, "…clusters of items that share sufficient covariation to justify their existence as a factor measured" (McCoach et al., 2013, p.114) by the i-SEED Scale.

Determining the Number of Factors to Be Extracted

A preliminary EFA was conducted as the first step of decision regarding the number of factors to be extracted. Preliminary EFA results showed that up to three factors could be extracted from the solution. Three methods were used to examine the optimal number of factors to extract (McCoach et al., 2013), including the Kaiser Criterion (eigenvalues-greater-than-one rule; Costello & Osborne, 2005; Kaiser, 1960), scree plot test (Cattell, 1966), and parallel analysis (Horn, 1965; Turner, 1998). First, as shown in Table 19, principal axis factoring eigenvalues provided evidence supporting a three-factor solution. This method has been commonly used for determining the number of factors to retain in EFA; however, some researchers signaled that this rule could under-extract or over-extract the appropriate number of factors to retain (Beavers et al., 2013; Costello & Osborne, 2005; Pett et al., 2003). Second, visual inspection of the Cattell's scree plot in Figure 5 supported a 3-factor solution. However, this method is often criticized as being quite subjective in identifying the precise cut point (Beavers et al., 2013; Henson & Roberts, 2006).

Table 19 Principal Axis Factoring – Initial Eigenvalues

	Initial Eigenvalues		
Factor	Total	% of Variance	Cumulative %
1	5.819	52.899	52.899
2	1.824	18.24	68.28
3	1.239	12.39	80.67
~~4~~	~~.478~~	~~4.78~~	~~85.45~~
~~5~~	~~.399~~	~~3.99~~	~~89.44~~
~~6~~	~~.314~~	~~3.14~~	~~92.59~~
~~7~~	~~.300~~	~~3.00~~	~~95.59~~
~~8~~	~~.183~~	~~1.83~~	~~97.42~~
~~9~~	~~.152~~	~~1.52~~	~~98.94~~
~~10~~	~~.106~~	~~1.06~~	~~100.00~~

Finally, we conducted parallel analysis (Horn, 1965) using O'Conner (2000) syntax for SPSS software, to choose among one-, two-, or three-factor models. Among different rules and criteria to determine the number of factors to extract, researchers have suggested that parallel analysis is one of the best methods for accurate estimation of the number of factors (Henson & Roberts, 2006; Lim & Jahng, 2019). As shown in Table 20, the first three eigenvalues from the actual data were larger than the corresponding first three 95th percentile (and mean) random data eigenvalues. Accordingly, three factors should be retained (Matsunaga, 2010), a result aligned with the hypothesized model.

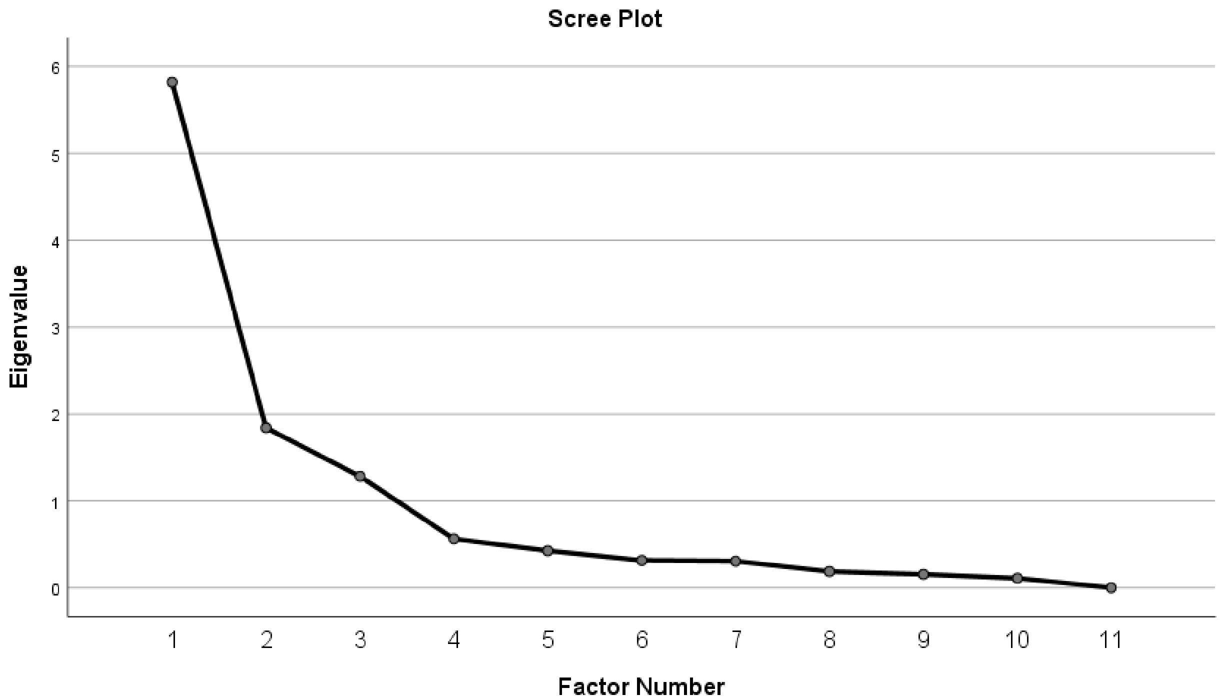

Figure 5 Scree Plot of the EFA of the i-SEED Scale

Table 20 Results for Parallel Analysis

	Random Data Eigenvalues	
Root	Means	95th Percentile
1	0.64	0.79
2	0.48	0.58
3	0.34	0.44
~~4~~	~~0.23~~	~~0.34~~
~~5~~	~~0.13~~	~~0.19~~
~~6~~	~~0.05~~	~~0.11~~
~~7~~	~~-0.03~~	~~0.02~~

Determining the Model and Items

All the three abovementioned rules on determining the optimal number of factors suggested a three-factor model. Considering the sample size and non-normal distribution of the scores, Unweighted Least Squares (ULS) was the most appropriate extraction method for these data, as the ULS estimation method is preferred for coping with small sample sizes (Zygmont & Smith, 2014). Additionally, this estimation method makes no assumptions regarding observed variable distributions (MacCallum, 2009). Further, as McCoach et al. (2013) suggested, Oblimin rotation was used, which is a type of oblique rotation. Oblique rotations allow for factor correlations (DeVellis, 2017). Based on the experts' feedback, correlations among the factors are expected. Communalities and the first ULS Oblimin rotated factor matrix for 11 items are presented in Table 21.

Table 21 Communalities and First ULS Oblimin Rotated Factor Matrix for 11 Items

Items	Communalities		Rotated Factor Matrix		
	Initial	Extraction	1	2	3
Annotations	.69	.73	-.19	.06	**-.89**
Shape Accuracy	.85	.83	**.85**	.07	-.06
Views	.69	.51	**.72**	.03	.05
~~Connections~~	~~.79~~	~~.92~~	~~**.57**~~	~~.05~~	~~**-.54**~~
Scale	.75	.66	**.76**	.03	-.09
Functionality	.79	.74	.17	.14	**-.70**
Complexity	.78	.72	-.02	**.81**	-.10
Feasibility	.79	.66	-.38	-.04	**-.60**
Aesthetic Sensitivity	.85	.87	**-.97**	-.00	-.11
Flexibility	.78	.88	.06	**.90**	-.02
Originality	.77	.68	-.01	**.86**	.08

Note. Extraction Method: Unweighted Least Squares. Rotation Method: Oblimin with Kaiser Normalization. Rotation converged in 6 iterations.

In the factor analysis literature, cutoff levels used by researchers for factor loading vary from .30 to .50 (Beavers et al., 2013; Carpenter, 2018). In this study, we applied .40 cutoff level (Ford et al., 1986; Hair et al., 2010; Reinard, 2006), which means cross-loading items with factor loading values greater than .4 on more than one factor should be deleted. As presented in Table 21, the first ULS Oblimin rotated factor matrix showed cross-loadings for one item, Connections, on factors one and three. The Connections item was also one of the items mentioned by the content experts as having an overlap with other items. As shown in Table 21, the Connections item was a candidate for deletion due to its loading of .57 and .54 on factors one and three. Thus, we removed this item and reran the EFA and recheck the items (Cabrera-Nguyen, 2010). The results of the second EFA (after deletion of the Connections item) are presented in Table 22

Table 22 Final EFA Model and Item Reliability Analysis for Subscales of the Three-factor Model (n = 113)

		Factor Loadings [a]			Reliability Analysis			
Factors	Items	1	2	3	Corrected Item-Total Correlation	Cronbach's Alpha if Item Deleted	Cronbach's Alpha for Sub-scale	Average Interitem Correlation
Factor 1: Visual-Spatial Characteristics	Aesthetic Sensitivity	**.97**	-.00	-.07	.87	.83	.90	.69
	Shape Accuracy	**.83**	.07	.10	.83	.85		
	Scale	**.75**	.01	.14	.77	.88		
	Views	**.69**	.05	-.05	.65	.91		
Factor 2: Design Creativity	Flexibility	.08	**.89**	.03	.85	.81	.90	.75
	Originality	.01	**.84**	-.07	.77	.88		
	Complexity	-.01	**.80**	.10	.78	.87		
Factor 3: Communicating Ideas	Functionality	.13	.08	**.84**	.81	.67	.84	.64
	Feasibility	.35	-.11	**.72**	.71	.77		
	Annotations	-.16	.10	**.71**	.61	.88		

a. Extraction Method: Unweighted Least Squares. Rotation Method: Oblimin with Kaiser Normalization. Rotation converged in 6 iterations.

After deleting the Connections item, we reran the EFA and re-checked the results. The remaining ten items satisfied the inclusion criteria. Thus, the EFA process provided evidence supporting a three-factor model with ten items. This three-factor model is aligned with the 3-pDS theoretical framework (Ghahremani et al., 2020), including three constructs: Visual-Spatial Characteristics, Communicating Ideas, and Design Creativity. The factor correlation matrix is presented in Table 23. This three-factor model explained 72.69% of the variance in the data.

Table 23 Factor Correlation Matrix

Factor	1	2	3
1. Visual-Spatial Characteristics	1.00		
2. Design Creativity	.33	1.00	
3. Communicating Ideas	.39	.45	1.00

Evidence for Reliability of Final EFA Model

Cronbach's alpha is one of the most widely used measures of reliability in social studies (Bonett & Wright, 2015). The Cronbach's alpha reliability measures estimate of internal consistency of the items. As presented in Table 22, the internal consistency estimates of the data for each subscale were evaluated. The Cronbach's alpha reliability estimates for the subscales ranged from .84 to .90, which exceeded the minimum recommended reliability estimate of .70 suggested by McCoach et al. (2013). None of the items had a corrected item-total correlation lower than 0.30, which provide evidence for acceptable items (Briggs & Cheek, 1986; Cristobal et al., 2007). Cronbach's alpha if an item is deleted was calculated for each item to determine if any other items would be good candidates for deletion (DeVellis, 2017). Moreover, the maximum alpha value of .90 suggests that items are not redundant (Tavakol & Dennick, 2011).

Description of High versus Low Scoring Sketches Using the i-SEED Scale

Sketches received high scores if shapes and proportions of the sketched objects were highly representative of the corresponding real objects; the student included at least two different views such as from the top, front, back or zoomed-in view in the design, attempted to visually represent three-dimensional objects in two dimensions; and included easily identifiable and familiar objects or elements as a reference point, that indicated the relative size of the elements depicted in the design. This means that although the sketch was not measured by the student, an appropriate indication of proportionality was evident. Additionally, sketches rated high if the student represented evidence of transferring scientific concepts and adapted them for the design context; generated relatively original ideas; used more complex techniques to transfer motion and energy, such as oscillation or elasticity, in addition to basic techniques, such as collision and gravity; and elaborated on functional relationships among different parts or steps of the design to an appropriate extent. Moreover, sketches received a high score if the student included signs, labels, and textual annotations (full sentences) to elaborate on the different steps; and represented relative position, distance, arrangement, and configuration of the design elements, in a way that it can be used by those outside the design process as a guide to building a prototype. Figure 6 presents two examples of high scoring sketches from our data.

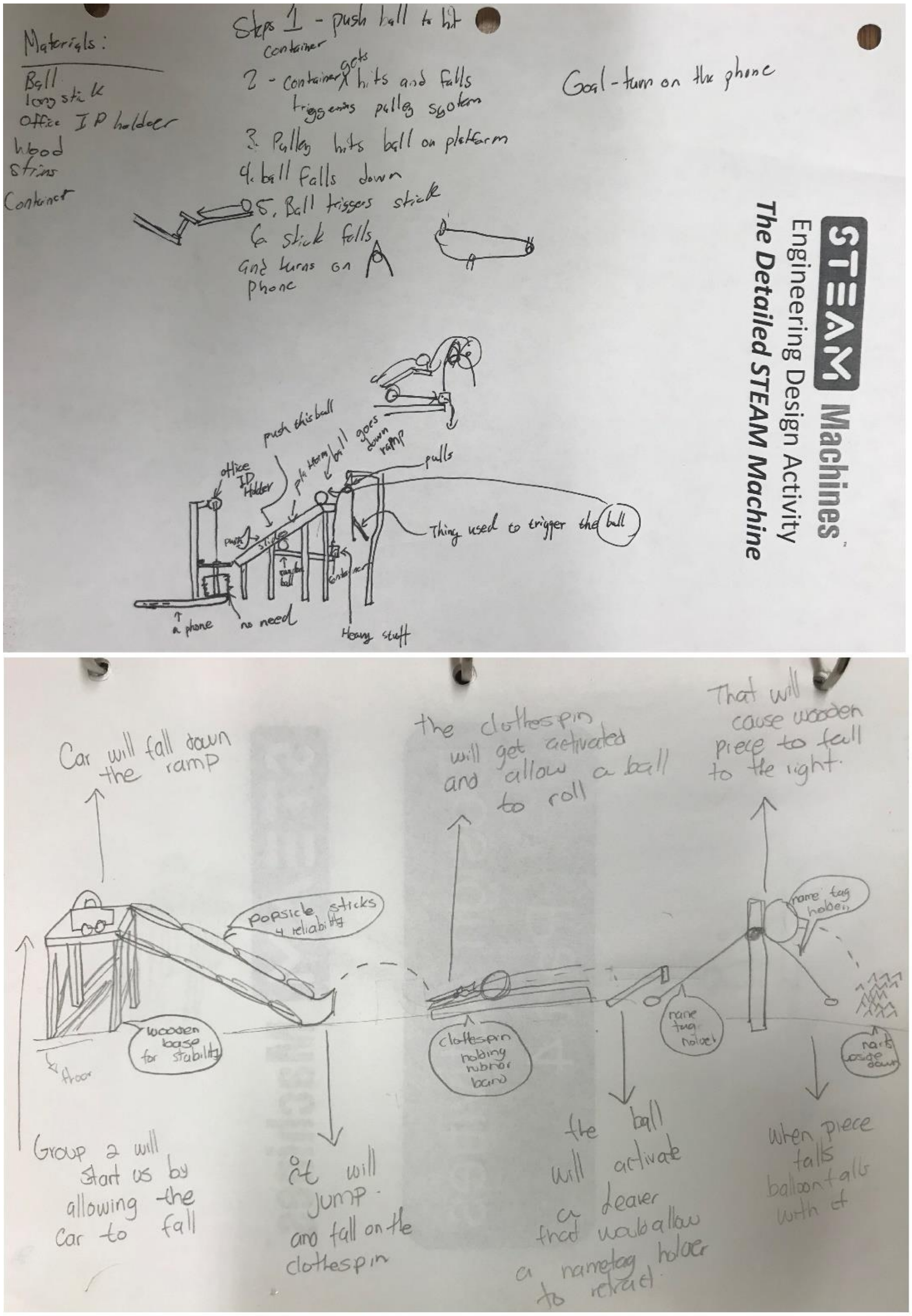

Figure 6 Two Samples of High Scoring Sketches from the Data

In contrast, sketches received low ratings if the objects in the design were reduced to their basic geometrical figures and shapes, in a way that missing details negatively affected communicating the design ideas; the shape of the sketched objects was far from that of the corresponding real objects; there was no numerical or textual elaboration or a familiar object that indicate the relative size of the design; and the viewpoint was unclear and confusing. Additionally, sketches rated low if there was no evidence of adapting scientific concepts for the design; lacked relatively original ideas; and no elaboration or visual cues suggesting anticipated functionality of the design parts. Moreover, sketches received a low score if there was no sign, label, or textual annotations; and it was not possible to build a prototype based on the sketch. Figure 7 presents two examples of low scoring sketches from the data.

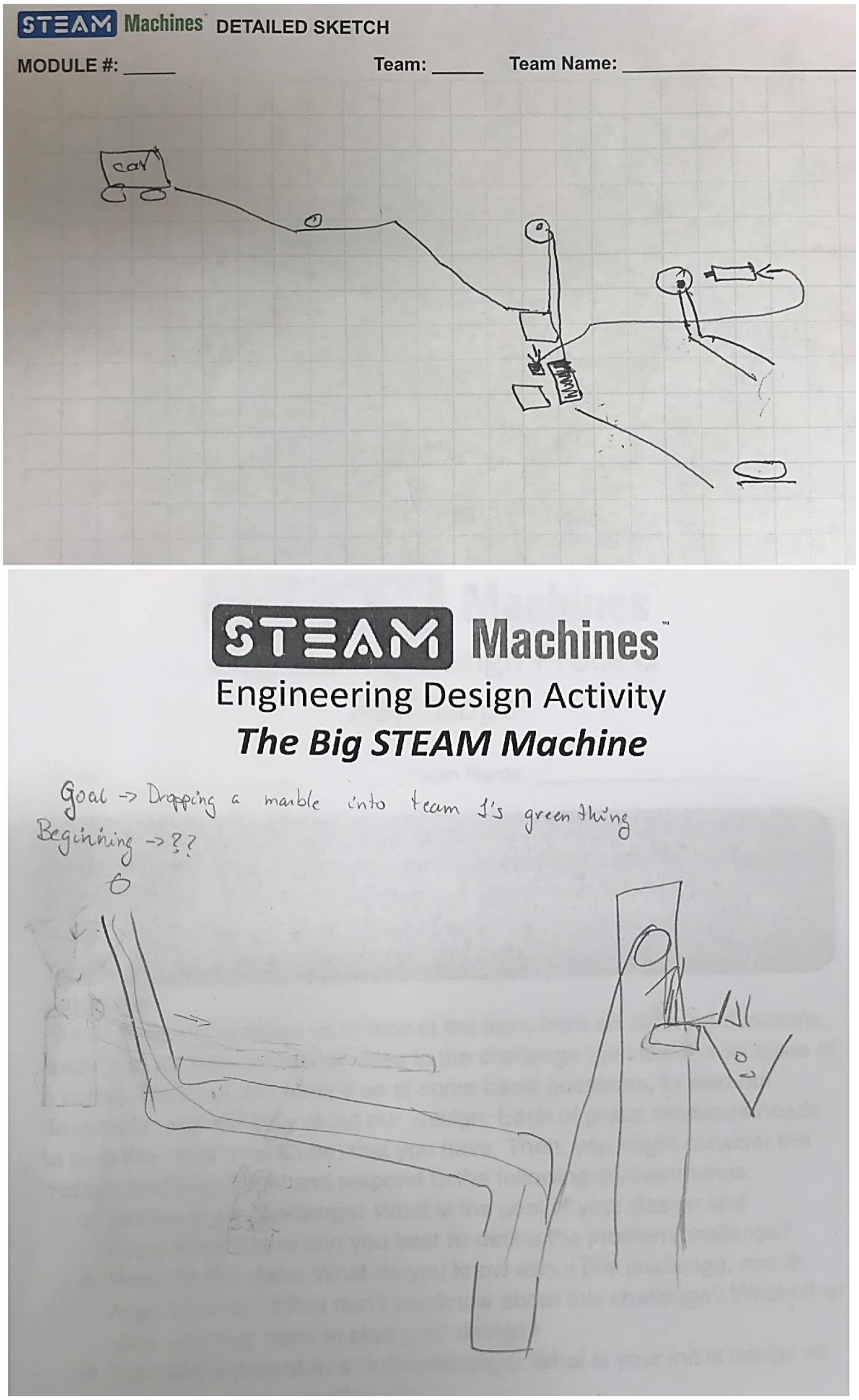

Figure 7 Two Samples of Low Scoring Sketches from the Data

Discussion

Based on the 3-pDS theoretical framework (Ghahremani et al., 2020), in this study, we developed the idea-Sketching Early Engineering Design (i-SEED) Scale and presented initial reliability and validity evidence from the data on its use. Through exploratory factor analysis, we provided initial evidence to support the internal structure of the i-SEED Scale. This result supported the idea that there were three distinct, latent factors addressed by the i-SEED Scale items. Using this three-factor model, educators can potentially promote thinking and learning through visualization, in pre-college educational settings. Conducting validity study advance theory development, as scale-development processes contribute to understanding the constructs in the theory and their relationships (Shoemaker et al., 2011). Developing a theoretical model is an ongoing process (Alvesson & Karreman, 2011). We will continue to develop this model through future research.

Domain Generality versus Specificity of the i-SEED Scale

Items in Factor 1 (Visual-Spatial Characteristics) and Factor 3 (Communicating Ideas) involve domain-general characteristics of design sketches, that can easily apply to different design contexts. However, items in Factor 2 (Design Creativity) involve more domain-specific characteristics with contextual descriptions of the performance levels. For instance, the performance levels of the Complexity of Ideas criterion relied on designs that used simple machines (i.e., inclined plane, lever, wedge, pulley, screw, and wheel and axel) and combined them, representing multiple steps in the design. Rube Goldberg-like chain reaction machines are designed to perform a simple job in a very complicated way (Jordan et al., 2016). Thus, complexity is the inherent characteristics of designing chain reaction machines. Therefore, it is mostly a domain-specific characteristic of design creativity.

There is an ongoing debate about whether creativity is domain-general or domain-specific, and many researchers have investigated this issue from different perspectives (An & Runco, 2016; Qian et al., 2019). The generality-specificity debate has evolved to develop hybrid models (Qian & Plucker, 2018) that incorporated domain-general and domain-specific components. For example, in the Amusement Park Theoretical Model of Creativity, Baer and Kaufman (2005, 2017) attempted to bridge the gap between generality and specificity views on creativity. In the i-SEED instrument, three items of the Design Creativity factor resonate with the contextual and domain-specific view on creativity. As Qian and Plucker (2018) indicated, existing empirical studies suggest that the use of performance-based creativity assessment usually supports the domain-specificity of creativity. In contrast, the use of creativity checklists or self-report assessment methods provides evidence supporting the domain-generality of creativity (Baer, 2010; Silvia et al., 2012). Further research is required to investigate the generality-specificity of the i-SEED instrument.

Implications

Engineering design is a recent addition to the contemporary K-12 education standards. For example, engineering design is included in the *Framework for K–12 Science Education* (National Research Council, 2012), the *Next Generation Science Standards* (National Research Council, 2013), and *STEM Integration in K-12 Education* (National Academy of Engineering and National Research Council, 2014). Sketching is an essential part of the design (Booth et al., 2016; Crismond & Adams, 2012), This study provided initial evidence of validity and reliability for the data that were used in developing the i-SEED Scale. The i-SEED Scale can provide educators with a practical set of criteria to evaluate students' sketching. This scale can also help teachers understand what they need to address when they teach sketching. The i-SEED Scale can serve as a skeleton for teaching how to generate a high-quality sketch of design ideas.

Results from the i-SEED Scale can help teachers foster design thinking in the classroom. Design is generally considered as one of the main activities in engineering practice. Engineering design is being recognized and taught as a collaborative process with several socio-technological elements (Dym et al., 2005). Additionally, the i-SEED Scale can provide insights into the curriculum development to nurture engineering talent in K-12 formal settings and non-formal enrichment programs. Furthermore, as there is an expressed need in the literature to investigate students' design abilities (Kelley, 2017), and how students apply their knowledge and abilities through design (Purzer et al., 2015), the i-SEED Scale can be used in research on these areas of design thinking.

Students will also benefit from the i-SEED Scale in numerous ways. Using this scale as a rubric can help them learn what they are required to address in their design sketches. Such awareness helps students produce high-quality work. In a systematic review of the use of rubrics in educational settings, Brookhart and Chen (2015) provided evidence supporting the positive influence of the use of rubrics on students' performance. For example, the use of rubric was associated with an increase in student achievement in general science (Sadler & Good, 2006), social studies (Panadero et al., 2012), physics (Kocakülah, 2010), and mathematics (Yopp & Rehberger 2009). This scale can serve as a guideline for students and can provide students with the criteria and expectations for a high-quality design sketch. Using this scale as a rubric can also reduce students' anxiety (Andrade & Du, 2005) and help them focus on their design tasks.

Limitations

We acknowledge some limitations to this scale-development study. First, in the pre-pilot stage, based on the feedback from the development sample, we added more descriptions to the different performance levels for each item. However, these expanded descriptions lengthened the scale and caused limitations. As McCoach et al. (2013) stated, lengthy items may increase misreading or misinterpreting of the content. Second, the number of raters for CAT varies in the research. The number of raters in Amabile's (1982) original CAT studies ranged from three to 21. Some researchers have used as few as two raters (Daly et al., 2016). In this study, three raters were involved in the scoring, which is another source of limitation. Although the inter-rater reliability among raters was excellent, Kaufman et al. (2008) suggested having five to 10 raters as an appropriate number for CAT. Third, items in Factor 2 (Design Creativity) involve more domain-specific characteristics with contextual descriptions of the performance levels. This reliance may have placed limits on the use of this instrument in different design contexts.

Future Directions

Scale-development is an ongoing process (DeVellis, 2017). This study was the first step in developing the i-SEED Scale. The results of this study need to be further verified through confirmatory factor analysis, using a different set of sketch data. Additionally, for future research, it would be helpful to revise this scale to shorten the length of the performance-level descriptions (DeVellis, 2017) and to examine the possibility of simplifying the performance level descriptions, without losing important distinctions. We also need to investigate the domain generality-specificity characteristic of the i-SEED Scale to examine the possibility of modifying this instrument for different areas of engineering design.

This study was a factor-level evaluation of the i-SEED Scale. In the future, we will conduct a multidimensional IRT analysis (Reckase, 2009) to investigate the item characteristics of this scale. Moreover, it is of further value to use the i-SEED Scale in a mixed-method study, incorporating in-depth interviews to investigate teachers' reflections on the use of this scale. Finally, the i-SEED Scale can be used in an exploratory study of informed engineering practices to probe patterns of design behavior and conceptualize these patterns with a more diverse group of students (Purzer et al., 2015).

Conclusion

Through this scale-development study, we provided evidence of content validity, construct validity, and internal consistency of the data we used to develop the i-SEED Scale. Focusing on the Represent Ideas strategy in the Informed Design Learning and Teaching Matrix (Crismond & Adams, 2012), this study aimed to address the need to develop an instrument to differentiate among different performance levels of K-12 design sketching. This study of the i-SEED scale provides initial steps toward the evaluation of design in pre-college settings. We encourage STEM teachers and educators to re-evaluate their design-oriented pedagogical approaches to emphasize the importance of idea-sketching. As Kelley and Snug (2017) suggested, design sketching can be considered as a new form of assessment for teachers to appraise K-12 students' design competencies and their conceptual understanding of STEM contents. The i-SEED Scale can serve as a reliable measure for this purpose.

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Appendix A: Content Validity Form

Engineering and design are considered not only a part of talent development, but also the contemporary K-12 educational standards. Sketching is an integral part of the design-thinking process. We aim to develop and validate the idea-Sketching Early Engineering Design (i-SEED) Scale, an instrument to evaluate middle- and high-school (grades 6-12) students' sketches in response to a design task. This scale can be used in research and early identification of high-potential designers in formal and informal educational settings. We have conducted a systematic literature review to investigate how novice and K-12 students' idea sketching has been appraised, operationalized, or assessed, in the context of STEM education. Based on our inquiry, three broad themes/constructs were identified that researchers use to conceptualize sketching of ideas, in novice and K-12 design activities: Communicating Ideas (CI), Visual-Spatial Characteristics (VS), and Design Creativity (DC). Based on our systematic review, 23 characteristics of sketching were identified.

An important phase in the development of any instrument is that of content validation. Validity evidence based on instrument content should receive the highest priority during the early stages of the instrument development process. Experts' feedback on the definition of constructs, content coverage, the relevance of the proposed items, and the wording of item stems are extremely important for improving the content validity of the scale. By offering your expertise, you are contributing to the development of this instrument and providing evidence of its content validity. Your assistance in this phase of instrument development is sincerely appreciated.

Thank you in advance for your time and help!

Instructions: Each of these 23 items is being considered for inclusion in the new instrument (i-SEED Scale) that Mehdi Ghahremani and his co-researchers are developing. You will be providing three ratings for each item: item category, your certainty that the item belongs to that category, and relevance of item for the category. The conceptual definitions of the constructs these items are supposed to reflect are listed below. The rating tasks are listed on the next pages.

Construct	Conceptual Definition
I. Design Creativity (DC)	This construct measures the degree to which a student's sketch presents indicators of a creative design, such as producing a perceptible design that is both novel and useful as defined within the design context.
II. Communicating Ideas (CI)	This construct measures the degree to which a student's sketch clearly communicates the design idea(s) and effectively represents the design information.
III. Visual-Spatial Characteristics (VS)	This construct measures the degree to which a student's sketch properly involves visual cues related to the spatial characteristics of the design and combination of the parts.
IV. None of the above	(If an item does not fit into any of the above categories.)

Rating Tasks

You will rate (mark and/or highlight) each item stem with regard to the following three aspects:

A. Category
Please indicate the construct that each item best fits into by marking or highlighting the appropriate numeral. (Items not fitting any category should be placed in Category IV.)

I. Design Creativity
II. Communicating Ideas
III. Visual-Spatial Characteristics
IV. None of the above

B. Certainty
Please indicate how certain you feel about your placement of the item into the construct by circling the appropriate number as follows:

1. Completely Unsure
2. Unsure
3. Pretty Sure
4. Very Sure

C. Relevance
Please indicate how relevant you feel each item is to the construct.

1. Completely Irrelevant
2. Somewhat Relevant
3. Highly Relevant

Scaling Format and Sample Item
A 5-point Likert-type measure of sketching quality will be applied. The format of the items will be as follows: (In this item, "Annotation" is the characteristics of sketching which is being evaluated.)

- To what extent does the student design sketch incorporate annotations to clarify elements and their functions in the sketch?

1 = Not at all/Naïve level,
2 = To a small extent/Novice level,
3 = To a moderate extent/Intermediate level,
4 = To an appropriate extent/Informed[1] level,
5 = To a great extent/Advanced level

Please Note:
Feel free to write comments regarding item stems directly on the stem. (These comments could regard suggested changes in wording or if you feel the item should be combined with other items or eliminated).

[1] Within the design matrix of Crismond and Adams (2012), an "informed designer" is considered to have gained a level of competence that lies beyond that of a novice designer but not that of an expert.

Content Validation Survey

Items	Category					Certainty					Relevance		
	Design Creativity	Communicating Ideas	Visual-Spatial	None of the above		Completely unsure	Unsure	Pretty sure	Very sure		Completely irrelevant	Somewhat relevant	Highly relevant
Aesthetic Sensitivity. Comprised evidence of aesthetic sensitivity, such as use of color, pattern, or other visually appealing elements.	I	II	III	IV		1	2	3	4		1	2	3
Annotations. Incorporated annotations to clarify elements and their functions in the sketch.	I	II	III	IV		1	2	3	4		1	2	3
Cause-Effect Relationships. Included visual signs, labels, or annotations to indicate casual relationships between/among different parts of the design.	I	II	III	IV		1	2	3	4		1	2	3
Complexity. Showed adequate level(s) of complexity for the age-level group.	I	II	III	IV		1	2	3	4		1	2	3
Configuration. Represented position, distance, and arrangements of elements with precision.	I	II	III	IV		1	2	3	4		1	2	3
Connections. Contained functional indicators such as arrows, numbers, letters, or symbols to show relationships between different parts or steps.	I	II	III	IV		1	2	3	4		1	2	3
Context. Included familiar object(s) or elements that indicate the context or environment in which the design will be used.	I	II	III	IV		1	2	3	4		1	2	3
Feasibility. Involved elaborations and details that make building a prototype of the design feasible.	I	II	III	IV		1	2	3	4		1	2	3
Flexibility. Involved evidence of flexible thinking such as considering different types of design ideas or uses of materials.	I	II	III	IV		1	2	3	4		1	2	3

Items	Category					Certainty					Relevance		
	Design Creativity	Communicating Ideas	Visual-Spatial	None of the above		Completely unsure	Unsure	Pretty sure	Very sure		Completely irrelevant	Somewhat relevant	Highly relevant
Applied Forces. Employed arrows or other visual elements to indicate forces.	I	II	III	IV		1	2	3	4		1	2	3
Functionality. Used visual components such as words, symbols, drawings, and callouts to illustrate the intended functional aspects/mechanisms of the design.	I	II	III	IV		1	2	3	4		1	2	3
Imagination. Included imaginative ideas, stories, or creations of the mind that are not real.	I	II	III	IV		1	2	3	4		1	2	3
Labels & Symbols. Labeled components of the design using symbols, signs, or texts to identify different parts.	I	II	III	IV		1	2	3	4		1	2	3
Materials. Indicated each component of the design by its material.	I	II	III	IV		1	2	3	4		1	2	3
Motion. Indicated anticipating motion and its direction.	I	II	III	IV		1	2	3	4		1	2	3
Numerical Elaboration. Included numbers or quantities to elaborate and add information.	I	II	III	IV		1	2	3	4		1	2	3
Originality. Included relatively original ideas, compared to others in the same group or at the same level of experience.	I	II	III	IV		1	2	3	4		1	2	3
Purpose. Clearly communicated purpose(s) of the design.	I	II	III	IV		1	2	3	4		1	2	3
Scale. Incorporated visual or textual components that indicate the relative size of the concept depicted in the sketch.	I	II	III	IV		1	2	3	4		1	2	3
Sequence. Incorporated visual signs or labeling to show the sequence of events.	I	II	III	IV		1	2	3	4		1	2	3
Shape Accuracy. Illustrated geometric elements such as	I	II	III	IV		1	2	3	4		1	2	3

Items	Category					Certainty					Relevance		
	Design Creativity	Communicating Ideas	Visual-Spatial	None of the above		Completely unsure	Unsure	Pretty sure	Very sure		Completely irrelevant	Somewhat relevant	Highly relevant
lines, circles, and triangles with precision.													
Size of the Sketch. Used the entire paper in making the drawing. .	I	II	III	IV		1	2	3	4		1	2	3
Views. Used different viewpoints such as from the top, front, back or zoomed in the design.	I	II	III	IV		1	2	3	4		1	2	3

Please provide qualitative feedback as well! We appreciate your time and expertise.

- Do you have any suggestions regarding the definitions of the constructs?
- Do the items appear to cover the full range of content within each construct? Do you have any suggestions for improving content coverage?
- Are the instrument items clearly worded and unambiguous? Are they appropriate for middle- and high-school educators? Do you have any suggestions for improving the item stems? (feel free to provide comments directly on the item stems regarding rewording and/or eliminating.)
- Do you have any suggestions for items that you would add?
- Please feel free to add any additional thoughts or comments below.

Appendix B: The 11 Items Used in the Scoring Phase

Definitions.

Step: The smallest action that is performed.
Module: A series of two or more steps.
Machine. A set of 2 or more modules, executed in series to accomplish a task.

Direction. For each item, please read descriptions for all the performance levels and choose the performance level that fits the sketch characteristics better, with the following options: 1 (Not at all/Naïve level), 2 (To a small extent/Novice level), 3 (To a moderate extent/Intermediate level), 4 (To an appropriate extent/Informed level), 5 (To a great extent/Advanced level).

Annotations. To what extent does the student incorporate annotations in the design sketch to clarify elements and their functions in the sketch? [For level 4 and 5, Requires having a minimum of two of the following distinctions for the selected performance level]

Naïve level (1)	Novice level (2)	Intermediate level (3)	Informed level (4)	Advanced level (5)
Not at all Presented drawing with *no* sign, label, or textual annotations.	To a small extent Presented the sketch using *some* symbols or signs (such as arrows), *to a small extent*. OR Contained *less than three* textual labels to elaborate on the components of the design.	To a moderate extent Incorporated symbols or signs, *to a moderate extent*. OR Contained *some* textual labels (at least three labels) to elaborate on the components of the design.	To an appropriate extent Incorporated symbols or signs, to an appropriate extent. Contained textual labels (at least one per step) to elaborate on the steps of the design. Included some textual annotations (*phrases*) to elaborate on the different steps of the design and to explain the function(s) of design elements.	To a great extent Incorporate symbols or signs, to a great extent. Contained textual labels (more than three) to elaborate on the steps of the design. Included textual annotations (*full sentences*) to elaborate on the different steps of design and to explain the function(s) of design elements.

Shape Accuracy. To what extent does the student illustrate objects and geometric elements in the design sketch with precision?

Naïve level (1)	Novice level (2)	Intermediate level (3)	Informed level (4)	Advanced level (5)
Not at all Shape of the sketched objects may be far from that of the corresponding real objects.	To a small extent Shape and proportions of the sketched objects (more than half) are representative of the corresponding real objects, *to a small degree*.	To a moderate extent Shape and proportions of the sketched objects are representative of the corresponding real objects *to a moderate degree*.	To an appropriate extent Shape and proportions of the sketched objects (more than half) are representatives of the corresponding real objects, and drawings represent the objects *to an appropriate degree*.	To a great extent Shape and proportions of the sketched objects (almost all) are highly representative of the corresponding real objects, and drawings correctly represent the objects *to a great degree*.

Note. This item is NOT comparing among different objects in the design. This item individually evaluates sketched objects.

Views. To what extent does the student use different viewpoints in the design sketch, such as from the top, front, back or zoomed-in, in the design?

Naïve level (1)	Novice level (2)	Intermediate level (3)	Informed level (4)	Advanced level (5)
Not at all The viewpoint is not clear, and it is confusing.	To a small extent Used only one viewpoint (frontal view, for example) for the drawings and visualizing design elements.	To a moderate extent Used only one viewpoint (frontal view, for example) for the drawings and visualizing design elements. AND Used shading, texture, or other features to visually suggest three-dimensionality or depth.	To an appropriate extent Included two different views such as from the top, front, back or zoomed-in the design. OR Used isometric view, *with no precision*, attempted to visually represent three-dimensional objects in two dimensions.	To a great extent Juxtaposed multiple views (more than two), such as from the top, front, back or zoomed-in to communicate more details of an object and better demonstrate design idea(s). OR Used isometric view, visually representing three-dimensional objects in two dimensions, *with precision*.

Connections. To what extent does the student contain indicators in the design sketch to show connections among different parts of the design? [Requires having a minimum of two of the following distinctions for the selected performance level]

Naïve level (1)	Novice level (2)	Intermediate level (3)	Informed level (4)	Advanced level (5)
Not at all No visual or textual elements to indicate connections between/among different parts of the design.	To a small extent Used *only* physical contact suggesting the connection between two parts. Included *no* directional arrows indicating connections.	To a moderate extent Used physical contact suggesting connection between two parts. Included visual signs such as directional *arrows* indicating connections between/among different parts of the design. Used string, rope, or other similar *connectors* to link different parts of the design.	To an appropriate extent Employed arrows or other visual elements to indicate *applied forces* or source/flow of energy, *to an appropriate extent*. Included visual signs, labels, or text to indicate *cause-effect relationships* among different parts of the design, *to an appropriate extent*. Incorporated visual signs, letters, or labels to show the *sequence* of events, *to an appropriate extent*.	To a great extent Employed arrows or other visual elements to indicate *applied forces* or source/flow of energy, *to a great extent*. Included visual signs, labels, or text to indicate *cause-effect relationships* among different parts of the design that displays detailed and integrated clear links between the whole design and its parts. Incorporated visual signs, letters, or labels to show the *sequence* of events, *to a great extent*.

Scale. To what extent does the student incorporate visual or textual components in the design sketch that indicate the relative size of the concept depicted in the sketch?

Naïve level (1)	Novice level (2)	Intermediate level (3)	Informed level (4)	Advanced level (5)
<u>Not at all</u> No visual, textual, or familiar object that indicate the relative size of the design.	<u>To a small extent</u> Included familiar object(s) or elements that indicate only the context in which the design will be used.	<u>To a moderate extent</u> Included familiar object(s) or elements (as a reference point) that indicate the relative size of the elements depicted in the design, *to a moderate extent*. (Although the sketch is not measured, some indication of proportionality is evident.)	<u>To an appropriate extent</u> Included easily identifiable and familiar object(s) or elements (as a reference point) that indicate the relative size of the elements depicted in the design, *to an appropriate extent*. (Although the sketch is not measured, an appropriate indication of proportionality is evident.)	<u>To a great extent</u> Incorporated some numerical or textual elaborations that indicate the required size of the elements depicted in the sketch, and proportions of the sketched objects are highly representative of the corresponding real objects. Included some measures for different parts of the design.

Functionality. To what extent does the student use visual or textual components in the design sketch to communicate the intended functional aspects of the design? [Requires having a minimum of two of the following distinctions for the selected performance level]

Naïve level (1)	Novice level (2)	Intermediate level (3)	Informed level (4)	Advanced level (5)
Not at all No elaboration or visual cues suggesting anticipated functionality of the design parts/objects. Included *no* visual elements indicating motion and its direction.	To a small extent Represented some functional relationships among different parts or steps of the design *to a small extent*, indicating working principles *without* details of functional aspects of the design. Included visual elements such as arrows, indicating transfer of motion and its direction, for at least two moving parts or objects.	To a moderate extent Represented functional relationships among different parts or steps of the design *to a moderate extent*, indicating working principles with some details of functional aspects of the design. Included visual elements such as arrows, indicating transfer of motion and its direction, for at least three moving parts or objects. Communicated overall outcome of the design and met purpose(s) of the given task *to a moderate degree*.	To an appropriate extent Represented functional relationships among different parts or steps of the design *to an appropriate extent*, indicating working principles with details of functional aspects of the design. Included visual elements such as arrows or dotted-line objects, indicating transfer of motion and its direction for at least four objects or moving parts, as evidence of visual analysis of moving parts/objects. Communicated overall outcome of the design and met purpose(s) of the given task *to an appropriate degree*.	To a great extent Represented functional relationships among different parts or steps of the design *to a great extent*, indicating working principles, with more detail on spatial illustration and how the parts' functions supported its intended operation. Included visual elements such as arrows or dotted-line objects, indicating transfer of motion and its direction for more than four objects or moving parts, as evidence of graphical analysis of motion. Clearly communicated the overall outcome of the design and met the purpose(s) of the given task *to a very high degree*.

Complexity of Ideas. To what extent does the student show the adequate level(s) of the complexity of ideas for the age-level group in the design sketch? [Requires having minimum of two of the following distinctions for the selected performance level]

Naïve level (1)	Novice level (2)	Intermediate level (3)	Informed level (4)	Advanced level (5)
Not at all Not enough evidence to evaluate the complexity of ideas. Employed *only one* simple technique to transfer motion and energy (such as collision). Used *no* simple machines in the design.	To a small extent Employed simple and basic techniques (*at least two*) to transfer motion and energy such as collision and gravity. Used at least one simple machines (i.e., inclined plane, lever, wedge, pulley, screw, and wheel and axel) in the design. Represented two steps in the design.	To a moderate extent Employed *somewhat* complex techniques (at least one) to transfer motion and energy (such as oscillation or elasticity) in addition to simple/basic techniques (such as collision and gravity). Used at least three simple machines (i.e., inclined plane, lever, wedge, pulley, screw, and wheel and axel) in the design. Represented three steps or more in the design.	To an appropriate extent Employed more complex techniques (at least two) to transfer motion and energy (such as oscillation or elasticity) in addition to simple/basic techniques (such as collision and gravity). Used at least four simple machines (i.e., inclined plane, lever, wedge, pulley, screw, and wheel and axel) in the design. Represented four steps or more in the design.	To a great extent Employed combinations of different techniques to transfer motion and energy such as collision, gravity, periodic/oscillation, elasticity, magnets, and other scientific/Physics concepts. Combined different (more than four) simple machines (i.e., inclined plane, lever, wedge, pulley, screw, and wheel and axel), in the design. Represented multiple design steps (more than four).

Feasibility. To what extent does the student involve elaborations and details in the design sketch that make building a prototype of the design feasible? [Requires having a minimum of two of the following distinctions for the selected performance level]

Naïve level (1)	Novice level (2)	Intermediate level (3)	Informed level (4)	Advanced level (5)
Not at all It is not possible to build a prototype based on the sketch.	To a small extent Involved few elaborations and details that make building a prototype of the design feasible, *to a small extent*. Represented basic drawing with a high level of abstraction without physical, textual, or numerical elaborations on the idea(s). Less than half of the design objects are clear regarding what objects they are or what material(s) they are made of.	To a moderate extent Involved some elaborations and details that make building a prototype of the design feasible, *to a moderate extent*. Represented relative position, distance, arrangement, and configuration of the design elements, *to a moderate extent*. Half of the design objects are clear regarding what objects they are or what material(s) they are made of.	To an appropriate extent Involved elaborations and details that make building a prototype of the design feasible, *to an appropriate extent*. Represented relative position, distance, arrangement, and configuration of the design elements, *to an appropriate extent*. More than half of the design objects are clear regarding what objects they are or what material(s) they are made of.	To a great extent Represented relative position, distance, arrangement, and configuration of the design elements *with precision*, in a way that it can be used by those outside the design process as a guide to build a prototype. Almost all of the design objects are clear regarding what objects they are or what material(s) they are made of. Included numerical elaborations such as numbers or quantities for materials, representing those elements mathematically, added dimensions/measures for the elements, and quantifying distance to elaborate and add information.

Aesthetic Sensitivity. To what extent does the student comprise evidence of aesthetic sensitivity in the design sketch, using elements of visual Arts? [Requires having a minimum of two of the following distinctions for the selected performance level]

Naïve level (1)	Novice level (2)	Intermediate level (3)	Informed level (4)	Advanced level (5)
Not at all Included drawing in which lines are very low-quality. Almost all of the objects in the design are reduced to their basic geometrical figures and shapes, in a way that missing details negatively affected communicating the design idea(s).	To a small extent Represented *some* knowledge and understanding of art elements and design principles. Included drawing in which lines are well-drawn *to a small extent.* More than half of the objects in the design are reduced to their basic geometrical figures and shapes, in a way that missing details negatively affected communicating the design idea(s).	To a moderate extent Represented a *moderate* manipulation of art elements and design principles. Included drawing in which lines are well-drawn *to a moderate extent*. Half of the objects in the design are reduced to their basic geometrical figures and shapes, in a way that missing details negatively affected communicating the design idea(s).	To an appropriate extent Represented an *appropriate* use of art elements and design principles. Included drawing in which lines are well-drawn *to an appropriate extent*. Less than half of the objects in the design are reduced to their basic geometrical figures and shapes, and more than half of the design objects were pictorially depicted, representing actual visual appearance to an appropriate extent.	To a great extent Represented *in-depth* understanding of art elements and design principles. Included drawing in which lines are well-drawn *to a great extent*. More than half of the objects in the design were pictorially depicted and represented the design objects according to their actual visual appearance, to a great extent.

Flexibility. To what extent does the student involve evidence of flexible thinking in the design sketch, such as considering different uses of materials, or different types of ideas? [Requires having a minimum of two of the following distinctions for the selected performance level]

Naïve level (1)	Novice level (2)	Intermediate level (3)	Informed level (4)	Advanced level (5)
Not at all Not enough evidence to evaluate flexibility. No evidence of flexible use of objects/materials. No evidence of transferring scientific concepts/knowledge and adapting them for the design context.	To a small extent Used some of the objects (at least one) in different ways (Alternate uses of objects). Adapted at least one type of motion (such as linear or circular) in the design.	To a moderate extent Used some of the objects (at least two) in different ways (Alternate uses of objects). Adapted two different types of motions (such as linear and circular) in the design. Represented evidence of transferring scientific concepts/knowledge and adapting them for the design context, *to a moderate extent*.	To an appropriate extent Used some of the objects (at least three) in different ways (Alternate uses of objects). Adapted three different types of motions (such as oscillatory, linear, and circular) in the design. Represented evidence of transferring scientific concepts/knowledge and adapting them for the design context, *to an appropriate extent*.	To a great extent Used some of the objects (at least four) in different ways (Alternate uses of objects). Adapted four different types of motions (such as rotational, oscillatory, linear, and circular) in the design Represented evidence of transferring scientific concepts/knowledge and adapting them for the design context, *to a great extent*. Represented evidence of analogical thinking, which means taking and adapting ideas from a situation that is very different than the design context and applying them in the design.

Originality. To what extent does the student include relatively original ideas in the design sketch, compared to others in the same group or at the same level of experience?

Naïve level (1)	Novice level (2)	Intermediate level (3)	Informed level (4)	Advanced level (5)
<u>Not at all</u> Not enough evidence to evaluate originality. OR No *relatively* original idea(s).	<u>To a small extent</u> Generated ideas that are common in approximately 80% of the sample sketches, in the same group or at the same level of experience.	<u>To a moderate extent</u> Generated ideas that are common in approximately 60% of the sample sketches, in the same group or at the same level of experience.	<u>To an appropriate extent</u> Generated relatively original ideas that can be seen approximately in less than 40% of the sample sketches, in the same group or at the same level of experience.	<u>To a great extent</u> Generated relatively original ideas that can be seen approximately in less than 20% of the sample sketches, in the same group or at the same level of experience.

Note. Examples of original ideas could be using non-linear (e.g., branched) design instead of a linear design, use of three dimensions in the design, and use of unconventional objects in the design.

CHAPTER FIVE: SYNTHESIS OF FINDINGS

This thesis was an article-based (3-paper format) dissertation. In this final chapter, I will first summarize the findings of each study. Then, I will synthesize the results and implications of these three studies.

Summaries of the Findings

Study #1: The IPO Model of Collaborative Creativity (IPOCC)

In the first study, we examined students' teamwork experiences with the creativity-supporting activities in two engineering courses offered in a university-based summer enrichment program. This examination resulted in developing the IPO Model of Collaborative Creativity (IPOCC). In this proposed IPO model, we adopted the theoretical framework suggested by Webb and Palincsar (1996) and grouped our findings under Inputs, Group Processes, Outcomes, and Mediating Factors. Under each of these areas, we categorized different components of this model: We grouped three categories under the Inputs for joint creative engineering practice, including Group Composition, Task Structure, and Structuring Teacher's Role. Under the Group Processes, the IPOCC model involves three categories, including Joint Engagement, Co-construction of Ideas, and Challenges of Teamwork. We grouped two categories under the Outcomes for co-creative engineering practice, including Creative Products and Intellectual Outcomes. Finally, Environment & Creative Climate and Affective Aspects were categorized under the Mediating Factors.

This study provides empirical evidence to support Plucker et al.'s (2004) definition of creative thinking. The IPOCC mirrors Plucker and colleagues' definition of creativity as

“…aptitude, process, and environment by which an individual or group produces a perceptible product” (p. 90), that is original and valuable within a context. However, as Lubart (2018) mentioned, the Western perspective on creativity is “… relatively individual-oriented and product-oriented” (p. 139). The IPOCC can be considered part of the contemporary inquiries toward developing theories of process-oriented collaborative creativity. Additionally, through the IPOCC model, we provided initial steps to extend the 4P view (Rhodes, 1961) on creativity.

Our findings indicated that several components of the IPOCC are aligned with the Complex Instruction Approach (Cohen & Lotan, 2014; Cohen et al., 1994), including Challenging Tasks and Open-ended/Ill-defined Activities, Structuring Teacher’s Role, Joint Engagement, and Co-construction of Ideas. As Cohen and Lotan (2014) and Tomlinson (2018) suggested, our findings indicated that less-structured and more open-ended activities serve as an essential element to provide students with a creativity-fostering environment. Delegating agency and authority to the students facilitate collaborative learning (Tomlinson, 2018). A combination of challenging tasks, open-ended problems, and student teamwork provides a rich environment for learners’ joint engagement in thinking creatively.

Study #2: A Three-pronged Design Sketching (3-pDS) Framework

The purpose of this second study was to explore how novice and K-12 students’ visual representation of a design idea has been assessed, and what research and evaluation methods have been used to study novice and K-12 visual representation of a design (e.g., sketches)? In the different phases of screening in this systematic review, we applied our inclusion, exclusion, and quality criteria. From an initial sample of 958 articles, we included 40 studies in the final step of the coding process and qualitative synthesis. Applying provisional and open coding, three broad themes were identified in this inquiry that have been used by researchers to conceptualize sketching of ideas, in novice and K-12 design activities: Visual-Spatial Characteristics, Design Creativity, and Communicating Ideas.

The first emergent theme was Communicating Ideas that refers to the degree to which a student's sketch clearly communicates the design idea(s) and effectively represents the design information. This theme and its sub-categories, especially sub-categories of Annotations, were well-represented in approximately 85% (n = 34) of the 40 articles selected for our review. The second emergent theme was Visual-Spatial Characteristics that refers to the degree to which a student's sketch properly involves visual cues related to the spatial characteristics of the design and combination of the parts. This theme and its sub-categories are signified in 24 (60%) of our 40 selected articles, specifically sub-categories of Functionality such as Scale and Views. The third emergent theme was Design Creativity that refers to the degree to which a student's sketch presents indicators of creative design, such as producing a perceptible design that is both original and valuable as defined within the design context. This theme and its sub-categories were found in 20 (50%) of our qualifying articles. These three themes seem to form the basis of effective sketching for early engineering design practices.

Some of the scholars in our selected studies (16 out of the 40) applied a qualitative approach to explore learners' visual representations, using different metrics, classifications, and coding protocols. Some studies selected for inclusion employed mixed methods (n = 11) or a quantitative approach (n = 7) to quantify some of the sketching characteristics, particularly for the creative characteristics. In this systematic review, we could not find any scale or rubric to evaluate K-12 student-generated sketches. Through completing this qualitative systematic review, we selected, categorized, and provided a set of criteria and standards to inform the development of an appropriate measure to evaluate K-12 idea-sketching activities. Based on our systematic review, 23 characteristics were proposed and categorized into the three themes. We proposed this Three-pronged Design Sketching (3-pDS) framework as a conceptual framework for future examination of K-12 design visualizations.

Study #3: The idea-Sketching Early Engineering Design (i-SEED) Scale

Based on the 3-pDS theoretical framework (Author et al., 2020) that we developed in the systematic review of design studies, in this third research, we developed the idea-Sketching Early Engineering Design (i-SEED) Scale. Through this scale-development study, we provided evidence of content validity, construct validity, and internal consistency of the data we used to develop the i-SEED Scale. Through exploratory factor analysis, we provided initial evidence to support the internal structure of the i-SEED Scale. These analyses supported the idea that there were three distinct, latent factors addressed by the i-SEED Scale items. The EFA process provided evidence supporting a three-factor model, including ten items:

- Factor 1, Visual-Spatial Characteristics, including four items (i.e., Aesthetic Sensitivity, Shape Accuracy, Scale, and Views)
- Factor 2, Design Creativity including three items (i.e., Flexibility, Originality, and Complexity)
- Factor 3, Communicating Ideas, including three items (i.e., Functionality, Feasibility, and Annotations.

This three-factor model is aligned with the 3-pDS theoretical framework (Author et al., 2020).

Focusing on the idea-representation strategy in the Informed Design Learning and Teaching Matrix (Crismond & Adams, 2012), this study addressed the need to develop an instrument to differentiate among different performance levels of K-12 design sketching. This study of the i-SEED scale provided initial steps toward the evaluation of design in pre-college settings. Our findings indicated the importance of idea-sketching in the design-oriented pedagogical approaches in terms of supporting creativity and peer-collaboration. As Kelley and Snug (2017) suggested, design sketching can be considered as a new form of assessment to evaluate K-12 students' design competencies and their conceptual understanding of STEM contents. Evidence from content validity, construct validity, and internal consistency of the data we used to develop this scale suggest that the i-SEED Scale can serve as a reliable measure for this purpose. The results of this study need to be further verified through confirmatory factor analysis.

Synthesizing the Results and Implications

Brophy et al., (2008) stated that design-based instruction in science and mathematics can develop K-12 learners' competencies in different areas, such as abilities to (a) evaluate and explain the configuration and function of complex systems; (b) develop cognitive models of working systems; (c) design and conduct experiments to inform decision making; (d) communicate ideas; (e) utilize geometric and visual-spatial reasoning; (f) represent and manage the complexity of a system; (g) elaborate on ideas and results with mathematics, and (h) synthesize ideas toward an appropriate solution that meets the required goals. As described in the Informed Design Teaching and Learning Matrix (Crismond & Adams, 2012), idea-generating and visual representation are an integral part of the design-thinking process. The co-construction of ideas in a creativity-stimulating environment and visualization of these ideas were the focus of these three studies.

Visualization of Ideas: Peer-collaboration through Idea-communication

In our first study of developing the IPOCC model, 13 out of 16 interviewees addressed visualization of design as an important outcome of participation in their enrichment courses. Learning How to Sketch was another outcome mentioned by nine out of 16 interviews. Thus, based on my interest in drawing and background in physics, visualization of design ideas was the focus of the second and third studies. Free-hand sketching has been used and taught in different disciplines, such as architecture and industrial design, as an approach to problem-solving and idea generation (Bilda et al., 2006; Booth et al., 2016; Eissen & Steur, 2011). As suggested in the previous studies (e.g., Cardella et al., 2006; Crismond & Adams, 2012; Uziak & Fang, 2018), our findings indicated that sketching supports collaborative design-thinking through enhancing communication. Sketches are an important approach to embody engineering design ideas (Ullman et al., 1990), especially for the purpose of idea communication (Cardella et al., 2006; Jordan et al., 2016; Römer et al., 2001).

Free-hand sketching is among the most common techniques applied by engineers to express and communicate ideas, specifically during the idea-generation process (Galil et al., 2017; Pei et al., 2011). Kelley and Sung (2017) provided evidence that design-oriented instruction enhanced student's communication competencies, "…moving from using sketching as a container of ideas to the use of sketching as a form of design communication and to refine design ideas." (p. 363) Our findings of these three studies indicated that a combination of challenging design-oriented tasks and open-ended problems enhance student teamwork and peer-collaboration. This combination can provide a rich environment for learners' collaborative engagement in creative-thinking processes, such as brainstorming ideas, problem sensitivity, and openness to explore different ideas. Less-structured and more open-ended activities serve as a critical element to provide students with a creativity-supporting environment. Giving authority to the learners facilitates peer-collaboration (Tomlinson, 2018).

Intersection Area of the Studies: Co-construction of Ideas in Group Processes

In the first study, we developed the IPO Model of Collaborative Creativity (IPOCC), in which different categories of this model were grouped under Inputs, Group Processes, Outcomes, and Mediating Factors. In the IPOCC model, processes that influence group creativity and creative outcomes are classified into three categories, including Joint Engagement, Co-construction of Ideas, and Challenges of Teamwork. These categories represent collective aspects of creativity and the perception of creativity as social and communal processes (Miell & Littleton, 2004; Sawyer, 2012; Sawyer & DeZutter, 2009). Several components of the second category (Co-construction of Ideas) emerged in our second and third studies. For example, the Annotations criterion and item in the 3-pDS Framework and i-SEED Scale reflects the Elaboration sub-category in the IPOCC model.

Regarding Design Creativity, Flexibility and Originality criteria/items in the 3-pDS Framework and i-SEED Scale signify the Flexibility and the Originality sub-categories under the Co-construction of Ideas, in the IPOCC model. Additionally, Connections and Imagination were categorized as components of the Design Creativity theme in the 3-pDS Framework. These two components represent two sub-categories, in the IPOCC model—Making Connections and Fantasy & Imagination. As another example, Aesthetic Sensitivity appeared as an important component in all three studies, including the IPOCC model, 3-pDS Framework, and i-SEED Scale.

Furthermore, in the first study, Complexity and Feasibility were mentioned by nine interviewees as two essential characteristics of a creative product. These two criteria also emerged in the second and third studies. These commonalities among the three studies indicate that idea-sketching can potentially serve as a mediator and a recorder of design creativity (McGown et al., 1998; Yang & Cham, 2007), as sketching has been strongly associated with promoting creativity in design thinking (Daly et al., 2016; Galil et al., 2017; Joshi & Summers, 2012; Kelley & Sung, 2017; McGown et al., 1998; Römer et al., 2000). Further, these commonalities among the three studies suggest that idea-sketching activities can be used as an effective technique to promote collaborative creativity in K-12 settings.

Implications

Helping learners to engage in collaborative inquiry and supporting their creative behavior in co-construction of ideas is currently a primary educational goal for K-12 programs (Chan, 2013). The results of these three studies can help teachers to pursue this educational goal. Teachers can potentially use the IPOCC model and 3-pDS framework to enhance learning collaboratively and thinking creatively, in pre-college educational settings. The findings of these three studies offer valuable insights for teachers in terms of the essential components of group-level creativity. The results of this article-based dissertation can inform teachers to develop strategies to support collective design thinking in their classrooms.

Design is one of the most common and widely used practices to develop engineering talent. Engineering design is recognized and taught as a collaborative process with several socio-technological elements (Dym et al., 2005). The IPOCC model and 3-pDS framework can provide insights into the curriculum development to nurture engineering talent in K-12 formal settings and non-formal enrichment programs. Furthermore, the IPOCC model and 3-pDS framework can serve as a foundation to investigate students’ collaborative design abilities and how pre-college learners apply their knowledge and abilities through design. Researchers can use IPOCC model, 3-pDS framework, and i-SEED scale in investigating different areas of collaborative design thinking.

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