SUPPORTING ADOLESCENT METACOGNITION IN ENGINEERING DESIGN

THROUGH SCRIPTED PROMPTS FROM PEER TUTORS:

A COMPARATIVE CASE STUDY

by

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A dissertation submitted in partial fulfillment of the requirements for the degree of

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ABSTRACT

Supporting Adolescent Metacognition in Engineering Design

Through Scripted Prompts from Peer Tutors:

A Comparative Case Study

by

Kristin M. Strong, Doctor of Philosophy

Utah State University, 2018

In the last decade, directives at the national level have urged the infusion of engineering design into the public schools. Developers of the Next Generation Science Standards (2013) implemented the directives and elevated engineering design to the level of scientific inquiry. Teaching design, however, is challenging to educators due to the complex nature of design problems, which cannot be solved via simple algorithms. Solving design problems requires a more reflective and iterative approach that emphasizes metacognitive skills like planning, monitoring, introspection, and taking another person’s perspective. Educators are further challenged by children’s immature metacognitive skills, which may be insufficient to engage fully in all phases of the design process.

A pedagogical method for supporting adolescent metacognition during the earliest phases of the design process was investigated. Using a qualitative, comparative case methodology,
seven pairs of seventh graders in a Career and Technical Education classroom were studied as they responded to a design challenge. Three additional pairs were partially studied. The objectives were to explore whether metacognitive prompts delivered by a peer in a paired environment stimulated adolescents to reflect upon and revise their initial designs, and if so, how those design changes arose.

Findings revealed that design revisions were stimulated through verbal phenomena (explanations, feedback, questions, and affirmations), and through socio-emotional means. Which verbal phenomena contributed to the revisions and the degree to which the socio-emotional component played a role depended upon the interaction style of the peer pairs. Regardless of a pair’s interaction style, though, the learning activity helped adolescents avoid design fixation. Students were stimulated and motivated to alter their designs. They primarily created new criteria (design features), or refined or eliminated existing criteria. The metacognitive prompts used in the learning activity can be modified to apply to any design challenge.

Furthermore, an additional, exploratory case demonstrated a restructuring of the learning activity in which metacognitive prompts were generated naturally by the students themselves. The student-generated prompts were design-specific and timely; delivered in the moment when a student was struggling with a design element. The result was a dynamic co-construction and co-ownership of the designs.

(249 pages)
PUBLIC ABSTRACT

Supporting Adolescent Metacognition in Engineering Design

Through Scripted Prompts from Peer Tutors:

A Comparative Case Study

Kristin M. Strong

In 2013, developers of the Next Generation Science Standards implemented national K-12 directives and elevated engineering design to the level of scientific inquiry. Teaching design, however, is challenging to educators due to the complex nature of design problems, which cannot be solved via simple algorithms. Solving design problems requires a more reflective and iterative approach that emphasizes metacognitive skills like planning, monitoring, and taking another person’s perspective. Educators are further challenged by children’s immature metacognitive skills, which may be insufficient to engage in the entire design process.

A qualitative study of paired seventh graders demonstrated a pragmatic learning activity for enhancing adolescent designs during their earliest phases through guided peer interactions with metacognitive prompts. Four distinct interaction styles were observed among the pairs. Each style varied by which verbal and social phenomena were used to make changes. The metacognitive prompts used in the learning activity can be adapted to any design challenge.

Furthermore, an additional, exploratory case demonstrated a restructuring of the learning activity in which the metacognitive prompts were generated naturally by the students themselves. The student-generated prompts were design-specific and timely; delivered in the moment when a student was struggling with a design element. The result was a dynamic co-construction and co-ownership of the designs.
DEDICATION

To my parents, William J. and Carol J. Strong, my first teachers.
“…she would rather light candles than curse the darkness…”
—Adlai Stevenson eulogizing Eleanor Roosevelt, 1962, United Nations General Assembly

Democracy has to be born anew every generation, and education is its midwife.
—John Dewey, 1899

“…when you get, give. When you learn, teach.”
—Dr. Maya Angelou, 2011

Understanding is love’s other name.
—Thich Nhat Hahn, 2014
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CHAPTER I
INTRODUCTION

Background of Study

For nearly a quarter-century, there has been a consensus among the national academies and government organizations that the United States must improve the quality of its science, technology, engineering, and mathematics (STEM) education in order to compete in an increasingly global economy. Improvement is thought to be needed at all educational levels, but the kindergarten through 12th grade (K-12) level is considered to be critical to (a) maintaining and increasing the STEM pathway (the number of people interested in and able to engage in STEM careers), and (b) increasing STEM literacy among the general population (United States Department of Labor, 2007).

While science and mathematics have a long history within K-12 education with well-established curricula and standards, technology education has only recently become standards-based and compulsory, and engineering has been the most poorly attended to of all (Carr, Bennett, & Strobel, 2012; Katehi, Pearson, & Feder, 2009). K-12 engineering education has received little attention from policy-makers, and has had no central agency to develop and collect assessments, or provide guidance to teachers. While there has been some recent infusion and mapping of engineering standards into other disciplines (e.g., The Next Generation Science Standards, 2013, integrates engineering design into science education), there are no stand-alone, comprehensive engineering standards at the national level (Carr et al., 2012).

In 2009, the Committee on Engineering Education at the National Academy of Engineering and National Research Council issued their report, *Engineering in K-12 Education*:...
Understanding the Status and Improving the Prospects, in which they outlined the benefits of K-12 engineering education to the national STEM agenda. In addition to widening the STEM pathway and improving technology literacy for all students, the committee believed that engineering education could act as a “catalyst,” integrating all the STEM disciplines and making them more effective.

The committee also gave general principles for the implementation of engineering education. Their first key principle was that “K-12 engineering education should emphasize engineering design” (Katehi et al., 2009, p. 4). Teaching design, however, presents a great challenge to educators because of the fundamental nature of design:

- Design is ill-structured, ill-defined, and complex (Christiaans & Venselaar, 2005; Cross, 2004; Goldschmidt & Weil, 1998).
- Design is a recursive, feedback process of “action and reflection” (Christiaans & Venselaar, 2005, p. 217).
- Design requires the regulation and integration of multiple forms of knowledge; it relies heavily on metacognition (Christiaans & Venselaar, 2005; Jonassen, 2000).
- Design requires the simultaneous “co-evolution” of the problem space and the solution space (Cross, 2001, 2004; Dorst & Cross, 2001).

Due to these characteristics, design problems do not lend themselves to simple solutions via algorithms that can be easily implemented in a K-12 classroom (Goldschmidt & Weil, 1998; Jonassen, 2000). While educational researchers may study the “science of design,” Cross (2001, p. 49) argues that a “design science” with logical, systematic, and rigid algorithms for solving design problems is not congruent with the process of design. Instead, the pedagogy for solving
design problems requires a more flexible, reflective, and creative approach that emphasizes *metacognitive skills* to help students “know what they know” and regulate their knowledge (Lawanto et al., 2013a, 2013b; Pintrich, 2002).

Metacognition must be emphasized because design and other ill-structured problems are dominated by metacognitive processes (Christiaans & Venselaar, 2005; Jonassen, 2000). During the design process, students must repeatedly identify and define sub-problems, generate solutions, then iterate back to the original top-level problem (Sheppard, Macatangay, Colby, & Sullivan, 2009). Thus, design is distinctly non-linear, requiring the awareness, management, and integration of many forms of knowledge through metacognitive skills (Christiaans & Venselaar, 2005; Jonassen, 2000; Mawson, 2003).

Educational research has shown, however, that students’ metacognition may be insufficient for students to engage successfully in all phases of the design process (Lawanto et al., 2013a, 2013b; Luo, 2015; Wilson, Smith, & Householder, 2014). Brain science supports this conclusion of metacognitive insufficiency (Casey, Jones, & Hare, 2008; Choudhury, Charman, & Blakemore, 2008). Recent advances in brain imaging have revealed that human brain development is not fixed in early childhood, as was once believed (Choudhury et al., 2008). It is now known that gray matter in the brain (neuron cell bodies, their branches, and support cells) continues to grow in volume and reaches a peak in late childhood or early puberty. Then, during adolescence and beyond, gray matter volume *declines* as unused synaptic connections between cell bodies are pruned away. Only the well-worn neural pathways are kept (Casey et al., 2008; Choudhury, Blakemore, Charman, 2006; Choudhury et al., 2008; Weil et al., 2013). In addition, while the gray matter volume is declining, there is a linear, age-related *increase* in white matter volume (Choudhury et al., 2008; Kolb & Gibb, 2011) which strengthens
neural pathways and greatly increases the speed of electrical signal transmissions in the brain (Fields, 2010).

The restructuring and reorganization of the brain during adolescence is especially dramatic in the prefrontal cortex, one of the last areas of the brain to develop (Casey et al., 2008; Choudhury et al., 2006; Choudhury et al., 2008). The prefrontal cortex is known to be involved in metacognitive skills, like planning, monitoring, decision-making, self-awareness, introspection, and taking another person’s perspective (Elliott, 2003; Fleming & Dolan, 2012; Schmitz, Kawahara-Baccus & Johnson, 2004).

Taking another person’s perspective is a skill critical to design because a designer must consider the user’s point of view. Adolescents have been shown to have more difficulty with this skill than adults do. They also use a different part of their brain to accomplish this task than adults do (Choudhury et al., 2006). Because the brains of adolescents are still undergoing profound development, a need exists to support their metacognitive skills so that they can engage more successfully in design.

**Purpose and Objectives**

The purpose of this research was to explore a pedagogical method of supporting adolescent metacognition during the earliest phases of the design process: the interpretation of the design task and the generation of design ideas. The interpretation of the design task was accomplished when a student created a design brief. The generation of ideas was explored and captured in a student’s solution sketches. The researcher hypothesized that student metacognition could be supported during the earliest phases of the design process through metacognitive prompting in a peer tutoring environment.
The metacognitive prompting was accomplished through “structured” peer tutoring in which tutoring was not ad-lib, but *guided* with a script. As students worked in pairs, each student was guided in a role as a peer tutor to ask the other student questions about his or her design. Embedded within each question was a metacognitive prompt. Both students got the chance to take on the role of peer tutor--thus, the peer tutoring was *reciprocal*.

The research objectives were:

1. To study whether or not metacognitive prompts delivered in a reciprocal and structured peer tutoring environment cause adolescent designers to reflect upon and revise their interpretation of the design task, as well as its solution sketch.

2. To study *how* metacognitive prompts delivered in a reciprocal and structured peer tutoring environment elicit changes to design briefs and solution sketches, that is, to explore whether changes occur primarily through explanations, questions, or feedback; or through a combination of these interactions; or through some other means.

**Research Questions**

To meet the purpose and objectives, the research was guided by the following research questions:

1. How do metacognitive prompts delivered in a reciprocal and structured peer tutoring environment alter adolescent design briefs (the explicit task interpretation) of an engineering design problem?

2. How do metacognitive prompts delivered in a reciprocal and structured peer tutoring environment alter adolescent solution sketches (the design problem solution space) of an engineering design problem?
Research Design

The research was conducted using a qualitative methodology, specifically a comparative case study approach in which comparisons were made within and across multiple, comparable, “information-rich” (Patton, 1990) cases to look for patterns (Levy, 2008; Wilson et al., 2014). A case within the research was defined as a pair of adolescent students from the same grade engaged in a reciprocal and structured peer tutoring session as part of an engineering design activity. The research focus was the students’ verbal responses to peer-delivered metacognitive prompts (questions about their designs), and the students’ subsequent design revisions.

Based on the children’s literature in STEM education of Chin (2016), Disessa (2014), King & English (2016), Parnafes (2007), and Wilson et al. (2014), the researcher chose a sample size of 10 pairs of adolescents. Due to limitations of the research classroom, seven pairs were ultimately studied in full, with another three pair partially studied. The reduced sample size met the recommendations of Miles, Huberman, and Saldaña (2014).

Reflecting the researcher’s desire to develop a pragmatic intervention, the study site was a required career and technical education class for all seventh graders in a western, public middle school with a potential for variation in STEM exposure and socio-economic status. A mixed, “purposeful” (Patton, 1990) sampling strategy was employed. Student participants were selected using (a) typical sampling, and (b) criterion sampling by grade and course. Students received token compensation ($10) for their participation.
Significance of the Study

This study was designed to inform secondary STEM teachers, engineering policy makers, curriculum developers, standards writers, and instructional designers about the need to support adolescent metacognition in the context of engineering design. The study demonstrated a pragmatic intervention for enhancing adolescent designs during their earliest phases through guided peer interactions with metacognitive prompts. The scripted prompts stimulated design revisions by evoking verbal phenomena between paired peers. The researcher identified which prompts were most effective at stimulating design revisions, and observed a socio-emotional component as well. Four distinct peer interaction styles emerged from the data analysis within and across multiple case pairs. Each style varied by the types and amounts of verbal phenomena that were evoked by the prompts, and the degree to which the paired peers offered socio-emotional support to each other for revision.

Assumptions of the Study

The assumptions of the study were that:

1. Student participants would complete their initial design briefs and sketches independently with no help from peers or teachers.
2. Student participants would honestly complete their self-report surveys.
3. Student participants would know how to communicate in English.
4. Student participants would have prior experience using a computer and web browser to do research.
5. Student participants would be adolescents, in the stage of human development between early puberty and adulthood.

6. Paired student participants would be in the same grade and within two years of each other in age.

**Limitations of the Study**

The scope of this research was limited by the following:

1. The student participants were limited to those who (a) attended a public middle school in Northern Utah, USA, (b) were taking a required seventh-grade course in career and technical education, and (c) were members of the same career and technical education classroom.

2. The number of student participants who completed the full curriculum was limited to seven pairs. Three additional pairs were partially studied.

3. The time each participant engaged with the research curriculum, surveys, and design activity was limited to approximately two hours total.

4. As a qualitative study, the findings may be interpreted differently by different readers.

**Definition of Key Terms**

Key terms that were relevant to the study are defined below.

*Adolescence:* The developmental stage of life between childhood and adulthood marked by significant brain, body, and psychological changes. It begins approximately with the onset of puberty and ends when the individual reaches a “stable, adult role” in society (Choudhury, 2010).
**Design brief:** A written document in which a designer captures the essential information that is relevant to a design problem and sets the goal(s), criteria, and constraints (Cross, 2000); it does not typically suggest or specify a design solution.

**Dyad:** A pair. In sociology research, a group of two participants.

**Fixation:** The tendency of designers to fixate (or stick with) the first design idea that comes to mind, or to fixate on design solutions that they have seen before (Luo, 2015).

**Gray matter:** Brain matter that consists mainly of (a) neuronal cell bodies, (b) axons (extensions of cell bodies that carry signals between the bodies), and (c) support cells. The color is gray because the axons are unmyelinated, lacking a whitish-colored fatty protein sheath. Gray matter reaches a peak in early childhood, around the initiation of puberty, and then declines throughout adolescence (Casey et al., 2008; Choudhury, Blakemore, Charman, 2006; Choudhury et al., 2008; Weil et al., 2013).

**Metacognition:** Knowledge of one’s own cognition or regulation of one’s own cognition (Flavell, 1976).

**Neuron:** A specialized cell in the nervous system that is electrically excitable and transmits signals through electrical and chemical processes.

**Peer tutoring:** A type of collaborative learning in which one or more students are assisted by a peer in learning (De Smet, Van Keer, & Valcke, 2009; King, Staffieri, & Adelgais, 1998).

**Prefrontal cortex:** The part of the cerebral cortex that covers the frontal lobes and is important in higher-order thinking skills. One of the last parts of the brain to develop (Casey et al., 2008; Choudhury et al., 2006; Choudhury et al., 2008).

**Self-regulated learning:** A style of active learning in which a student uses cognitive, behavioral, and motivational strategies to take charge of his or her own learning in a process of action and
reflection (Zimmerman, 1990).

White matter: Brain matter that consists mainly of (a) bundles of axons (extensions of nerve cell bodies) coated with white myelin sheaths, and (b) support cells. It is deep brain tissue connecting regions of gray matter that greatly increases the speed of transmission of electrical signals (Fields, 2010). It develops in a slow, linear fashion throughout adolescence (males have a greater rate of increase than females). The frontal areas of the cerebral cortex (involved in higher-order thinking skills, like metacognition) are the last to develop or become “myelinated” (Blakemore, Burnett, & Dahl, 2010).

Organization of the Dissertation

The dissertation is organized into six chapters. Chapter 1 presents an introduction detailing the background of the study, its purpose and objectives, research questions, research design, as well as its significance, assumptions, and limitations. Chapter 2 reviews literature relevant to the study with an overview of cognitive neuroscience, cognitive psychology, engineering design, metacognition, peer tutoring, self-regulated learning, design briefs, and solution sketches. Chapter 3 presents the objectives and findings of a pilot study as well as the lessons learned from that study. Chapter 4 describes the methodology used in the comparative case study, including its rationale, the participant selection, and the methods of data collection and analysis. Chapter 5 presents the findings of the comparative case study with discussions following each finding. Chapter 6 reports the conclusions, lessons learned, recommendations for future study, and significance to adolescent educators.
CHAPTER II
REVIEW OF THE LITERATURE

Introduction

The study required the integration of six areas of research: cognitive neuroscience, cognitive psychology, metacognition, self-regulated learning, peer tutoring, and engineering design as shown in the literature map of Figure 1. Cognitive neuroscientists attempt to determine through modern brain imaging techniques which neural circuits are active, and which are quiescent, under different cognitive states. Cognitive psychology, “the study of higher mental processes such as attention, language use, memory, perception, problem solving, and thinking” (APA, 2002), includes the study of the higher level mental processes of metacognition.

There is a lack of consensus among scholars upon the hierarchical relationship between the terms metacognition and self-regulated learning, a style of learning in which students take charge of their own learning by adjusting their cognition, behavior, or motivation (Zimmerman, 1990). While metacognition is classically defined by Flavell (1976) as knowledge about one’s own cognition and regulation of that cognition, some researchers have reserved the regulatory part of metacognition for the term self-regulated learning. Others have suggested that the two terms are equivalent or interchangeable (Dinsmore, Alexander, & Loughlin, 2008; Ibabe & Jaureguizar, 2010). However, in a literature review, Dinsmore, Alexander, and Loughlin (2008) described a delineation between metacognition and self-regulated learning with metacognitive studies highly focused on cognition, while self-regulated learning studies had a triad of behavioral, motivational, and cognitive components. In this research, the hierarchy shown in Figure 1 was adopted which suggests that metacognitive knowledge is required to be a self-
regulated learner, that is, metacognition is *used* in self-regulated learning.

A self-regulated learner is able to adjust cognition, motivation, or behavior to control learning in a feedback-based cycle of forethought, performance, and reflection (Zimmerman, 1990) as shown in Figure 1. The forethought phase includes *task interpretation*, which Hadwin’s
2006 model of task understanding differentiated into three types: explicit, implicit, and socio-cognitive. The explicit task interpretation is the traditional notion of what it means for a learner to understand a task, such as an awareness of criteria, grading, instructions, and standards. Implicit task interpretation requires that the learner move beyond the written or verbal instructions and become aware of the resources that are available to accomplish the task, the relationship of the task to other concepts or tasks, and the purpose of the task. Socio-cognitive task interpretation contains the awareness-of-self-and-others variables, such as personal motivation, beliefs about efficacy, personal knowledge, and awareness of instructor values (Hadwin et al., 2009). In this research, an intervention (metacognitive prompts delivered in a peer tutoring environment) attempted to affect the learner’s explicit task interpretation.

Peer tutoring is a type of collaborative learning in which one student in a pair of students, or in a small group, takes on a tutoring role (De Smet et al., 2009). In reciprocal peer tutoring, each student gets the opportunity to assume both a tutor and tutee role (Rittschof & Griffin, 2001), developing social support between the students (Ismail & Alexander, 2005). In structured peer tutoring, the tutoring sessions are scripted or semi-scripted. Research has shown that structured peer tutoring helps student to engage in relatively high level “knowledge-building” rather than low level “knowledge-telling” during tutoring sessions (Ismail & Alexander, 2005; Roscoe & Chi, 2007; Topping, 2005).

Finally, as shown in the literature map, there are three forms of knowledge required to conduct engineering design: Domain-specific engineering knowledge, domain-specific design knowledge, and domain-independent, metacognitive knowledge (Christiaans & Venselaar, 2005). This research explored the activation and exercise of the domain-independent, metacognitive knowledge pathway through metacognitive prompts delivered in a peer tutoring
environment (the intervention). The research path is highlighted in blue in Figure 1.

In the following section, an overview and introductory review of relevant literature are presented for each of the six main areas of research shown on the literature map. In addition, because design briefs and solution sketches are the artifacts that were collected during the research to capture the design process, a brief introduction to those topics and why they are theoretically important are included as well.

**Cognitive Neuroscience**

Only since the late 1990’s have scientists come to understand (through advances in scanning technology) that the human brain is not fixed in early childhood (Blakemore, 2012). Instead, the human brain continues to undergo profound changes in both architecture and neural connections throughout adolescence and into adulthood. Initially, in early childhood, the brain “overproduces” both neurons and synapses (connections between neurons), but then in early puberty a process called “synaptic pruning” begins. Weak synaptic pathways are eliminated, while well-used pathways are strengthened (Casey et al., 2008; Choudhury, Blakemore, Charman, 2006; Choudhury et al., 2008; Weil et al., 2013). Pruning is a “fine-tuning” of the brain for the environment it is developing in (Blakemore, 2012).

The synaptic pruning is accompanied by an age-related, non-linear *decrease* in gray matter (nerve cell bodies and their branches) and a linear, age-related *increase* in white matter volume (Choudhury et al., 2008; Kolb & Gibb, 2011) with males showing a higher rate of increase than females (Blakemore, Burnett, & Dahl, 2010). The white matter, which gets its color from an electrical insulator called myelin, dramatically increases the conduction speed of electrical signals in the brain (Fields, 2010). For example, Choudhury et al. (2006) found that
differences in reaction times of adolescents when taking another person’s perspective versus their own perspective decrease with age. As the brain matures—restructures, reorganizes, and becomes more myelinated—the adolescent gains a more efficient ability to see another person’s perspective (a skill important in engineering design), and uses different, more adult-like, perspective-taking strategies.

According to Fields (2010), the linear increase in white matter (myelinization) occurs through adolescence until at least the third decade of life. However, Petanjek et al. (2011) reported that synaptic pruning continues throughout the third decade in the prefrontal cortex. They reviewed functional magnetic resonant imaging (fMRI) studies which suggested that the density of gray matter and the integrity of white matter change into the third decade in the neocortex, the part of the brain involved in complex thought, planning, and language. In addition, many researchers (Casey et al., 2008; Choudhury et al., 2006; Chouhury et al., 2008) have indicated that the prefrontal cortex is one of the last areas of the brain to develop.

The profound restructuring and reorganization of the human brain during adolescence and beyond, which is especially prolonged in the prefrontal cortex, has implications for engineering education. Engineering design relies heavily upon metacognitive skills and the prefrontal cortex is known to be responsible for many of those skills, like planning, monitoring, decision-making, self-awareness, introspection, and taking another person’s perspective (Elliott, 2003; Fleming & Dolan, 2012; Schmitz et al., 2004).

For example, taking another person’s perspective is a skill critical to design because a designer must consider the user’s point of view. Adolescents have been shown to have more difficulty with this skill than adults do. They also use a different part of their brains to accomplish this task than adults do (Choudhury, Blakemore, & Charman, 2006). Because the
brains of adolescents are still undergoing profound development, a need exists to support their metacognitive skills, so that they can engage more successfully in design.

**Cognitive Psychology**

With the rapid development of the computer in the 1960s, cognitive psychology underwent a dramatic paradigm shift from the psychology of human learning to the psychology of memory (Royer, 1986). The psychology of human learning was guided by associative learning theory (connectionism) that developed in the 1930s with the rise of Skinner and Radical Behaviorism (Bye, 2011). In associative learning theory, associations are developed between two stimuli or an association and a stimulus. The human brain is treated as a “black box.” It is impossible to know the transformative processes occurring within the box (the brain) and it is unnecessary to know them. Only the inputs and outputs to and from the brain, and the transformation of behavior in a positive way are of interest (Gall, Gall, & Borg. 2007).

In 1959, though, Noam Chomsky systematically dismantled Skinner’s behaviorism as it applied to linguistics. Chomsky argued that “the complexities of language cannot be explained without the existence of internal mental representations of objects and ideas. This [argument] sharply rebuked the perspective of behaviorism, which denied the mind and instead characterized human behavior as simply a function of stimulus and response associations” (Bye, 2011, p. 3).

In addition to Chomsky’s rebuke, the 1960s ushered in the development of the computer and early forms of artificial intelligence, so that by the late 1960s, associative learning theory was thought to be inadequate to develop and explain the full range of human learning (Royer, 1986). Now researchers believe that there are anatomical regions of the brain (with neural circuits) that are responsible for certain types of brain activity, and that this activity develops internal
cognitive structures and processes. Cognitive psychology is currently defined as the “study of structures and processes involved in mental activity, and how these structures and processes are learned or develop” (Gall et al., 2007, pp. 634-635).

Royer (1986) developed a taxonomy of four types of educational problems: (a) problems with observable behavior, (b) problems for developing basic knowledge, (c) problems for developing understanding, and (d) problems for developing problem solving and thinking skills. He explained that (modern) cognitive learning theory is ill-suited to developing approaches to handle the first two categories of educational problems (observable behavior and developing basic knowledge), but it is well-suited to developing approaches for the last two (understanding and problem solving). Through a detailed analysis of the relationships between incoming knowledge and existing knowledge, cognitive learning theory can be used to develop educational methods that attempt to promote understanding and problem solving skills, like those used in design (Royer, 1986).

In the constructivist perspective of cognitive learning theory, understanding occurs when incoming knowledge is interpreted by the learner through the language of his or her own knowledge and experiences, and is then integrated into the learner’s previous knowledge. Without previous foundational knowledge or experience that can be used for interpretation, “memorization may occur, but understanding will not” (Royer, 1986, p. 87). Research informed by cognitive learning theory suggests that understanding can be practically developed by activating prior knowledge (e.g., through mnemonics or analogies, or by using advance organizers [Royer, 1986], such as engineering design briefs).

With traditional associative learning theory, problem-solving was taught by having the learner replicate a domain-free sequence of skills. However, research informed by modern
cognitive learning theory has determined that some of the problem-solving skills needed in fields like engineering design are domain-specific, while others, like metacognition, are domain-independent, as described below.

**The Design Process**

Based on Jonassen’s taxonomy of problems (2000), design problems present some of the most complex and ill-structured of all problems to be solved. Design problems are also frequently ill-defined with multiple or undefined criteria, vague goals, and few constraints. These characteristics require the problem-solver to exert significant effort in defining and structuring the problem. Problem definition and structuring is the first activity in the design process which Cross (2000) described (at the highest level) as having four phases: (a) exploration, (b) generation, (c) evaluation, and (d) communication. Feedback and iteration are frequently required from the evaluation stage back to earlier stages.

Because the definition and structure of the problem—the problem space—cannot be fully defined independent of the solution space, a solution space or concept is often sketched out early in the design process. The early solution concept is then analyzed and evaluated and used to redefine the problem space. The redefined problem space is then used to generate a more refined solution space. Thus, the problem space and the solution space co-evolve along parallel, but linked paths as shown in Figure 2.
This iterative process of solution generation, analysis, evaluation, and refinement requires significant awareness, regulation, and integration of different forms of knowledge. In contrast to solving well-structured problems, design problem solving relies heavily upon metacognitive skills to manipulate multiple forms of knowledge. Recent studies on engineering design have suggested, however, that student metacognitive skills may be insufficient to engage successfully in all phases of the engineering design process (Lawanto et al., 2013a, 2013b; Luo, 2015; Wilson et al., 2014).

For example, in a study comparing secondary students and college freshman in engineering design, Lawanto et al. (2013a, 2013b) found that while all students had good awareness of the importance of task requirements, the secondary students (adolescents) were less aware than college freshman of the need to translate task descriptions into plans and were also less knowledgeable of how to execute those plans once they were translated.
In another study of adolescents in engineering design, Wilson, Smith, and Householder (2014) conducted a comparative case study to determine which types of literary practices best enable adolescents to address a client’s needs in an authentic design challenge. They found that literary practices in the earliest stages of the design process were especially important. The group of adolescents which engaged in fewer of these practices--intended to define the problem, and manipulate what was known and unknown about the problem (metacognitive skills)--were less successful at meeting the client’s needs.

In another case study, Luo (2015) found that elementary school children (ages 7-11 with little prior knowledge of design) tended to “fixate” on their first engineering design. They often did not reiterate or improve upon their first design, despite working in a cooperative learning environment. Instead, they showed little self-awareness (limited metacognition), fixating on design features that they had seen before in popular culture, or that they were already familiar with.

**Metacognition**

Classical theories of metacognition divide it into two areas: Knowledge about cognition and regulation of cognition (Lawanto et al., 2013a, 2013b; Pintrich, 2002). Knowledge about cognition refers to one’s own cognition, or to cognition in general. Brown (1987) and Jacobs and Paris (1987) described three types of knowledge about cognition: declarative, procedural, and conditional, which roughly correspond to about, how, and when or why knowledge, respectively (Schraw & Moshman, 1995). For example, knowing factual information about something, or about oneself as learner, is a form of declarative metacognitive knowledge; knowing how to execute a procedure is a form of procedural knowledge; and knowing when or
why to use a strategy to solve a problem is an example of conditional metacognitive knowledge. Scholars also describe three types of *regulatory* metacognitive knowledge: planning, monitoring, and evaluation. Some also add in a fourth type—controlling (Peteranetz, 2016). Knowledge of cognition and regulation of cognition are not thought to be independent of one another (Schraw & Moshman, 1995).

In problem-solving, including design, metacognition involves the active control over cognitive processes, such as reflection about the problem (framing the problem, determining what is known, and what still needs to be determined), planning an approach, selecting appropriate strategies, and monitoring progress towards completion of a task (Lawanto et al., 2013a, 2013b). In reflecting about an engineering design problem, students must first *understand* the problem. This means activating prior knowledge, experiences, and feelings about the problem and the problem’s context (e.g., the course instructor and the curriculum). The student can then make a *personal* interpretation of the problem statement and the tasks that are required to solve it (Dixon, 2010; Hadwin, Oshige, Miller, & Wild, 2009).

**Peer Tutoring to Invoke Metacognition**

Metacognitive skills are considered to be more difficult to develop than cognitive skills (Vos & DeGraff, 2004). According to cognitive neuroscientists, areas of the brain associated with metacognition undergo a prolonged and uneven developmental trajectory during adolescence (Casey et al., 2008; Choudhury et al., 2006; Choudhury et al., 2008; Petanjek et al., 2011). Substantiating these developmental studies are engineering educational researchers who have observed immature metacognitive skills in adolescence (Lawanto et al., 2013a, 2013b; Wilson, Smith, & Householder, 2014). Some have noted that students do not automatically
employ their metacognitive skills unless they are actively encouraged to do so (Lin, 2001). Adolescents may require metacognitive scaffolding.

To support the development of metacognition, Lin (2001) identified a two by two matrix of instructional approaches that researchers recommend:

1. Strategy training in domain-specific knowledge and self-knowledge, and
2. Social supports for domain-specific knowledge and self-knowledge.

Lin (2001) advised a more balanced, holistic, or systems approach when designing learning activities for metacognitive scaffolding: Instead of focusing solely on strategy-training to enhance domain-specific knowledge or self-knowledge, she recommended that designers expand and balance metacognitive learning activities. Designers should structure the environment surrounding the learning activities so that it, too, can enhance domain-specific and self-knowledge through a social support system.

Peer tutoring, a type of collaborative learning in which students teach other students, delivers one such balanced approach. During peer tutoring, students question, assess, explain and give feedback to their peers. The interaction provides multiple opportunities for developing metacognition—domain-specific and self-knowledge—in both tutors (the ones providing the instruction) and in tutees (the ones receiving the instruction) (Dioso-Henson, 2012; Ismail & Alexander, 2005; King, 1998; Topping, 2005).

During explanations, students must organize their knowledge and express it in ways that a peer can understand, making explicit what they know and do not know (Bargh & Schul, 1980). They may discover holes in their knowledge when they cannot explain something fully, or when they realize that something they’ve said does not make sense.

The learning benefits tutors or tutees experience while providing explanations may be
analogous to the benefits students experience when they are prompted to *self-explain* (Roscoe & Chi, 2007). Self-explanations are vocalized or internal explanations generated for oneself during which new knowledge is constructed or integrated with existing knowledge. Self-explanation, like peer tutoring, is a piecewise process which provides many opportunities for structuring knowledge, revising mental models, or repairing misconceptions (Chi, DeLeeuw, Chiu, & LaVancher, 1994).

Questions that arise during peer tutoring are another way to stimulate metacognition. Questions may be provoked by inconsistencies between incoming knowledge and existing knowledge. Questions can act as an “epistemic probe” or a “heuristic tool” (Chin & Osborne, 2010), sorting out what a student knows and doesn’t know, and supporting argumentation. Like explanations, questions also make visible a student’s knowledge and reasoning, setting the stage for peers to co-construct knowledge by offering confirmations, corrections of knowledge, or the filling in of gaps. Questions are essential to developing the metacognition skills involved in critical reasoning (Chin & Osborne, 2008; Chin & Osborne; 2010).

The feedback or assessment that arises from a peer during peer tutoring is also instrumental in promoting metacognition. Many researchers have described how feedback from an external source, such as peers, sets in motion self-regulatory processes (Butler & Winne, 1995; Greene & Azevedo, 2007; Labuhn, Zimmerman, & Hasselhorn, 2010). For example, Butler & Winn (1995) described how feedback can act as a “catalyst” for metacognitive activities such as monitoring.

The rationale for using a peer rather than a teacher or other source for external feedback is tied to adolescent brain development. During adolescence, peers become especially important and influential due to changes that take place in the prefrontal, parietal, and superior temporal...
cortex (Choudhury et al., 2006). Peer tutoring, like the intervention used in this research, capitalizes on the natural affinity of the adolescent for peer interaction; the adolescent is preferentially attuned to interactions with a peer.

The interactions that arise during peer tutoring, then—the explanations, questions, and feedback—can all exercise metacognition and contribute to knowledge building through reflection (Roscoe & Chi, 2007). The knowledge construction during peer tutoring is not, however, limited only to tutees (the ones receiving the instruction); it also extends to tutors (the ones providing the instruction). The phenomenon of tutor learning gains or knowledge-building during peer tutoring is called the tutor learning effect. Researchers vary as to why this phenomenon occurs depending upon their personal theory of learning.

Rohrbeck et al. (2003) subscribed to a sociocognitive theory of learning which draws from the work of Vygotsky (1978). Sociocognitive theorists believe that knowledge is constructed socially, mostly in interactions and activities between parents, teachers, peers, and friends. Embedded in this theory is the idea of scaffolding in which a more knowledgeable individual withdraws cognitive support as the less knowledgeable individual becomes more competent (Azevedo & Hadwin, 2005; Choi, Land, & Turgeon, 2005). In peer tutoring then, tutor learning gains arise in the social process of interacting with a peer and assessing the peer’s knowledge. Rohrbeck et al. also suggested that the tutor learning effect is influenced by Piagetian theory in which an individual reflects on and reconstructs his or her own knowledge during interactions with others.

Robinson et al. (2005) took a very different view of why the tutor learning effect occurs. They framed the tutor learning effect in terms of role theory which suggests that individuals adjust their behavior to conform to the role they are assigned. As a peer tutor then, students are
temporarily taking on the role of teacher, which is associated with competence in, and positive attitudes towards, the subject being taught.

Finally, Roscoe and Chi (2007) theoretically tied the tutor learning effect to two hypotheses: *The Explanation Hypothesis* and *The Questioning Hypothesis*. Adopting a cognitive perspective, Roscoe and Chi described how explanations and questions, both common processes in tutoring, contribute to reflective knowledge-building for the tutor: While peer tutors may have more advanced knowledge in the domain that they are tutoring than the tutees, they often do not possess expert knowledge, which frequently requires many years of practice. Consequently, in the process of explaining during tutoring, tutors must reflect upon their own knowledge, organize it, and transform it into information that the tutee can understand. In addition, while attempting to give explanations, gaps in the tutor’s knowledge become evident and must be confronted. Explanations may force tutors to correct their own misconceptions or rectify flaws in their knowledge. In a similar manner, tutor-generated questions, especially if they are deep questions, require that tutors reflect upon their existing knowledge, organize it and evaluate it for completeness, all high-level metacognitive skills.

Peer tutoring efficacy can be enhanced through structure or guidance (Ismail & Alexander, 2005; King et al., 1998; Roscoe & Chi, 2007; Topping, 2005). Researchers have observed that without structure, peer tutors often resort to low-level, “knowledge-telling” rather than knowledge-building explanations, or ask only low-level, factual knowledge questions. Structuring or guiding the peer tutoring session with prompts is one way to elevate the quality of the peer tutoring and reach higher cognitive and metacognitive knowledge construction (King et al., 1998; Lin, 2001; Roscoe & Chi, 2007).
Self-Regulated Learning as a Framework for Researching Metacognition in Design

Metacognition is classically defined as “knowledge concerning one’s own cognitive processes or anything related to them,” (Flavell, 1976, p. 232). Metacognition is essential for self-regulated learning, a style of learning in which students are able to take charge of their own learning by adjusting their cognition, behavior, or motivation (Zimmerman, 1990). It has been determined to greatly foster academic success. Butler and Winne (1995, p. 245) called self-regulated learning the “pivot upon which students’ achievement turns.”

Self-regulated learning is not a fixed quality in students. It can be taught and encouraged through curriculum, pedagogical practices, and the learning environment. For example, many researchers have described how feedback from an external source, such as peers, sets in motion self-regulatory processes (Butler & Winne, 1995; Greene & Azevedo, 2007; Labuhn, Zimmerman, & Hasselhorn, 2010).

Historically, self-regulated learning has its roots in educational psychology and behavioral interventions. People were taught techniques to self-regulate or modify negative behaviors to have more positive life experiences. These techniques were then expanded and applied to education with the goal of greater academic success through modification of cognition, behavior, or motivation.

There are many models of self-regulated learning, which have gotten increasingly more detailed and complex with time (Butler, 2002a). One of the simplest is Zimmerman’s (2000) cyclic, three-stage process of (a) Forethought, which includes Task Analysis and Self-Motivational Beliefs; (b) Performance, which includes Self-Control and Self-Observation; and (c) Self-Reflection, which includes Self-Judgment and Self-Reaction (Labuhn, Zimmerman, & Hasselhorn, 2010; Zimmerman, 2002). Novices tend to skip high-quality forethought, in which
cognition is the area of self-regulation, and instead attempt “reactively” to self-regulate (Schunk, 2005; Zimmerman, 2002). Experts, on the other hand, invest significant effort in planning (e.g., with advance organizers, and setting different levels and types of goals, Zimmerman, 2002).

Model refinements, such as Butler and Cartier’s 2005 model of self-regulated learning in context, have now made it possible to research sub-processes within the larger self-regulated learning model (Figure 3). The “context” in the model refers to the constructivist perspective of understanding in cognitive theory, which says that learners must interpret and integrate incoming new knowledge with pre-existing knowledge and experiences (the layers of context).

One critical sub-process is *task interpretation* which Lawanto (2013a, p. 45; 2013b, p. 16) called the “heart” of self-regulated learning because it sets the stage for all further recursive self-regulating strategies. Learners interpret tasks in light of their own mediating variables (knowledge, perceptions, conceptions, and emotions) and layers of context (history and experience, strengths, challenges, interest, etc.). Butler and Cartier (2004, p. 1735) called task interpretation “foundational” to learning and to task “engagement.” They described how a student’s metacognitive knowledge about tasks (task purpose, task structure, and task components) is essential for successful task interpretation and engagement. They also explicated that of these three task characteristics, student knowledge and understanding of *task purpose* is especially critical because “…the relevance of other types of metacognitive knowledge is determined based on knowledge of task purposes (e.g., the task purpose suggests the text genres or structures are relevant for a particular writing task), and students’ ability to successfully and flexibly direct learning depends on a clear vision of what they are trying to achieve” (Butler, 2004, p. 1743). The next section describes how task interpretation in the context of design is captured through design briefs.

**Design Briefs**

The National Center for Engineering and Technical Education (NCETE) outlined eight steps in the engineering design process: Identification of need, definition of the problem and specifications, search, development of designs, analysis of designs, decisions, testing of prototypes and verification of the solution, and communication (Childress & Maurizio, 2007). Design briefs are the *bridge* between the earliest identification of need and the start of the “creation phase of design, development, and production” (Cross, 2000, p. 200). They are
developed early in the design process and capture the essential information that is relevant to the design problem. Design briefs contain goals, constraints, and criteria, sometimes prioritized. They do not typically suggest or specify solutions—those can only come about during the creation phase of design (Cross, 2000).

Design briefs are *authentic activities* in the sense that they are commonly used in professional design practice. They are the essential document or presentation that captures the second phase of NCETE’s design process: The definition of the problem and specification. In essence, *design briefs embody explicit task interpretation*. Authentic activities and assessments, such as design briefs, promote the use of self-regulated learning strategies (Butler, 2002; Butler & Cartier, 2004; Greene & Azevedo, 2007).

Sipila and Perttula (2006) demonstrated through design briefs that the problem and solution space are *coupled* (as described previously in Figure 2). They found that the contents of the design brief (the explicit task interpretations) impacted performance in the generation of design solutions. The next section describes how the solution space is captured through sketches.

**Sketches**

Since before the Renaissance, sketches have been used not only to communicate designs to others, but to aid in thinking and reasoning during the design process. Sketches capture the dialogue between the internal thought processes (the reasoning) and the external representation of those ideas. Cross (2000) noted that the great advantage of sketches is they allow for the *simultaneous* exploration of the problem space and the solution space. Reflection upon the sketches and the concepts they embody helps the designer refine the problem space. This
facilitates convergence upon a *problem-solution pair*.

In addition, sketches help to keep designers *open* to many ways of thinking. Many aspects of design problems (such as trajectories, forces, inputs, outputs, elevations, or viewpoints) can all be considered simultaneously through the sketch. The designer can also highlight and reflect upon critical details. Sketches give a unique window into the thinking and reasoning that occur during the design process, that is, during the co-evolving problem space and solution space.
CHAPTER III
PILOT STUDY

Purpose and Overview

Developing, implementing, and assessing a research protocol is critical in multiple-case study research (Yin, 2008) and offers several advantages. Assessment allows a researcher to see if a protocol is realistic and feasible (van Teijlingen & Hundley, 2002), while applying the same protocol to multiple cases increases reliability (Yin, 2008). In addition, early assessment of data analysis techniques illuminates problems with coding and extraction of themes, so that modifications can be made prior to the full-scale study.

A pilot study was conducted to practice and assess the research protocol, data collection methods, and analysis techniques for the multiple-case study. The pilot study explored one of the cases—one pair of students; it was a “dress rehearsal” in preparation for the larger study.

Tasks of the Pilot Study

There were two tasks in the pilot study:

1. Conduct a single case study to practice the research protocol, data collection methods, and analysis techniques.

2. Assess the research protocol, data collection methods, and analysis techniques. Make recommendations for modification.

Task #1: Conduct a single case study

An exploratory, single case study was conducted in the summer of 2015 with a pair of
seventh-grade girls recruited from a public, middle school of moderate poverty. The study was designed to investigate the following: (a) whether metacognitive prompts delivered in a paired, peer tutoring environment encouraged students to reflect upon and revise their engineering designs; and, if so (b) how the designs came to be revised. The researcher wanted to determine if the revisions occurred because of questions, explanations, feedback, or a combination of these interactions between peers. The following sections detail the interest inventory, design brief curriculum, design challenge curriculum, and tutoring scripts that were developed and used to conduct the pilot study, and to collect data.

**Interest Inventory**

To conduct the study using case study methodology, the researcher needed to “get to know” the student participants through both casual conversations and through a more formal survey of student interests. The researcher investigated and selected an interest inventory developed by teacher educators to help teachers better understand their students’ motivation in science (Schmow & Schmidt, 2014). The researcher modified the inventory (Appendix E), as directed by the paper’s authors, who advised paring it down to approximately five to eight questions, selecting those questions most relevant to the population or domains of interest.

As shown in Appendix E, the modified inventory consisted of eight questions selected from two domains: school and career, and general interests. The inventory asks about a student’s favorite and least favorite school classes, future careers, and whether a student prefers working alone or in small groups. It also requests that a student provide a three-word self-description, indicate a subject he or she would like to learn more about, describe special interests or talents, and provide a description of a past accomplishment. The researcher read over the
participant responses to become acquainted with the students and better able to engage in casual conversation.

Design Brief Curriculum

In addition to the interest inventory, the researcher needed to develop a curriculum introducing design briefs, since the term *design brief* was likely to be a foreign concept to the participants. For the students to be successful at the task of writing their own design briefs, they needed, according to Butler and Cartier (2004), to have metacognitive knowledge of the task’s purpose, structure, and components. Using a “backward design” approach (Wiggins & McTighe, 1998), the researcher started designing the curriculum with the goal of imparting the purpose, structure, and components of a design brief. First, the words *design* and *brief* were defined and explored with example images. Then a design brief template, *My Design Brief*, was introduced. The template was developed by the researcher (Figure 4) based on Cross’s (2000) description of the design process (Cross, 2000, p. 29-31).

Finally, the components of the design brief template (goal, criteria, and constraints) were each defined and explored through a concrete design example with sketches. The researcher transformed the entire presentation into a five-minute video with music, narration, and animated graphics entitled *What is a Design Brief?* (Appendix F).
Figure 4. Design brief template for student participants, developed by the researcher from Cross’s (2000) description of the design process.

For the next segment of the design brief curriculum, the researcher developed a survey to assess formatively student understanding of a design brief’s purpose, structure, and components (Appendix G). Butler and Cartier (2004) described how a student’s metacognitive knowledge about tasks (task purpose, task structure, and task components) is essential for successful task interpretation and engagement. The survey was intended to be taken by the student participants immediately after watching the What is a Design Brief? video.


**Design Challenge Curriculum**

In addition to the interest inventory, design brief curriculum, and formative assessment, the researcher also needed to develop curricular materials to introduce the design challenge. The design challenge was based on the K-12 engineering fair project, *The Cat’s Meow: Designing an Enrichment Toy*, developed by the researcher for the non-profit educational organization, Science Buddies (www.sciencebuddies.org) in 2008:


The design challenge was chosen because animals and pets appeal to a wide variety of children and are motivating (Chen, Chou, Deng, & Chan, 2007). In addition, the researcher felt that this challenge would yield designs with great variability, as opposed to challenges in which students designed for the same user(s).

In the design challenge, students learn that all animals, including pets, need exercise to stay healthy, and the exercise that is best is the type that uses an animal’s natural skills and instincts (like climbing, swimming, hunting, pouncing, fetching, or digging). Exercise using natural skills and instincts conditions the animal’s brain, as well as its body. Animals kept in zoos have special difficulty staying healthy because they do not have to work for their food, guard their territory, or avoid predators. They can become bored or even depressed. Consequently, zookeepers try to design “enrichment” activities to stimulate the animals and make their lives richer, fuller, or more interesting. The goal of an enrichment toy is to provide a stimulating activity that exercises both the brain and body of an animal.

To introduce the idea of animal enrichment to the student participants, the researcher selected two videos, *Animal Enrichment* (produced by the Oregon Zoo), and *Tigers and Otters*
by Chelsea and Camille (produced by DragonFly TV and sponsored by the Best Buy Children’s Foundation and the National Science Foundation). In the video, Animal Enrichment, the Oregon Zoo introduces the concept of animal enrichment and shows workers making various toys, like a paper-mâché prey with hidden food inside:

- [http://www.youtube.com/watch?v=jVBkW-hEUAU](http://www.youtube.com/watch?v=jVBkW-hEUAU)

The researcher modified the video to make it more expeditious and age-appropriate, shortening it from eight minutes to approximately five minutes.

In the video, Tigers and Otters by Chelsea and Camille, a pair of adolescent girls go to a zoo, select two species of animals, and propose enrichment toys for the animals. After gaining approval from the zoo, they then make the toys and test them on the animals:

- [http://pbskids.org/dragonflytv/show/tigersandotters.html](http://pbskids.org/dragonflytv/show/tigersandotters.html)

The researcher did not modify this video and its entire length was approximately ten minutes.

Besides the two videos introducing animal enrichment, the researcher developed a written introduction to animal enrichment (with images), a step-by-step “how-to” guide to designing an animal enrichment toy, and an advance organizer to help get the students started (Appendix H). The material in Appendices E thorough H, as well as the two videos, comprised the surveys and curriculum required to conduct the study up to the point of the student’s initial design brief and solution sketch.

**Tutoring Scripts with Metacognitive Prompts**

The final materials required to conduct the study were the tutoring scripts with metacognitive prompts. The researcher designed two tutoring scripts (Appendix J). The first script was intended to be used by the tutor to question the tutee about his or her design and elicit
explanations. The second script was intended to be used by the tutee to ask for feedback from
the tutor. It included a question about what the tutor liked about the tutee’s design, and
requested advice for strengthening weak points.

The first script contained several “neutral” questions intended to help the tutee describe
his or her design and reflect upon how it worked. Examples of neutral questions were “How
does your design work?” and “Why do you think your design will make the animal playful?”

These neutral questions were followed by a single “positive” question: What do you think is the
best part of your design? The positive question was then followed by a single “negative”
question: What do you think is the weakest part of your design?

The second script, in which the tutee requested feedback from the other student,
contained only two questions with metacognitive prompts—one positive and one negative. The
second script was meant to elicit both positive (praise) and negative (constructive criticism)
feedback from the tutor to the tutee.

In summary, the materials in Appendices E thorough J, as well as the two videos,
comprised the surveys, curriculum, and tutoring scripts required to conduct the entire study,
including data collection. The researcher then attended to recruiting the participants and
sequencing the materials in a research protocol, as described below.

**Participant Recruitment**

To recruit the participants, the researcher verbally invited a student participating in a
STEM, after-school club as part of GEAR-UP, a United States Department of Education grant
program intended to increase enrollment and success in post-secondary education. The middle
school students in the GEAR-UP club were building, test-driving, and refining “green-power”
(electric) cars.

After delivering informed consent, the researcher gained the first student’s written agreement to participate, and her parent’s written consent as well. The researcher then asked the student if she had a seventh-grade friend with whom she would like to partner with in the study. The recruited student provided a name and the researcher then invited that student, who was not a member of the GEAR-UP club, and did not have a particularly strong interest in STEM. The second student and her parents also received informed consent, and provided written agreement to participate.

**Research Protocol**

According to Yin (2008), a research protocol is essential in multiple case study methodology to increase reliability. With a research protocol in place, one can use replication logic and consider multiple cases as multiple experiments.

With the surveys, research curriculum, videos, and tutoring scripts established, the researcher prepared the research protocol for use in data collection. A data collection timeline showing the sequence of research events was developed. As shown in the timeline of research events, Figure 5, the data collection session with the student participants lasted approximately two hours. There were two phases to the research protocol—phase one and phase two. In the first and longest phase (approximately 90 minutes), student participants were given the interest inventory, design brief curriculum, and formative assessment. They then watched the two short videos on animal enrichment, read the introduction to the design challenge, and were asked to select an animal. Student participants were then asked to design an enrichment toy for their chosen animal based on its natural skills and instincts. They were told they could use the internet
or books to determine what the animal ate, what its strongest senses were, and what its natural skills were if they did not know. They were asked to fill in the graphic organizer (Appendix H) as they determined their animal’s characteristics.

**Figure 5.** Timeline of research events in the data collection session.

Upon completion of the advance organizer, student participants were given the design brief template (Figure 4) and were asked to write a design brief for their animal enrichment toy (give their interpretation of the design goals, criteria, and constraints). They were then given a
blank piece of paper and pencils and asked to draw their enrichment toy (create a solution sketch based on their design brief). When each student participant was finished, the design briefs and solution sketches were collected and digitally scanned. At this point, phase one of the pilot study was completed and the students took a break for 30 minutes.

In the second phase of the data collection session, the design briefs and solution sketches were returned to each student. The students were told that they were going to interview each other about their designs, and that the interviews would be audio recorded. The audio recorder was turned on and each student took a turn delivering tutoring scripts containing metacognitive prompts (Appendix J) to the other student. Once the tutoring scripts were finished, the audio recorder was turned off and the students were asked to redesign both the design brief and the solution sketch on a new design brief template and a fresh sheet of paper. As soon as both students finished their redensigns, the design briefs and solution sketches were collected and digitally scanned. Students were thanked and given a token payment ($20) for their participation. The case study from the pilot study data collection session is reported below.

Findings from the Single Case Study, Task #1

Biographical Sketch

Ella and Jessie (pseudonyms) met by chance at the beginning of seventh grade when a teacher placed them together on a seating chart. They got along so well that the teacher decided to separate them because they were talking and laughing too much. The two girls soon began having lunch together every day.

Jessie was a year younger than many of her seventh grade classmates. Gifted artistically and highly verbal, the teachers reported that she talked faster than any student in the school and
was quite uninhibited in the classroom when she was comfortable, asking many questions, especially about Science. She participated in an afterschool “green power” program in which electric cars were being designed, built, and driven by the students. It was in this program that she learned how to create Solid Edge Computer-Aided Design (CAD) drawings.

Ella was direct and honest in her interactions with adults. With her peers she was playful, approachable, and friendly. Her strongest interests were English and animals (especially horses, which she rode every day). In addition, she loved science fiction shows, like *Doctor Who*, and reading Marvel comics. Both girls enjoyed playing *Minecraft*, a “sandbox” (no rules), construction video game.

**Ella’s Metacognitive Strategies**

Ella’s interest survey indicated that one thing she was proud of was riding a horse on a timed circuit course in under one minute. In addition, she said in casual conversation that she liked to ride horses nearly every day. Not surprisingly, when presented with the design challenge, she chose to design an enrichment toy for a horse.

She did not feel that she needed to do any research to fill out the advance organizer’s questions on eating habits, senses, and natural instincts. Instead she used her pre-existing knowledge and experience to describe the characteristics of a horse. She then began working on her *My Design Brief* template in which she wrote down her task interpretations for the design challenge, describing her design goals, criteria, and constraints.

In her *initial* design brief, Ella stated that her *goal* was to design a “horse toy/treat.” Her *criteria* or features were that the toy needed to have: (a) a “twine ball full of hay”; (b) a fishing pole type of device to hold up the hay; (c) an ability to attach the fishing pole device to the “horn
of the saddle so that the horse will run after” the ball of hay; (d) an ability to move the fishing pole device up and down; and (e) no interference with the rider’s ability to hold the reins and maneuver the horse. Her constraints were that: (a) the cost of the toy needed to be under $50 (for all parts, including the hay, twine, fishing pole device, and its attachment parts); and (b) that the toy needed to be able to fit on the “horn” (front part) of a rider’s saddle.

During the intervention, Ella participated fully and interacted well with Jessie, frequently laughing and bantering back and forth, but she was less verbal than Jessie—a quality reflected in the data analysis. The researcher felt that Jessie was perhaps the dominant participant in the pair because of her extremely rapid and prolific speech patterns. This may have impacted Ella’s metacognition and ability to reflect upon her design and revise it.

In her revised design brief, Ella did not change her goal or constraints. However, one criteria was changed to establish stability—a critical criteria. She wrote that she wanted hardware that would create a firm attachment of the fishing pole handle to the horn (front part) of the saddle, which would not interfere with the horse’s ability to run after the ball of hay. In addition, another criterion was clarified with details about a crank. She wrote that she wanted to be able to raise and lower the ball of hay with a crank on the fishing pole. Her initial and revised solution sketches are shown in Figure 6.
Jessie’s Metacognitive Strategies

Jessie chose to design an enrichment toy for a cat, her favorite household pet. As with Ella, she was so familiar with cats, she did not feel that she needed to do any research to fill out the advance organizer’s questions on a cat’s eating habits, senses, or natural instincts. Instead she used her pre-existing knowledge and experience to describe the characteristics of a cat. She then began working on her My Design Brief template in which she wrote down her task interpretations for the design challenge, describing her design goals, criteria, and constraints.

Jessie’s initial design brief stated that her goal was to design a “yarn box” (for a cat). Her criteria for the yarn box were: (a) that it have “a crank on the back of the box to reel the yarn back in”; (b) that it “have three legs to keep it from falling over”; and (c) that the yarn “be easy to pull out.” Her constraints for the yarn box were: (a) that the cost needed to be under $30 for all parts; and (b) that it be made out of plastic.

Jessie was very animated during the intervention, talking rapidly and evoking many images and similes. The researcher speculated that she was using existing mental models of
objects she was familiar with to simulate in her mind how the new toys would work.

In Jessie’s revised brief, she did not change her goal or constraints. However, one criteria was changed to improve stability—a critical criteria. The criteria that the yarn box “have three legs to keep it from falling over” became “have three legs to keep it from falling over as well as a platform.” [Italics added.] In addition to this change to an existing criteria, she added two new criteria, writing that she wanted to “be able to change the yarn” and “add toys to the end of the yarn to make it more fun.” Her initial and revised solution sketches are shown in Figure 7.

![Figure 7. Jessie’s initial (left) and revised (right) solution sketches.](image)

**Students’ Reponses to Metacognitive Prompts**

Audio recordings were made of the student participants’ interactions during the
intervention phase (gold box in Figure 5). In other words, the students were recorded when they were responding to the metacognitive prompts embedded in the tutoring scripts. The researcher transcribed the audio recordings into text. Sentence fragments were coded as either questions, explanations, or feedback.

Analysis of the audio recordings revealed that Jessie provided nearly twice as many explanations as Ella (40 as compared to 21) during the discussion of her design, as shown in Table 1 and Table 2. Jessie also provide more than twice as much feedback (17 fragments as compared to 8) when discussing Ella’s design than Ella did when discussing Jessie’s design. Some of Jessie’s feedback (on color) was also not adopted by Ella in the revised design.

Table 1

*Analysis of Ella's design from the audio recordings*

<table>
<thead>
<tr>
<th>Event</th>
<th>Number of Questions from Jessie</th>
<th>Number of Explanations from Ella</th>
<th>Quantity of Feedback from Jessie</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ella explains her design to Jessie</td>
<td>9</td>
<td>20</td>
<td>7</td>
</tr>
<tr>
<td>Ella requests feedback from Jessie</td>
<td>3</td>
<td>1</td>
<td>10</td>
</tr>
</tbody>
</table>

Ella’s Design

<table>
<thead>
<tr>
<th>Event</th>
<th>Number of Questions from Jessie and Ella</th>
<th>Number of Explanations from Ella</th>
<th>Quantity of Feedback from Jessie</th>
</tr>
</thead>
<tbody>
<tr>
<td>Totals</td>
<td>12</td>
<td>21</td>
<td>17</td>
</tr>
</tbody>
</table>
Table 2

**Analysis of Jessie’s design from the audio recordings**

<table>
<thead>
<tr>
<th>Event</th>
<th>Number of Questions from Ella</th>
<th>Number of Explanations from Jessie</th>
<th>Quantity of Feedback from Ella</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jessie explains her design to Ella</td>
<td>7</td>
<td>33</td>
<td>3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Event</th>
<th>Number of Questions from Jessie</th>
<th>Number of Explanations from Jessie</th>
<th>Quantity of Feedback from Ella</th>
</tr>
</thead>
<tbody>
<tr>
<td>Jessie requests feedback from Ella</td>
<td>5</td>
<td>7</td>
<td>5</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Jessie’s Design</th>
<th>Number of Questions from Ella and Jessie</th>
<th>Number of Explanations from Jessie</th>
<th>Quantity of Feedback from Ella</th>
</tr>
</thead>
<tbody>
<tr>
<td>Totals</td>
<td>12</td>
<td>40</td>
<td>8</td>
</tr>
</tbody>
</table>

Further detailed analysis of the explanations and feedback showed that for both girls’ design revisions came about through a combination of explanations (from the designer) and feedback (from the peer partner), as shown in Figures 8 and 9. In addition, it was the two negative metacognitive prompts (guided questions) that elicited revisions for both girls. For Jessie, the neutral metacognitive prompt (*How does your design work?*) also seemed to be effective.
Figure 8. How Ella’s design was revised. Note that Jessie’s feedback on color (dashed arrow) was not adopted by Ella.

Figure 9. How Jessie’s design was revised.
Imagery and Similes in the Single Case Study, Task #1

The researcher observed that Ella and Jessie evoked imagery and similes during their interaction: *like floss, like a floss box, like one of those beach balls, like a fishing reel*. The students seemed to be calling upon mental models of items they were familiar with to understand how their designs worked.

Lessons Learned from the Single Case Study, Task #1

1. The results of the pilot study strengthen theories suggesting that metacognition can be stimulated through explanations, questions, feedback, and prompts; all of which may induce peer tutoring pairs to reflect upon and re-organize their own knowledge, and repair mental models.

2. The imagery and similes observed during the peer interaction supports *constructivism*—students were developing their own understanding of the designs based on previous knowledge and experiences.

3. Design fixation was not observed with the intervention.

4. The guided questions elicited explanations and feedback that prompted students to change their design *criteria* in both design briefs and sketches, but *not* their *constraints*.

5. Post-intervention sketches had more design criteria, more detail, and more labels than those made before the intervention. However, constraints were not explicitly identified in any sketch.

Task #2: Assessment of protocol, data collection methods, and analysis techniques

1. The coding scheme in the original pilot study proposal was too fine-grained to be
meaningful. The original coding scheme broke down sentence fragments into questions, explanations, and feedback (assessment) about goals, criteria, and constraints for a total of nine different codes. In the pilot study, there was almost no discussion between the students about the goals or constraints, so the researcher collapsed the coding scheme down into three major categories: questions, explanations, and feedback. It is recommended that the reduced coding scheme be used as a starting point for the multiple case study research as well. The new coding scheme will provide more meaningful categorization of sentence fragments. It will also make findings easier to compare with theories suggesting that metacognition can be stimulated through structured prompts during peer tutoring, which may invoke explanations, questions, and/or feedback (King et al., 1998; Lin, 2001; Roscoe & Chi, 2007).

2. Student handwriting can be difficult to read, but modifying the protocol so that students read their design briefs into the audio recorder alleviates the problem of illegibility and avoids the need to type responses into a computer.

3. Students seemed to enjoy the design challenge and were well-engaged throughout the activity. The vocabulary level and instructions seemed age-appropriate based on the successful completion of the surveys, quality of the peer interactions, and the design challenge results.

4. The length of the entire exercise was approximately two hours broken up into two parts—phase one and phase two. Phase one was the longest (approximately 90 minutes) because it was the preparatory part of the exercise in which students completed interest surveys, watched videos on animal enrichment and design briefs, and were quizzed on their understanding of design briefs. The researcher recommends for the multicase study that
students complete the preparatory curriculum together as a class, and the initial design independently (but in class) over a two-day period. It is recommended that phase two (30-40 min) be completed on a third day with students working together in pairs. The researcher believes that extending the entire exercise to three days will reduce fatigue. In addition, reduced peer interaction during the initial design stage of phase one will make the designs more novel when shared with a peer partner, and may lead to more significant design changes during the revision stage of phase two.

5. Not surprisingly, guided questions (metacognitive prompts) that elicited the most reflection (and subsequent changes) were the negative ones. For example, “What do you think is the weakest part of your design?” elicited more reflection and changes than “What do you think is the best part of your design?” Likewise, “Is there any part of my design that you think could be improved? If so, how would you change it?” elicited more reflection and changes than “What do you like best about my design?” The “positive” questions, however, seem to enhance student rapport, so the researcher believes both should be kept.

6. The researcher recommends that one guided question be eliminated as it did not enhance the interaction: Was any part of the design assignment confusing or difficult for you? This question can be replaced with the metacognitive prompt: What senses does your animal use when it plays or hunts?

7. Students continued to interact informally after the peer tutoring session (the intervention) was over (and they worked on their design revisions). Therefore, the researcher recommends that digital audio recording continue throughout all of phase two, so that any salient interactions that take place during revisions can be captured.
Implications for the Comparative Case Study

The exploratory, single case pilot study suggested that guided peer interactions with metacognitive prompts can enhance adolescent engineering design in its earliest phases. Design revision is stimulated. Adolescent designers are encouraged to reflect upon their design when asked by a peer to explain how their design works and what they think are its strongest and weakest points. Reflection is also encouraged when an adolescent designer requests feedback from a peer, asking what he or she thinks are the design’s strongest and weakest points. Future research must be conducted to determine whether more diverse student pairs in a typical classroom setting respond similarly to peer-delivered metacognitive prompts during a design challenge activity.
CHAPTER IV
RESEARCH METHODOLOGY

Overview

The research examined how metacognitive prompts delivered in a peer tutoring environment affected the design briefs (task interpretations) and solution sketches of adolescents during a design activity. The goal was to gain insight into how responses to metacognitive prompts reorganized the co-evolving problem space and solution space through explanations, questions, feedback, or other means. Because it was unclear in advance how much or in what ways the intervention would affect the research outcome, the case study was exploratory (Baxter & Jack, 2008). The research was conducted using a qualitative methodology, specifically a comparative case study approach, as described below.

Case Study

Qualitative case study methodology provides the tools to study a bounded, social phenomenon in context through the collection and analysis of multiple sources of data (Baxter & Jack, 2008). Although case study is a versatile method, and used frequently throughout the social sciences, its design and implementation are contested among methodologists who come from different epistemological traditions (Yazan, 2015). Indeed, methodologists do not even have consensus on what constitutes a “case” (Levy, 2008; Yazan, 2015). Nonetheless, Yazan (2015) indicated that researchers may blend case study tools from different traditions to develop an approach that best addresses their research questions.

The two questions guiding the research asked “how-type” questions about the social
phenomenon of task interpretation and design in the context of a peer-tutoring environment:

1. How do metacognitive prompts delivered in a reciprocal and structured peer tutoring environment alter adolescent design briefs (the explicit task interpretation) of an engineering design problem?

2. How do metacognitive prompts delivered in a reciprocal and structured peer tutoring environment alter adolescent solution sketches (the design problem solution space) of an engineering design problem?

Yin (2008), who has positivist leanings, indicated that the case study method is appropriate when a study’s research questions ask how or why about a contemporary, social phenomenon, when the investigator has little control over the phenomenon, and when the boundaries of the phenomenon and its context are not clearly evident. Clearly, the research questions ask how, and the student responses to the metacognitive prompts are naturalistic, but the researcher was attempting to guide the phenomena of task interpretation and design through the prompts. In addition, the boundaries of both the phenomenon and its context were evident (a pair of students interacting, reflecting, and revising their own designs).

While the research did not fully meet all of Yin’s “appropriateness” criteria, which focus on the research process, it did meet the more general criteria put forth by constructivist methodologists, such as Merriam, who defined the case as the most important delimiting criteria in case study research. Merriam emphasized qualitative case study as a holistic analysis and description of a bounded system or phenomenon (Merriam, 2015; Yazan, 2015). Defining a case study in this way broadens its application beyond program evaluation (an application emphasized by Yin, 2008 and Creswell, 2014) to a much wider range of research cases, including programs, schools, people, and phenomena. The social phenomenon under study in the research was well-
bounded by time and activity, thereby meeting Merriam’s broader definition of a case study.

**Comparative Case Study**

Comparative case studies, sometimes called multicase (Merriam, 2015) or multiple-case studies (Yin, 2008), are a special form of case study in which comparisons are made within and across multiple, comparable, “information-rich” (Patton, 1990) cases to look for patterns (Levy, 2008; Wilson et al., 2014). Multiple case studies have the advantage of being more robust than single-case studies (Yin, 2008), and enhancing external validity (Merriam 2015). Their use is supported by educational and methodological scholars.

Butler (2002b, p. 62) suggested that in documenting interventions in qualitative studies involving self-regulated learning, one should describe what happens “across cases or events more comprehensively,” instead of focusing on a single case or using extreme cases. Documenting across multiple cases can provide a sense of what might be happening generally, as well as give a sense of the variability. The multiple, comparative case approach may appeal to those researchers looking for a comprehensive understanding of a phenomenon.

Yin (2008) also advised a multiple-case approach whenever sufficient resources are available, suggesting that multiple cases are more powerful analytically and follow the logic of replication design (i.e., “consider multiple cases as one would consider multiple experiments,” Yin, 2008, p. 53). Based on the literature of Butler (2002b) and Yin (2008), the research used a multiple, comparative case study design.

**Definition of a Case and the Unit of Analysis**

The definition of a case varies based on the epistemology of the methodologist (Yazan, 2015). For those with a constructivist worldview (e.g., Merriam, 2015; Miles, Huberman, &
Saldaña, 2014), it is often described as a bounded or “fenced-in” system or entity. Miles and Huberman (1994) depict a case as circle with a heart in the center where the circle represents the boundaries of the case and the heart is the case study’s focus, as shown in Figure 10, left.

A case within the research was defined as a pair of adolescent students from the same grade engaged in a reciprocal and structured peer tutoring session during a design challenge activity (Figure 10, right). The “heart” or focus was the students’ responses to metacognitive prompts within a peer tutoring session, and their subsequent design revisions.

Figure 10. Depiction of a case (left), adapted from Miles & Huberman (1994); and definition of a case for the comparative case study (right), adapted from Britannica Kids, by G. Mendel, 2018, Retrieved from https://kids.britannica.com/students/assembly/view/115026
The focus also highlights the units of analysis. Yin (2008) advocated defining the units of analysis in relation to a study’s research questions; that is, defining what is being analyzed. For the study, the units of analysis were: (a) the students’ conversational turns; (b) the design briefs; and (c) the solution sketches. The sampling strategies used to select the individual students as well, as the hypothesized outcomes of the research, are detailed in the following two sections.

**Sampling Strategies**

In their review of case study methodology, Baxter and Jack (2008) suggested that after defining the cases, an investigator should bind the cases to make the research more focused and manageable. Binding the cases is accomplished through the selection of sampling strategies, and through research propositions that predict the outcomes of the research.

In his seminal review, Patton (1990) described how sampling in qualitative methods should be purposeful. He detailed how it is essential to select cases that are “information-rich,” allowing good exploration of the research topic. He listed sixteen different purposeful sampling strategies which can be selected and used individually by a researcher, or mixed to meet multiple research needs.

For the research, a mixed, purposeful sampling strategy was used. Student participants were selected using both typical case sampling and criterion sampling strategies. Typical case sampling is used to illuminate normal or average cases; there is nothing exceptional or unusual about the cases. Because the researcher wanted the results of this study to inform middle school teaching practice, a typical career and technical education class, a required course for all seventh graders, was the site from which the student participants were selected. The criterion sampling
was proposed to be with respect to grade and peer relationship. All students selected to participate were in the seventh grade and were hoped to be self-partnered with a peer acquaintance or friend. Friendship was desirable between the student participants in each pair because friendship enhances dialogue between adolescents (Azmitia & Montgomery, 1993). However, the limitations of the research classroom did not make the latter criteria possible for all case pairs. All students in the research classroom participated in the study, but not all gave consent to participate and some were absent, so the researcher was forced to pair some students who were not friends, nor even acquaintances. Also, due to the age of the students and the partnering teacher’s recommendation, the student pairs were the same gender in all but two cases.

With respect to sample size, Patton (1990) and Yin (2008) suggested sufficient size to explore the research topic. Patton advised specifying a minimum sample size that the researcher believes will sufficiently cover the topic given a study’s objectives: Sample to the point that no new information is being gained to strengthen or weaken the research propositions in question. Yin (2008) stated that in multiple case studies, the logic of replication is used. The first sample—the first case—is considered to be an experiment. The samples or cases that follow are either literal replications of that first case (where experimental results are expected to be repeated), or theoretical replications (where experimental results may differ from that first case for anticipated reasons).

In reviewing the literature on children’s collaborative learning in engineering or other STEM disciplines, several relevant case studies emerged that guided sample size selection: (a) Chin (2016) used four pairs of children—two of whom were friends and two of whom were acquaintances—in a case study of collaboration on computers; (b) Disessa (2014) compared a
small (six student) and a medium (twelve student) classroom in a study on the construction of
normative scientific knowledge; (c) King & English (2016) used eight groups of three students
each to study the collaborative engineering design and construction of a scientific instrument; (d)
Wilson et al. (2014) compared the literary practices of two groups of high-school students
engaged in an authentic engineering design challenge; and (e) Parnafes (2007) used eight pairs of
high school students to investigate the development of conceptual understanding in physics,
specifically simple harmonic oscillations.

Accompanying the aforementioned literature was guidance from Miles, Huberman, and
Saldaña (2014) who indicated in their qualitative methods sourcebook that the selection of
sample size is dependent upon the richness of the cases. For example, sampling more than ten
intricate cases in a comparative case study can become unmanageable and overwhelming
analytically. They recommended having five cases as a minimum, but added the caveat that
having even fewer cases is acceptable as long as generalizability is not asserted.

Based on the literature on children’s collaborative learning in engineering and the
guidance from Miles, Huberman, and Saldaña (2014), the researcher selected a sample size of 10
pairs of adolescents. The researcher wanted 10 literal replications of the pilot study to
investigate whether the pilot study results were repeatable with more diverse pairs in a classroom
environment.

The selected research site was a western, public school of moderate poverty (60% of the
students, as determined by the number of children receiving free or reduced school lunch). The
school was chosen for its ease of access to the student participants, previous support with STEM
educational research, and the potential for variation in STEM exposure and socio-economic
status in the student population.
Thirty-two students from a required seventh grade course in career and technical education were invited to participate. Twenty-one of the 32 students gave parental and personal consent, yielding just over the desired ten pairs. However, due to student absences, three consented pairs were lost. The final number of complete cases for the study (consented students who completed the full curriculum) was seven. There were two “half-consented” pairs, and another fully-consented pair who only completed one design due to absences. The seven complete cases is similar to the sampling numbers used by authors of research in children’s collaboration in engineering (Chin, 2016; DiSessa, 2014; King & English, 2016; Parnafes, 2007; Wilson et al., 2014) and falls within the comparative case study guidelines of Miles, Huberman, and Saldaña (2014). All students at the research site received 10 dollars compensation for partial or complete participation.

In summary, the multiple case study employed a mixed, purposeful sampling strategy utilizing both typical sampling and criterion sampling by grade and course. (The additional, desired criteria of friendship or acquaintance was not universal among the case pairs due to the limitations of the classroom.) To further bind the cases and make the research more focused and manageable, research propositions were also defined.

**Research Propositions**

Research propositions in qualitative case studies are akin to hypotheses in quantitative methods (Baxter & Jack, 2008). The researcher predicts one or more outcomes in advance and then tests the propositions through the case studies.

The following research proposition was developed for the problem space (captured by student-generated design briefs) and the solution space (captured by student-drawn sketches):
1. The designs created after the intervention have a greater number of criteria, or more refined criteria, than those created before the intervention.

The following propositions were developed for the solution space (captured by student-drawn sketches):

2. The solution sketches made after the intervention are more detailed than those made before the intervention.

3. The solution sketches made after the intervention more explicitly identify the criteria than those made before the intervention.

The three research propositions along with the mixed, purposeful sampling strategies defined and bound the cases. How the researcher ensured research quality throughout the data collection and analysis process is now described.

**Ensuring Research Quality**

Just as the definitions of case and case study are contested among methodologists, so are the strategies recommended to ensure research quality. Again, epistemology drives the differences in methodologist’s recommendations; nonetheless, overlap and agreement in some of their strategies are observed.

Yin (2008), from a positivist tradition, advised a tightly controlled research design that is highly planned in advance (Yazan, 2015). He considered concepts of validity and reliability throughout the entire research process. His strategies for improving construct, internal, and external validity, as well as reliability, included using multiple data sources, chains of evidence, member checking, pattern matching, analytic generalization, protocols, and databases.

Walther, Sochacka, and Kellam (2013) also advised quality control throughout the entire
research process. They presented a framework for quality control taken from manufacturing (TQM or Total Quality Management). In Total Quality Management, the burden of quality control shifts from the end product to the process used to make the product. They broadly separated the research process into two sub-processes: Making the Data and Handling the Data. Their strategies for process validation and process reliability included purposeful sampling, negative case analysis, triangulation, constant comparative method, interpretive awareness, member checker, participant diversity, digital recordings, and standardized procedures. As constructivists, they contested the use of the word validity, arguing that it is inappropriate for interpretive research.

Other constructivists, such as Freeman, deMarrais, Preissle, Roulston, & St. Pierre (2007), also found the term validity problematic for interpretive work, and so moved toward a preferred term of trustworthiness: How do we know that the inferences drawn from the data are trustworthy? As with other constructivists like Walther et al. (2013), Freeman et al. were concerned that the data from participants is interpreted, both when it is made (as the participants interpret and respond to questions), and as it is handled (when the researcher interprets the participants’ responses). The data from participants passes through at least two human interpretations, so that real “truth” is unknowable. However, the inferences and claims made from the data can be made more trustworthy by standards of practices such as (a) thorough descriptions of processes, procedures, research interpretations, reasoning, and research limitations, and (b) making transparent the research links between inferences and the data using a theoretical framework for structure (generalizing to theory). Both sets of constructivists (Walther et al. and Freeman et al.) were adamant that their recommendations were not prescriptive, but instead were frameworks or starting points for quality control.
To integrate these multiple points of view, the researcher selected strategies that all the
aforementioned methodologists agreed enhance research quality (regardless of terminology), and
then added in select strategies that are particularly suited to the research. The researcher
considered quality control over the entire research process with the following strategies:

- **Purposeful sampling:** As described previously, the researcher employed a mixed,
purposeful sampling strategy utilizing both typical sampling and criterion
sampling (Patton, 1990).

- **Interpretive awareness** (Sandberg, 1997): The researcher maintained awareness
  of subjectivity during coding of transcripts, design briefs, and sketches, and used
cross-checking practices (described below) with another coder, remaining open to
alternative interpretations of the data sets.

- **Digital audio recording:** Student participants were digitally audio recorded
during phase two of the research timeline, the phase in which they were
paired.

- **Chain of evidence construction:** The researcher linked each student’s design
  changes to coded conversational turns between a pair, creating a chain of
evidence so that empirical data was linked to theory (Yin, 2008). The researcher
also endeavored to describe thoroughly the reasoning used to make inferences
from the data.

- **Research protocol detailing** (Yin, 2008): To enhance data reliability (reduce
  errors and biases in data collection when moving from case to case), the
researcher fully described all procedures, curricula, and surveys used to implement the study.

- **Limitations detailing**: The researcher described the study’s limitations and reach.

- **Cross-checking** (Creswell, 2014): Conversational turns between paired students required coding. The researcher and a second coder coded transcripts of conversational turns according to the coding algorithm of Hruschka, Schwartz, St. John, Picone-Decaro, Jenkins, & Carey (2004). First, the researcher and a colleague developed a codebook together and then independently coded a random sample from the transcript. An intercoder reliability statistic (Cohen’s kappa) was calculated. Because the kappa was less than or equal to 0.85 (Wilson et al.), the researcher and the second coder modified the codebook and repeated the coding of a random sample until the reliability statistic was greater than 0.85. Then each coder independently coded half of the data sets, and reliability statistics were again calculated. The codebook was further modified until the intercoder reliability statistic was greater than 0.85. Finally, the two coders each independently coded the full data set—all the transcripts of conversational turns. Significant discrepancies were discussed and final codebook modifications made as needed. Finally, the entire data set was coded using the final codebook. The reliability statistic (Cohen’s kappa) over the entire data set was 0.86.

- **Data Audits** (Guba and Lincoln, 1985): Once the final codebook was developed and the entire data set coded, a sample of the coded data was sent to an outside
auditor (a committee member, Dr. Amy Wilson-Lopez) to confirm that the codebook was sound and that the codes were being applied logically.

**Data Collection**

Collecting data from multiple sources increases construct validity, a measure of research quality (Baxter & Jack, 2008; Yin, 2008). For the research, there were seven sources of data to be collected for each case, as described below:

1. *A student interest survey.* The survey, shown in Appendix E and developed in the Pilot Study, Chapter 3, was intended to “get-to-know” the student participants and inform the analysis and reporting of each case study.

2. *A survey of student understanding of the purpose, structure, and components of a design brief.* The survey, shown in Appendix G and developed in the Pilot Study, Chapter 3, was intended to be used by the researcher as a formative assessment to evaluate a student’s metacognitive knowledge of design briefs before proceeding on to the design task.

3. *An initial design brief containing the design goal, criteria, and constraints* was the first design brief (first task interpretation) developed by a student before working with another student in a pair. It was the design brief that was developed before hearing the metacognitive prompts from the other student.

4. *An initial solution sketch* was the first sketch developed by a student from his or her initial design brief. The initial solution sketch was developed before working with another student as a pair, that is, it was developed before hearing the metacognitive prompts from the other student.
5. *An audio recording of the peer tutoring session* was made by the researcher as the student pair read and responded to the metacognitive prompts in the tutoring scripts. The audio recording captured student interactions, which included questions, explanations, feedback, and other phenomena. Audio recording was also used to capture any design-relevant, informal conversation after the peer tutoring session (during revision).

6. *A revised design brief containing the design goal, criteria, and constraints.* This was a design brief (second task interpretation) developed by each student after working with another student in a case study pair, and hearing and responding to the metacognitive prompts.

7. *A revised solution sketch.* This was a sketch developed by each student from his or her revised design brief. The revised solution sketch was developed after working with another student in a case study pair.

How each of these seven sources of data was collected within the research protocol is described below.

**Case Study Research Protocol**

A case study protocol is essential in multiple case study research (Yin, 2008). The logic of multiple cases studies is one of replication: Multiple cases are like multiple repeated experiments. A protocol enhances data *reliability* by ensuring faithful replication of data collection procedures from case to case, reducing errors and biases.

The protocol for the research was first introduced in narrative form in the pilot study, Chapter 3. It is presented again, this time in step-by-step form, and with slight modifications, as it was used in the multiple case study. A modified version of the graphical timeline of research
events, Figure 11, is included as well. Note the addition of the “social environment” to the timeline which describes how the students were working in each stage, e.g., independently, paired, etc.

As shown in Figure 11, there were two phases to the research conducted in a classroom environment over three days: Phase one, the longest phase (approximately 90 minutes), was conducted partly together as class and partly independently on day one and day two. Phase two, which was shorter (approximately 40 minutes), was conducted on day three, and included the intervention (metacognitive prompts delivered in a peer tutoring environment) followed by the redesign.

Conducting the research over three days was a change in the protocol from the pilot study in which students completed both phases in the same day. The researcher believed that conducting the research over three days in a classroom instead of one, lengthy session (outside of class) would reduce fatigue and offer a more realistic implementation for secondary teachers.

An additional change from the pilot study was that for the comparative case study, students created their initial design briefs and solution sketches independently (without being under their partner’s watch). The researcher believed that with an independent approach, slower students would not feel rushed to complete their designs if their partner finished first. In addition, the designs would be novel when students saw them for the first time during the intervention, and the novelty might invoke more conversational interchanges.
Figure 11. Modified timeline of research events and the co-evolving problem and solution space. Adapted from Maher, Poon, and Boulanger (1996), as cited in Dorst and Cross (2001).

The case study research protocol in step-by-step form is presented below as it was applied to the multiple, comparative case study. (For a narrative presentation of the protocol, as it was applied to the single-case, pilot study, and a discussion of how the data collection instruments were developed, see the pilot study, Chapter 3.)
Steps for the Comparative Case Study Research Protocol, Phase One

1. Each student picked out an animal-themed folder containing a packet of instructional materials: An interest survey (Appendix E), a hard copy of images from a PowerPoint presentation called *What is a Design Brief?* (Appendix F), a formative assessment (Appendix G), an advanced organizer (Appendix H), and a *My Design Brief* template (Appendix I).

2. Students were introduced to the “invisible career” of engineering through a group discussion of some of the engineering products and systems that they used to get ready for school in the morning. As a class, they then watched the video, *What is Engineering?* (University of Newcastle et al., 2013).

3. As a class, students watched the video, *What is a Design Brief?* (Appendix F).

4. Students completed a survey (Appendix G) regarding their understanding of the purpose, structure, and components of a design brief. The researcher read over the student responses to ensure that students understood how to write a design brief as well as its purpose.

5. Students took an interest survey, Appendix E, to help the researcher “get-to-know” the participants.

6. Students selected an animal, either a pet or in zoo, and then filled out the advanced organizer (doing online research, if necessary) to document their animal’s senses, food preferences, and hunting or play habits.

7. Students were introduced to the design challenge and given an advance organizer (Appendix H) with the following prompts to help them get started:
• What does my animal like to eat?
• What are my animal’s strongest senses (vision, hearing, smell, touch, etc.)?
• What are my animal’s natural skills (running, digging, jumping, swimming, hunting, making noises, climbing, etc.)?

Students filled in the advance organizer by doing research from the internet, or by using their pre-existing knowledge.

8. Together, as a class, students watched a five-minute introductory video on animal enrichment developed by the Oregon Zoo and modified (shortened) by the researcher:
   ▪ http://www.youtube.com/watch?v=jVBkW-hEUAU

9. Together, as a class, students watched a ten-minute introductory video on animal enrichment in which a pair of students develops enrichment toys for two types of animals at a zoo. (The video was developed by PBSKids Go, shown on Dragonfly TV, and sponsored by the Best Buy Children’s Foundation and the National Science Foundation.)
   ▪ http://pbskids.org/dragonflytv/show/tigersandotters.html

10. Students were asked to create their first design brief using a “My Design Brief” template developed by the researcher and presented in Appendix I. The template has students provide three types of information:
    • Goal (what you are planning to make)
    • Criteria (special features or characteristics that you want in your design)
    • Constraints (limitations, things that hold you back from making anything you want)
11. Students were asked to draw their first solution sketch (design) on a blank piece of paper using their initial design brief as a guide.

12. At the end of the class period, students gave their first design briefs and solution sketches to the researcher. Both the design briefs and solution sketches were digitally photographed.

13. In preparation for the next day, the researcher examined the initial design briefs and sketches, and randomly paired the majority of students based on their gender and whether they were consented or not. The researcher attempted to make pairs the same gender as well and the same level of consent. Only one male pair was deliberately placed together based upon their observed friendship during the initial design phase.

**Steps for the Comparative Case Study Research Protocol, Phase Two:**

14. On Day 3, the students were given back their initial design briefs and sketches and told that they were going to present their designs to a partner. They were placed in pairs at a station and given sets of questions (tutoring scripts, Appendix J) with metacognitive prompts to ask the other. The conversations between the students during the paired interactions was digitally audio recorded.

15. Students were asked to redesign their design briefs and solutions sketches using a new design brief template and blank sheet of paper. The audio recordings continued to record during the revisions to capture any informal interactions that lead to revision.

16. The student participants were asked to read their design briefs into a digital audio recorder (to help the researcher decode any illegible handwriting).

17. Students were thanked and minimally compensated for their time and efforts ($10 each).
18. The revised briefs and sketches for each student were collected and digitally photographed.

With the case protocol complete, the researcher analyzed the surveys, design briefs, solution sketches, and audio recordings to evaluate whether student participants revised their design briefs and solution sketches, and if so, how they came to be revised through the peer responses to metacognitive prompts. In the next sections, the researcher details (a) how each source of data (surveys, briefs, sketches, and audio recordings) was analyzed, and (b) how each student’s design changes were linked to the paired verbal interactions.

**Analysis of Surveys**

Data from two surveys was collected during each case study: a student interest survey and a formative survey regarding student understanding (metacognitive knowledge) of design briefs. The student interest survey was used to gather background information on the participants to inform the analysis of their conversations, design briefs, and sketches, and aid in reporting the case study. The student understanding of design briefs—a formative survey—was conducted to ensure that student participants have a solid understanding of the purpose, structure, and components of a design brief before embarking on the design challenge (Butler, 2004).

The formative survey of students’ metacognitive knowledge of design briefs will also support future exploratory research. Potential research questions include: How does metacognitive knowledge of design brief purpose, structure, and components affect the quality of the design brief (and resulting solution sketches)? Are design briefs effective advance organizers for explicit task interpretation in engineering design? As adolescents, do males or females demonstrate more metacognitive knowledge of design briefs?
Analysis of Design Briefs

The differences between the revised and initial design briefs were analyzed both quantitatively and qualitatively. Quantitatively, the researcher determined the difference in the number of criteria and constraints between the revised and initial design briefs. Although quantitative data was collected from the artifacts, the quantitative data was not analyzed by statistical methods, but was used to test the first research proposition: *The design briefs written after the intervention have a greater number of criteria, or more refined criteria, than those written before the intervention.*

Qualitatively, the researcher looked at how the criteria and constraints changed between the design briefs. For example, was a new criterion simply altered from the original one, making it more refined? Was a new criterion a completely new, enhanced feature in the design? Was a new or altered criterion defined by the students as “critical,” that is, not just “nice to have,” but *essential* to its function? These qualitative characteristics were coded according to Table 3.

Table 3

*Coding of design brief changes*

<table>
<thead>
<tr>
<th>Revised design brief contains a:</th>
<th>Code</th>
</tr>
</thead>
<tbody>
<tr>
<td>Criterion that is altered from the initial brief.</td>
<td>AE</td>
</tr>
<tr>
<td>Criterion that is altered from the initial brief and a critical change.</td>
<td>AC</td>
</tr>
<tr>
<td>Completely new criterion for the design.</td>
<td>NE</td>
</tr>
<tr>
<td>Completely new criterion for the design and a critical change.</td>
<td>NC</td>
</tr>
</tbody>
</table>

To ensure research quality, a second coder independently analyzed the design briefs both
quantitatively and qualitatively, as described in the algorithm (Hruschka et al., 2014) of the section, *Ensuring Research Quality*, under cross-checking. The researcher and second coder engaged in rounds of coding and codebook modifications until an intercoder reliability statistic (Cohen’s kappa) greater than 0.85 was achieved (Wilson et al., 2014). Analysis of the solution sketches (corresponding to the design briefs) was conducted in a similar manner, as described below.

**Analysis of Solution Sketches**

The differences between the revised and initial solution sketches were analyzed both quantitatively and qualitatively. Quantitatively, the researcher determined the difference in the number of criteria and constraints between the revised and initial solution sketches. Qualitatively, the researcher looked at how the criteria and constraints changed between the two sketches. For example: How did labeling change? In addition, the level of relative detail in each solution sketch was coded (1, 2, or 3) according to the coding scheme of Yang and Cham (2007), as shown in Figure 12. The coders then determined if the revised sketch showed an increase in labeling or an increase in the level of sketch detail over the initial sketch.

![Figure 12. Sketch detail coding scheme (Yang & Cham, 2007).](image)
The qualitative characteristics of labeling and detail were coded according to the “yes and no” questions asked in Table 4.

Table 4

<table>
<thead>
<tr>
<th>Coding of solution sketch changes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Revised sketch contains an:</td>
</tr>
<tr>
<td>Increase in the level of sketch detail from initial sketch (Yes/No)</td>
</tr>
<tr>
<td>Increase in labeling from initial sketch (Yes/No)</td>
</tr>
</tbody>
</table>

The quantitative and qualitative analyses were used to test the second and third research propositions: The solution sketches made after the intervention are more detailed than those made before the intervention. The solution sketches made after the intervention more explicitly identify the criteria than those made before the intervention.

To ensure research quality, a second coder independently analyzed the solution sketches both quantitatively and qualitatively, as described in the algorithm (Hruschka et al., 2014) of the section, Ensuring Research Quality, under cross-checking. The researcher and a second coder engaged in rounds of coding until an intercoder reliability statistic (Cohen’s kappa) greater than 0.85 was achieved (Wilson et al., 2014).

Analysis of Audio Recordings

The researcher anticipated that the audio recordings of the peer tutoring session would contain clues as to how and why students made changes to their designs. The audio recordings were analyzed according to the following procedure:

1. The audio recordings were transcribed from sound information into text.
2. The text were segmented into sentence fragments that could be coded.

3. The researcher and a second coder coded the sentence fragments according to the algorithm of Hruschka et al. (2014), as described in the section, *Ensuring Research Quality*, under cross-checking. The text fragments were coded as to whether they were prompts, simple explanations, user-centered explanations, questions, feedback, simple affirmations, or irrelevant, as detailed in the codebook of Table 5.

4. Once a final, coded data set was developed, the frequency counts of each type of code (e.g., questions, simple explanations, user-centered explanations, feedback, etc.) were calculated for each participant and tabulated. Once the text fragments were *categorized* as questions, simple explanations, user-centered explanations, feedback, etc., they were then *linked to changes* in the design briefs and solution sketches, as described in the next section.
<table>
<thead>
<tr>
<th>Type of text fragment</th>
<th>Description</th>
<th>Examples</th>
<th>Code</th>
</tr>
</thead>
</table>
| Prompt                | Teacher-generated question that one student reads to another from a script. | How does your design work?  
What do you think is the weakest part of your design?  
What do you like best about my design?                                                                                                          | P    |
| Explanation           | Student’s simple description of his or her own design or chosen animal (without any user-centered perspective). | “...he plays by climbing trees and eating berries.”  
“I turned the art gallery into a viewing room.”  
“They’re probably one of the smartest dogs in the world. Like they use them in the military to jump out of airplanes.” | E    |
| Explanation with a user-centered perspective | Student’s more elaborate description of his or her own design or chosen animal with a user-centered perspective in which it is clear that the student is visualizing or simulating the user playing with the toy (or imagining a zoo patron watching a user play with the toy). Or, a student’s description of what he or she imagines that an animal is experiencing, thinking, or feeling. | “I haven’t finished, but the cat would go up some stairs into the toy room. If they don’t want to, they’ll go across a rope bridge that’s sealed off and netted. And they’ll go into the nap room. If they don’t want a nap, they’ll go up to an art gallery. I don’t know why I put that there, but I needed something. And then, they can go own a slide when they’re done.”  
“...so it’s an underwater toy...it’s filled with these little beads. And it has like cool colors on the outside...when the tides move, the water moves, and it makes them move...and so the hippos will...hear it and be like, ‘Wait, what is that?’”  
“...it will help them because they can...have not just each other to play with but something other than each other.” | EU   |
| Question              | Any student-generated query that is not obviously feedback.                  | “So, they are good at smelling, and [have] a good brain?”  
“Like one of those tennis things that shoots tennis balls?”  
“Hmmm, where should I store the LIPO battery?”  
“And how wide should it be?”                                                                                                                          | Q    |
| Feedback              | Suggestion, critique, or compliment about partner’s design or partner’s chosen animal. | “You should have a feeding room.”  
“Oh that’s nice!”  
“Maybe you could have like multiple animals?”                                                                                                       | F    |
| Affirmation           | Simple positive response to a partner that shows agreement with what the partner has just said. | “Yeah.”  
“Okay.”                                                                                                                                                    | A    |
| Irrelevant            | Irrelevant or off-topic comments.                                           | “Jason, stop hitting me.”  
“...I have a test next hour...”                                                                                                                               | I    |
Linking the Design Changes to Coded Peer Verbal Interactions

The final step in the data analysis was to link the design changes (analyzed design briefs and solution sketches) to the analyzed audio recordings (questions, simple explanations, user-centered explanations, feedback, etc.) to determine how the design changes arose. Linking the design changes to the code categories helped to answer the research questions regarding how metacognitive prompts delivered in a peer tutoring environment alter adolescent design briefs and solution sketches.

To create a visual map of the links, the researcher selected a student participant and identified one of his or her design changes. Then the researcher identified any verbal peer interactions related to that design change and which code categories corresponded to the interactions. A map showing the links between the code categories and the design change was then assembled, as shown in Figure 13, creating a chain of evidence.

![Figure 13. Process for mapping links between a student’s design change and relevant questions, explanations, feedback, or other phenomena during the peer interaction.](image)
The mapping process was repeated for each one of the student’s design changes, and for each student participant. It should be noted that if there was feedback from a peer that a student ignored in his or her revised design, that feedback was also mapped. Dashed, red arrows were used to indicate that the feedback was ignored, while solid arrows indicated that feedback was accepted and implemented.

Comparing Within and Across Cases

In comparative case studies, comparisons are made within and across multiple cases. The researcher analyzes each case individually, and then analyzes the entire set of cases, looking for patterns of similarities and differences in the phenomenon under study (Goodrick, 2014; Wilson et al., 2014). Results from comparative case studies are considered to be more robust and compelling than single case studies (Yin, 2008), enhancing transferability (Polit & Beck, 2010).

The researcher first analyze coded data maps for each pair of students, looking for patterns of interactions (e.g., questions, explanations, feedback, etc.) that drove design revisions. The researcher then synthesized patterns across all the pair cases and observed distinct interaction styles, which heavily influenced how the designs came to be modified.

Limitations of the Study

The study’s characteristics—its methodology, population, location, and curriculum—imposed limitations. As a qualitative, comparative case study, the findings may be interpreted differently by different readers. Although a “typical” seventh-grade, career and technical education classroom was studied, the student participants attended a public middle school of moderate poverty in Utah, USA. Seven pairs (four male, three female) who completed the entire curriculum were fully studied and three additional pairs (two female and one mixed gender) were partially studied. In
addition, the time each participant engaged with the research curriculum, surveys, and design activity was limited to approximately two hours total. The researcher has attempted to provide a “thick description” of the findings, so that readers may determine for themselves the transferability of the findings to adolescent populations of their interest (Polit & Beck, 2010). The researcher has also endeavored to report findings with sufficient richness and depth from multiple cases (analogous to replicated experiments [Yin, 2008]) so that analytic generalization may occur (Polit & Beck, 2010); that is, metacognitive learning theories may be strengthened or weakened.
CHAPTER V
FINDINGS and DISCUSSIONS

Overview

In January, 2018, the researcher conducted a comparative case study in a public middle school as part of an instructional unit on engineering careers. The study took place in a career and technical education classroom with 32 seventh grade students. Because career and technical education is a required course for all seventh graders, the demographics of the classroom likely reflected those of the school (approximately 61.1% Caucasian, 29.3% Hispanic, 3.8% Asian, 1.7% African American, 1.9% Native American, 0.7% Pacific Islander, 1.5% two ethnicities; and 23% English language learners, National Center for Education Statistics Common Core of Data, 2016-2017 school year).

Over the course of three days (Figure 11), the researcher introduced students to the engineering profession, as well as the concepts of design, design briefs and sketches, and animal enrichment. As part of the curriculum, all 32 students engaged in a design challenge activity during which time data was collected from 21 consented students. Consent was limited partly because of one student’s protest that she “did not want to be recorded.” This statement influenced several of her peers.

On Day Two, the first day of the design challenge activity, students worked independently and developed an initial design brief and sketch. On Day Three, each student was paired with another. Using tutoring scripts with metacognitive prompts, each student presented his or her initial design brief and sketch to a partner. The tutoring scripts guided students to ask each other about how their designs worked and inquired about their designs’ strengths and
weaknesses. One script (containing seven questions) was read by a presenting student’s partner. It prompted the presenting student to explain his or her design. The other script (containing two questions) had the presenting student ask his or her partner for feedback. Students then redesigned their own designs while sitting together as a pair. The conversations between the pairs were audio-recorded during all of Day Three, the second day of design, so that in many cases, conversational turns were captured both with and without script guidance during the redesign phase.

At the end of the unit, the researcher had collected data on seven pairs—four male pairs and three female pairs. Additional data was collected from a girl who was paired with an unconsented boy, and a girl who was paired with an unconsented girl. The latter case is presented in part, as the pair had an unusual metacognitive strength. Finally, data was collected from a pair of girls, who were absent on the initial design day, but who worked together dynamically to create single designs for the same user on Day Three. This case is also presented (at the end of the Findings) to show that questions, explanations, and feedback between a strong, interactive pair can lead to revision even in a first design without a script for guidance.

Upon reviewing the cases, the researcher noted four distinct patterns of interaction between the pairs. The patterns of interaction are now described and named, and the cases illustrating the patterns are presented along with each participant’s metacognitive strategies.

**Interaction Pattern One: The Guide and the Aspirant**

One pair of boys and one pair of girls were exceptionally strong at eliciting design changes in both partners. In each case, the pair had a student who was a “guide”—a self-regulated learner who used metacognitive strategies to guide not only his or her own redesign,
but also the redesign of the partner’s. Both participants, then, followed the same design path, as depicted in Figure 14. The challenge to climb the mountain represents the design (and redesign) task, while the climbers are the pair of the students.

Figure 14. Illustration of the “Guide and Aspirant” interaction pattern, courtesy of L. Strong.

Also in both cases, the partner to the Guide was a student who was an “Aspirant”—an unsure student, but one who was very motivated to improve. The motivation came from observing the Guide’s design and redesign. Note that in Figure 14 the climbers are linked together with the student in front acting as “the guide” and the student following acting as “the aspirant.” The combination of a Guide with an Aspirant was an effective and dynamic
combination, yielding the most design changes per pair.

The metacognitive strategies used by the guide partner included vocalized “private speech” (as described in the next section), questioning (e.g., “What would make this better?”), checking and verbalizing the task instructions, and explanations that contained simulations of how the user would interact with the design, or what the user was thinking or feeling. The metacognitive strategies used by the aspiring partner included explanations (with and without simulations) and requests for feedback. After redesigning, the aspirant’s design became much more like the guide’s with similar design features. In the next section, the two cases with a guide and an aspirant are described.

**Leo and Javier: Guide and Aspirant**

Leo and Javier (pseudonyms) were paired together by chance, and ended up being one of the most effective and dynamic pairs. Despite their lack of close friendship and Leo’s stated preference for working alone, the quality and quantity of the conversations and subsequent design changes were among the highest of all the pairs.

Leo reported that he had won a “Hope of America” award, which honors students who not only perform well academically, but who also show leadership skills and ethical character. He stated that he could see himself in a career as an electrical engineer or video game designer, and wished that he knew more about math.

Javier was proud of a district-wide award he had received for drawing. He had an interest in cars and stated that he could see himself in a career as a mechanic. He wished that he knew more about science.

As the boys worked together, the researcher noted Leo’s proliferation of vocalized
“private speech” (Alderson-Day & Fernyhough, 2015). Vocalized private speech is often seen in young children between ages three and eight. In the youngest children, vocalized private speech is a running commentary on some activity. In older children, it becomes self-regulatory, according to Vygotsky (1934/1987), helping children regulate cognition or behavior on a cognitive task. Private speech gradually transforms into an “inner speech” (internal language which is not audible). However, private speech also continues into adulthood even after inner speech develops. These forms of speech are thought to be important in metacognitive skills and creativity (Alderson-Day & Fernyhough, 2015).

By the seventh grade, many children no longer vocalize their private speech in a formal classroom setting, presumably because it is not culturally acceptable. However, in the more informal, paired setting, Leo’s private speech emerged. He talked about what he was doing at the moment and why. He talked about what he was planning to do. He even evaluated and questioned himself out loud, e.g., “I don’t know why I did that, but I needed something….,” and “What am I saying? That’s not big!” In addition, he easily simulated verbally how the user would interact with his design. Leo’s metacognitive skills were strong and apparent.

Javier was quieter than Leo and, like the majority of the other participants, did not display any vocalized private speech. Although he had a solid initial design, he seemed more hesitant and unsure of the design task. Upon seeing Leo’s more elaborate design during the reading of the scripted prompts, Javier sounded dissatisfied and negative about his own. At one point, as Leo’s redesign grew increasingly elaborate and Leo was showing off his enhancements (e.g., “Look at the improved slide. It’s all tunnel and then at the end it opens up for the cats to get up.”), Javier verbalized his frustration to Leo, “I don’t even know what to put in mine.” Javier ended up completely abandoning his initial design, even though it was solid, and making
one more like Leo’s.

**Leo’s Metacognitive Strategies**

Leo chose to design a “climbing enrichment toy for cats” that would use their natural skills of “running, jumping, and climbing,” and their strongest sense of smell. He initially wanted his design to be “large, interactive, and challenging.” Upon revision (Figure 15), he kept his initial version, but added refinements to the features (e.g., leather upholstery was added to the nap room, and the slide was “tubed” for safety). He then added new features which would bring “food and fun” to the mix.

Leo made seven explicit design changes. An eighth design change (a bathroom, which he talked about adding during the interaction) was never explicitly added to the revised design. As shown in Figures 16-17, three of the design changes came about directly through the prompts. The prompt in which Javier asked Leo how his design worked led to the rope bridge being netted for safety and the slide being enclosed in a tube for safety. The same prompt along with another in which Leo asked Javier for feedback on improving his own design led Leo to change the art gallery to a viewing room. The remaining design changes arose from unscripted interactions, or from Leo’s vocalized private speech during the redesign phase.
Figure 15. Leo’s initial (top) and revised (bottom) sketches.
JAVIER: How does your design work?
LEO: I haven’t finished, but the cat would go up some stairs into the toy room. If they don’t want to, they’ll go across a rope bridge that’s sealed off and netted. And they’ll go into the nap room. If they don’t want a nap, they’ll go up to an art gallery. I don’t know why I put that there, but I needed something. And then, they can go own a slide when they’re done.
JAVIER: I don’t think cats like slides.
LEO: This one will. It will be a fun slide. It will be a long drop and then a strong turn. Another long drop. Another strong turn. And then...
JAVIER: What is this...? Did you say sharp turn?
LEO: No, a strong turn. So, it’s just gonna go WHOOP.
JAVIER: Oh yeah, but if it’s a sharp turn, I mean, it’s got speed already... it’s...
LEO: Whoop. No, that’s why. Because around the corners, I’m gonna tube it. I’ll get a tube, yeah.

JAVIER: What do you think is the weakest part of your design?
LEO: The rope bridge... just a minute. I gotta put in the stairs.

LEO: Is there any part of my design that you think could be improved?
JAVIER: Probably the art gallery.
LEO: [Laughs.] But it’s not going to be just art, it’s going to be the cats’ art.

LEO: Look at the improved slide. It’s all tunnel and then at the end it opens up for the cats to get up.

**LEO “Guide”**

**Explanation** on bridge
nap room, & art gallery

**Explanation** on tube slide for safety

**Feedback** on slide

**Feedback** on art gallery

**Explanation** on bridge

7 DESIGN REVISIONS
1. Art gallery changed to a “viewing room.”
2. “Slippery slide” changed to a “tube slide.”
3. Nap room upgraded with leather upholstery.
4. Rope bridge netted for safety.
5. Rope bridge defined by size (unknown impetus).
6. Room with hanging cat toys more defined by size (unknown impetus).
7. New food room added.

*Figure 16.* How Leo’s design was revised.
Figure 17. How Leo’s design was revised (continued).
Javier’s Metacognitive Strategies

Javier chose to design a “dog enrichment toy” that was “bite-resistant, squeaky, and non-tippable.” He also emphasized that all materials in the design had to be safe. His initial design showed a squeaky ball hanging from a lever arm that was heavily weighted at the base to prevent tipping. For his redesign, though, Javier completely abandoned his initial design and decided to make “a play area” for dogs, like his partner, Leo, had done for cats.

To the researcher it seemed that the social and emotional aspects of the boys’ interactions drove and motivated Javier to make changes. Leo did a lot of unsolicited sharing of his design with Javier. Leo even directed Javier to look at (and admire) his design (e.g., “Look at the improved slide.” “See the stairs going up.” “This is a pretty great room…it’s got leather seating… I mean, look at this room, Bro.”) Leo was clearly proud of his design and showing it off, which led Javier to voice dissatisfaction and frustration with his own, and seemed to motivate him to improve.

Javier made seven design changes. All changes arose during the unscripted redesign phase through a combination of Javier’s own explanations in which he simulated how the user would interact with the design, and through direct feedback from Leo, as shown in Figures 19-20.
Figure 18. Javier’s initial (top) and revised (bottom) sketches.
Figure 19. How Javier’s design was revised.
Figure 20. How Javier’s design was revised (continued).
Jade and Luisa: Guide and Aspirant

Jade and Luisa (pseudonyms) were an extremely dynamic pair whose interactions resulted in many design changes for both students. Although not friends, there were some similarities between the two girls. In the student interest survey, both expressed a preference for working in small groups over working alone or in large groups. In addition, neither girl stated any interest in STEM subjects with Jade saying she could see herself working as a cosmetologist or teacher, and Luisa showing a strong interest in music.

Like the “guide,” Leo, in the previous case, Jade, displayed excellent metacognitive skills. While one of Leo’s metacognitive strategies was to utilize vocalized private speech, Jade’s strategies relied on questioning (e.g., “What would make it better?”) and checking and verbalizing task instructions. Like Leo, she also displayed a strong ability to verbally simulate how the user would interact with the design. She also well imagined what the user would think or feel while using the design (e.g., “I think it will help them because they can…have not just each other to play with, but something other than each other.” “I think the best part is that it triggers that….thing in your brain where it’s like: What is that? ….should I be scared of it? Should I like it? Or what?” “When they squeak it, it…opens up and…drops the treats out and they’re like, ‘Oh my gosh, what was that?’” “…when the tides move, the water moves, and it makes [the beads] move…the hippos will…hear it and be like, ‘Wait, what is that?’”)

The “aspirant,” Luisa, like Javier in the previous case, was more hesitant and unsure of the design task. While she was never verbally frustrated or negative about her initial design, in the way that Javier was, her initial design was tentative—a small ball—far in the upper corner of the page with no detail or labeling. Upon interacting with Jade, though, who was positive and offered ample constructive feedback, Luisa’s redesign became expansive and sure, filling the
Jade’s Metacognitive Strategies

Jade chose to design a toy for hippos. Through research she learned that hippos live near water and have a keen sense of hearing. Using both of these facts, she came up with an idea to design an underwater rattle that would make noise when powered by the movement of water.

Her initial rattle shape was a brown and green cylinder filled with beads (Figure 21, top). During revision, the cylinder shape changed to a sphere, and she added more noises by mixing pebbles with the beads (Figure 21, bottom). In addition, the outside design of the toy became “more natural” and “like a rock.” She also placed greater emphasis on safety in her redesign, which made her raise the price of the toy.

In total, Jade made six design changes, all of which arose during the redesign phase after the readings of the scripted prompts. She used a lot of broad questioning (e.g., “What would make it better?”) to open up the discussion and incite design changes. Along with her open-ended questions, her changes arose through both her own explanations, and feedback from her partner, Luisa, as presented in Figures 22-23.
Figure 21. Jade’s initial (top) and revised (bottom) sketches.
Figure 22. How Jade’s design was revised.
Unprompted questions and interactions during the redesign phase:

JADE: Okay, so it would be filled with little beads. And maybe with some like bigger things like to make even more noise?
LUISA: Yeah, that’d be cool.
JADE: Maybe like little rocks or something.
LUISA: Yeah, that’d be cool.
JADE: Okay, what else would make it better?
LUISA: I’m thinking maybe like a few treats on the outside. But...I’m thinking about how the water would affect it....I’m not sure anyone would see the design from the outside.
JADE: Yeah. For me the biggest thing is I don’t want it to like decompose underwater.
LUISA: Yeah.
JADE: Like plastic, I don’t want it to get into the hippo’s digestive system. And like I don’t want them to eat it. But wood...softens underwater...so it could...break under water....
LUISA [uses the word design to mean decoration]: Hmmm. Um, I’m probably thinking that maybe like a little design here and there, so that they feel at home and it’s....
JADE: Like maybe it’s like the color of the rock or something....
LUISA: Yeah. They’re like, "Okay, that’s one that I know...."
JADE: This is looking like earth.
LUISA: Looks good.

JADE: Um, yeah, so this would be...like 3 feet-ish...no, that’s huge...Three feet is huge.
LUISA: Yeah. Maybe like 2 and a half or something.
JADE: Yeah, like how tall it is.
LUISA: Yeah.
JADE: Like a foot tall.
LUISA: Yeah, that’d be good.
JADE: And how wide should it be? I think it’s a foot tall and this wide.
JADE: So maybe like half a foot wide.
LUISA: Yeah.
JADE: What else?....
JADE: I think this is good.
JADE: I’ll add a few more beads. OK, I think that’s good.

Feedback on decoration
Explanation & affirmation on color
Question, explanation, & affirmation on size
Explanation & affirmation on noise

6 DESIGN REVISIONS
1. Changed filling from just little beads to little beads mixed with bigger objects like pebbles to make more noise.
2. Changed shape from a cylinder to a sphere.
3. Decorate outside and change color from brown and green so that it looks more natural, “like home,” “like a rock”
4. Changed size (from 4 ft x 2 ft to 1 foot by ½ foot).
5. Modified materials to ensure safety over the entire toy, not just the beads.
6. Changed the cost of the toy from $40 to $50.

Figure 23. How Jade’s design was revised (continued).
**Luisa’s Metacognitive Strategies**

Luisa chose to design a ball toy for a dog. Her first design brief and sketch were tentative and simple—a small, squeaky ball (Figure 24, top). Her initial brief listed *no* design criteria or constraints. Upon ample encouragement and suggestions from her partner, though, Luisa became confident, fleshing out her design brief with multiple design criteria and constraints, which she detailed in the upper left-hand corner of her sketch as well (Figure 24, bottom).

Luisa made seven design changes, only one of which arose during the scripted prompts when her partner, Jade, gave her feedback following the prompt: *Is there any part of my design that you think could be improved? If so, how would you change it?* Jade told her to make the design bigger so that it would get noticed more. All other design changes arose during the *unscripted*, redesign phase through considerable feedback from Jade, as well as explanations from herself, as shown in Figure 25.
Figure 24. Luisa’s initial (top) and revised (bottom) sketches.
Figure 25. How Luisa’s design was revised.
Interaction Pattern Two: The Supporters

Three of the student pairs—two female pairs and one male pair—shared many characteristics that are illustrated by the linked climbers in Figure 26. First, the participants in each supporter pair seemed to the researcher to be at a similar level in their abilities, as depicted by the climbers being at similar heights on the mountain. Neither participant in a pair was overly dominant, or appeared to have significantly greater technical or metacognitive knowledge than his or her partner.

Second, the participants were supportive. Although the participants tended to follow their own path up the mountain (their own climb up the design challenge), they did so with the support of their partner. The female pairs especially showed a great deal of “mirroring” of one
another’s comments and behavior. They were positive, encouraging, and complimentary about their partner’s design. The boys were more competitive, but in a teasing way. They were well-matched and showed camaraderie.

Finally, for participants in these three pairs, the design changes came about through a combination of explanations about their own design and feedback from their partner. While the numbers of the design changes were not as numerous as those of the guide and aspirant pairs, each participant made solid redesigns. There was no design fixation. In the next section, the three supporter cases are described.

**Elise and Naomi: Supporters**

Elise and Naomi (pseudonyms) were a highly social pair who closely mirrored each other in both language and behavior. Elise enjoyed math and hoped to become a teacher or go into some sort of social career like counseling. Naomi also expressed an interest in the social professions of teacher and pediatrician. Both girls were excellent students, earning “straight A’s” or a “presidential award.”

One notable quality of Elise and Naomi interactions was that each praised the other’s design. They were careful to be positive and complimentary in their comments. When the tutoring script prompted the girls to be more critical and provide feedback (*Is there any part of my design that you think could be improved?*), Elise did not venture there, saying that Naomi’s design “….looks good the way it is.” Throughout the redesign process, Elise remained staunchly positive with exclamations of, “Oh, that’s nice!” or “You are a really good artist!” or “I like the leaf shape….” Naomi also was cautious when asked for critical feedback, but unlike Elise, she was able to provide some suggestions in the form of gentle questions, “…I’m not
sure…it’s…pretty flawless. Maybe you could have…multiple animals? Like antelope and maybe…other prey? And then…they could switch out, so…it lasts longer, maybe?”

Elise’s Metacognitive Strategies

Elise chose to design a toy for a cheetah that would engage its strongest senses of “smell and vision.” She learned through research that its prey was “deer and gazelles,” so she decided to design an antelope-shaped shell made out of papier-mâché with meat inside. She wanted her toy to be “big as a real prey,” “light not heavy,” and “able to float,” so she also designed a raft to float the antelope shell and make the toy more challenging (Figure 27, top).

During the redesign phase, though, Elise came to the realization that cheetahs “don’t like water.” She was afraid her design might not work if she placed it on a raft. Consequently she removed the raft feature altogether (Figure 27, bottom). Complete elimination of a feature was an unusual design change. Instead, most student participants refined featured or added new ones during the redesign.

Elise, then, made two design changes, one of which came about through her partner’s feedback in response to the scripted prompt, “Is there any part of my design that you think could be improved?” Her partner’s feedback led her modify the prey shape. The other design change occurred when Elise was prompted by Naomi about the weakest part of her design (Figure 28). Her response to the prompt caused her to realize that the user would not enjoy being in the water, so she completely removed the raft during revision.
Figure 27. Elise’s initial (top) and revised (bottom) sketches.
Metacognitive Prompt (Guided Question):
ELISE: Is there any part of my design that you think could be improved? If so, how would you change it?
NAOMI: Um, maybe...I'm not sure...it's like pretty flawless.
Maybe you could have like multiple animals?
ELISE: Um huh.
NAOMI: Like antelope and maybe like other prey? And then like they could switch out, so it's like...
ELISE: Uh huh
NAOMI: ...so it lasts longer maybe?
ELISE: Alright.

Metacognitive Prompt (Guided Question):
NAOMI: What do you think is the weakest part of your design?
ELISE: Um, I think the weakest is probably the raft because I don't think cheetahs like water. So I think the raft would probably be the weakest even though it would help a lot if they could get it...If we're re-doing it, then I'll probably take off the raft because they don't like water.

Figure 28. How Elise’s design was revised.
**Naomi’s Metacognitive Strategies**

Naomi chose to design a toy for a giraffe. Through research she learned that they ate “leaves, shrubs, and buds” and that their strongest senses were “vision, smell, and hearing.” She also noted that they “see in color.” Based on the facts about leaves and color she design a rainbow-colored, leaf-shaped toy with a loop on the stem to hang from a tree (Figure 29, top).

During redesign, Naomi enhanced the sound capabilities from simple rattling sounds to “noises of the wild.” She also enhanced sections of the leaf, so that they would not only be colorful, but would glow (Figure 29, bottom).

Naomi, then, made two design changes, one of which came about when her partner, Elise, asked her the scripted prompt: *What do you think is the weakest part of your design?* Her explanation to this question led Naomi to enhance the sound capabilities (Figure 30). The other design change (leaf sections made to glow) occurred during redesign, apparently through internal self-reflection, since there was no overt mention by Naomi about this change, nor any feedback from Elise.
Figure 29. Naomi’s initial (top) and revised (bottom) sketches.
Figure 30. How Naomi’s design was revised.

Metacognitive Prompt (Guided Question):
ELISE: *What do you think is the weakest part of your design?*
NAOMI: *probably... the rattle because it’s not exactly useful. Like if the giraffe doesn’t move it at all.*

Explanation on rattle.

2 DESIGN REVISIONS

1. Some sections of the leaf were changed so that they will glow (unknown impetus).
2. Dry leaves for a rattling sound changed to a “simple sound box for making noises of the wild.”
Franco and Manuel: Supporters

Franco and Manuel (pseudonyms) provided a reference case in which both students in the pair were English language learners. Manuel had stronger verbal and literacy skills than Franco, but even so, he stated that the English language arts was his most difficult academic subject. While Franco excelled at math, Manuel was athletic and loved sports, and had also been honored with a “student of the month” award. The boys displayed camaraderie with teasing and boasting, “The best thing about my design is that it is better than your design…” which was quickly followed by “Just kidding! Just kidding!”

While both boys were successful at creating an initial design, they struggled with reading and responding to the scripts. They did not read the scripts fully or in the right sequence. Consequently, they were only partially prompted to improve their designs.

Franco’s Metacognitive Strategies

Franco chose to design a “dog enrichment toy.” He wanted his toy to have a “ball shape,” a “small knot” for grabbing, and be inflatatable (like a “balloon”). He also wanted the ball to have a “little hole for a piece of chicken”—his own dog’s favorite food. His initial sketch is shown in the top of Figure 31.

Franco made four design changes. One arose from direct (unscripted) feedback that his partner, Manuel, gave him after the prompt: Why do you think your design will make the animal playful? After Franco’s explanation, Manuel cautioned, “What if it pops?” Although Franco assured Manuel that the ball would not pop, this cautionary question led Franco to modify his design brief and deflate the ball slightly so that it was no longer spherical, making it harder to pop, as shown in Figure 31 (bottom).
Another change arose through his own explanation in response to: *What do you think is the weakest part of your design?* Franco explained that he was worried about the grabbing knot’s attachment. His partner, Manuel, confirmed his concern and told him to “put it on better” (Figure 32). The other two changes—modifying the bait and selecting a material for the design—are assumed to have arisen through internal self-reflection as there was no discussion about these changes between the pair.
Figure 31. Franco’s initial (top) and revised (bottom) sketches.
Figure 32. How Franco’s design was revised.
Manuel’s Metacognitive Strategies

Manuel’s design was similar to Elise’s in that he chose to design a meat-filled, papier-mâché prey animal for a large carnivore—in his case, a lion. Based on his research, the prey animal shape he selected was a zebra (Figure 33). He also wanted his design to have movement, but expressed concern about safety issues, e.g., “it can choke or get harmed by batteries,” he wrote as a design brief constraint.

During the interaction and reading of the scripted prompts, Manuel realized that the material for his design needed improvement and “hardening.” He was concerned that the lion could too easily destroy the papier-mâché. He wanted it to be “tough for the lion to get [in]to,” thereby increasing the challenge.

Manuel made three design changes, but only one of the three could be traced to an inappropriate explanation in response to the prompt: *Is there is any part of my design that you think could be improved?* Because Manuel was an English language learner and not fully proficient in English, he did not understand that the “my” pronoun in the prompt was asking him to give feedback to Franco about Franco’s design. Instead he provided suggestions for improving his *own* design (Figure 34). Manuel’s other two design changes are assumed to have arisen through internal self-reflection since there were no overt explanations from Manuel about these changes, nor any feedback from Franco.
Figure 32. Franco’s initial (top) and revised (bottom) sketches.
Metacognitive Prompt (Guided Question):
FRANCO: *Is there any part of my design that you think could be improved? If so, how would you change it?*

MANUEL [misunderstanding that the pronoun *my* in the prompt refers to FRANCO’s design, not MANUEL’s]: I think my design needs to be improved by like the papier-mâché. If it’s papier-mâché, then it’s like gonna break easy. So I need to make it harder and better and cooler.

**Explanation on material hardness**

**MANUEL “Supporter”**

**3 DESIGN REVISIONS**

1. Changed to a “harder material” than papier-mâché.
2. Changed from “remote-controlled” to “blue tooth.” (Unknown impetus. Described concern in design brief about the lion swallowing batteries.)
3. Slight increase in size. (Unknown impetus.)

*Figure 34. How Manuel’s design was revised.*
Kate and Partner: Supporters

Kate (pseudonym) and her unconsented partner had a classic “supporter” group style with reflection about their own designs in addition to offering extensive feedback and interaction beyond the scripts. The girls had an obvious friendship with each mirroring the other in comments and behavior. They complimented each other’s design features, but neither was afraid to offer gentle, constructive criticisms. Each girl also asked spontaneous questions of the other during the redesign phase, seeking affirmation or requesting feedback on a possible design change.

The girls displayed unique metacognitive abilities that were not seen in any other pair—they developed designs to not only benefit the user (the animal), but the patrons to the zoo who were watching the user interact with the design. This was a whole other level of user-centered design—having a primary user (the animal) and secondary ones (the zoo patrons). They discussed wanting to make their designs “naturalistic” so that they would fit in with the zoo habitat and be attractive to look at for the patrons. This metacognitive thinking about two users at the same time was exceptional.

Kate’s Metacognitive Strategies

Kate was an outstanding student and athlete who could see herself in a “hands on” career like welding or carpentry. She chose to design an enrichment toy for hedgehogs or other rodent-type animals in a zoo. Her initial design had many twists and turns (Figure 35, top), but after her partner cautioned her that it might be too complicated for the intelligence of a hedgehog, she simplified the maze (Figure 35, bottom). Through reflection on her own design and asking her partner unscripted questions to get feedback, she also added sound features, made the design
upright, and added glass, so that zoo patrons could view the animals at play. Her design changes, therefore, came about through a combination of her partner’s feedback as well as her own reflection, questions, and explanations (Figure 36).

Figure 35. Kate’s initial (top) and revised (bottom) sketches.
Figure 36. How Kate’s design was revised.
Interaction Pattern Three: The Soloists

Two student pairs—one male pair and one female pair—share some characteristics with the supporter pairs, but differed in others. Just like the supporter pairs, the “soloist” participants in each pair seemed to the researcher to be well-matched. No one participant was dominant. No one participant appeared to have significantly greater metacognitive or technical knowledge.

However, they differed from the supporter pairs in that they offered little or no feedback to their partner. Even when prompted by a script, or asked a spontaneous question by a partner, little or no feedback was forthcoming. In addition, they offered no complimentary (emotional) support to their partner. Therefore, the design changes for each of the participants in the soloist pairs came about only (or primarily) through the explanations about their own designs. This dynamic is illustrated in Figure 37 in which the climbers ascend the mountain up their own paths with no support rope connecting them. In the next section, the two soloist cases are described.

Figure 37. Illustrated of the “Soloists” interaction pattern, courtesy of L. Strong.
Terence and Bryce: Soloists

Terence and Bryce (pseudonyms) had very different academic and personal styles. Terence was meticulous, cautious, and slow in speech and work, which Bryce was more rushed, eager to compete his assigned tasks without delay. Terence indicated that he was often frustrated by math, but enjoyed science and art. He reported that he could see himself working as a zookeeper, artist, or marine biologist. Bryce, on the other hand, liked math the best, and could see himself as a pediatrician.

The boys did not appear to be close friends, but still were able to make design changes through reflection on their own designs when stimulated by the prompt, *What do you think is the weakest part of your design?* Both boys stated that they preferred working in groups over working alone, yet neither boy gave feedback to the other, offered compliments, or elaborated beyond the scripted prompts. They were “soloists” in that they approached the redesign task without much apparent interest in their partner’s design. Neither seemed to see the other as a source of emotional or practical support.

Terence’s Metacognitive Strategies

Terence had a keen interest in elephants and was quite proud that he had painted one. Not surprisingly, he chose to design a painting easel for an elephant (Figure 38), noting that painting and elephants were two subjects he knew a lot about. He spoke almost dreamily about how his elephant would interact with the paintbrush, emphasizing how tactile, intelligent, and creative elephants are. He displayed an excellent ability to design from the elephant’s point of view.

Terence made four design changes, all through his own explanations or internal
reflections. For Terence, the prompt that elicited the most revision was the one in which his partner, Bryce, asked him: *What do you think is the weakest part of your design?* Upon reflection, Terence became concerned that the base of the painting easel, despite its thickness, was not stable enough (Figure 39). So, he devised a fold-up mechanism to lock it into place. In addition, the same prompt made him verbalize that he was dissatisfied with the canvas shape and size. So, the canvas was also redesigned from a circular to rectangular shape, and made bigger “to last long.”
Figure 38. Terence’s initial (top) and revised (bottom) sketches.
Metacognitive Prompt (Guided Question):
BRYCE: How does your design work?
TERENCE: Elephants are sort of creative... it's a canvas holder thing. And it won't fall because it's thick. It's to hold the brush and the paint.... So the elephant holds the brush and gets to be creative. Moves his trunk back and forth to make [paintings]...

Metacognitive Prompt (Guided Question):
BRYCE: What do you think is the best part of your design?
TERENCE: The thick at the base, so that it won't fall over.

Metacognitive Prompt (Guided Question):
BRYCE: What do you think is the weakest part of your design?
TERENCE: Probably, um, the canvas.... Probably the supports holding it up because it could possibly fall.

4 DESIGN REVISIONS
1. Made canvas bigger ("to last long")
2. Changed shape of the canvas from a circle to a rectangle.
3. Changed the platform for the canvas so that it was heavy (and "wouldn't tip"), but would still be "carry-able."
4. Fold-up mechanism at base for extra stability and portability (unknown impetus for portability).

Figure 39. How Terence’s design was revised.
Bryce’s Metacognitive Strategies

Bryce initially chose to design a “tree wall or pole” for a black bear. Through research he learned that black bears eat berries, so he placed berries along the climbing pole as “rewards” to encourage the bear to climb. Bryce identified constraints related to the size of the bear, saying that the tree wall or climbing pole “…would have to be big and support a lot of weight because the bears are big.” His initial climbing pole looked like the trunk of a stocky tree with no branches (Figure 40, left).

During redesign, he emphasized that he wanted to climb to be “fun for the black bear” and he added more rewards (berries) and made the climb more challenging. In addition (as shown in Figure 40, right) he decided to move from a pole (or trunk) shape to a full tree shape to make the bear feel like “he was in his natural habitat.”

Bryce made three design changes, all through his own explanations or internal reflections. Only one of the changes—creating multiple rather than a single reward—could be traced to his explanation in response to the prompt: What do you think is the weakest part of your design? He decided upon reflection that the bear’s reward at the end for interacting with the tree could be improved (Figure 41). The other changes, modifying the tree shape and making the climb more challenging, were not discussed, so may have arisen through his own internal reflection.
Figure 40. Bryce’s initial sketch (left) of a climbing pole with a single reward for a black bear, and his revised sketch (right) of a climbing tree showing a greater climbing challenge and multiple rewards (berries).
Figure 41. How Bryce’s design was revised.
Zoe and Lauren: Soloists

Out of the fifteen pairs of students in the entire class, Zoe and Lauren (pseudonyms) were the one pair that the researcher felt struggled to work together effectively. Zoe said she liked technology and seemed quite capable of visualizing her ideas, but she faltered when attempting to communicate them. Her reading skills were labored, too, when she went through the scripts. And it took her time to process and respond to prompts. She behaved in a much younger way than her partner, Lauren.

Lauren was mature in her demeanor and highly competent in her literary skills, describing her passion for history and Greek mythology. However, she seemed socially anxious both with her peers and adults. She indicated that she preferred working alone and was “quiet.” She and Zoe were not friends, nor did they know each other before beginning the redesign assignment. The girls’ interactions were mechanical and strained with long pauses and no elaboration beyond what was required from the script.

The researcher believes that an introductory video showing the paired, interaction process would have helped both the girls communicate more effectively. In addition, placing the girls together in a quieter, more isolated part of the room might have also reduced Lauren’s discomfort with the loud environment.

Zoe’s Metacognitive Strategies

Zoe chose to design “an enrichment toy for a dolphin.” Through her research she learned that dolphins eat “fish and squid,” so she incorporated that fact into her design criteria. She also wanted her toy to be “water sustainable” and for it to be “hard to get out the fish/squid.” An additional criteria was that the toy itself was not meant to be edible (although the prey inside
was). Her initial design showed a live prey (like a fish or squid) surrounded by water, and then surrounded by a harder, clear shell. The dolphin would have to break the shell to get to the fish (Figure 42).

As shown in Figure 43, Zoe made three design changes which were initiated through the prompt which asked her to explain how her design worked, and through the request-for-feedback prompt in which her partner, Lauren, was asked: *Is there any part of my design that you think could be improved? If so, how would you change it?* Lauren weakly whispered that perhaps the design could be made out of some safer material. Zoe took the safety comment to heart.

During the redesign phase, she tried repeatedly to get her partner, Lauren, to engage with her about the safety issue. Zoe asked Lauren an unscripted question and made multiple comments about the qualities the material needed to possess for her design (e.g., “…what do you think should be the material [so] that the dolphin won’t choke on [it]?”, “…has to be able to…not get destroyed in water.”, “…also has to be safe.” “I mean, it has to be hard, but it can’t be like dangerous…maybe cardboard.”) Lauren, however, was unable to fully engage with Zoe and provide any suggestions or debate possible ideas (e.g., “Possibly like….I don’t know….I’ll have to think about it.”) Consequently, Zoe was left to figure out the safety fix on her own.
Figure 42. Zoe’s initial sketch of a fish enclosed water toy for a dolphin (top), and her revised sketch showing more labels, an emphasis on safety, and different materials (bottom).
Figure 43. How Zoe’s design was revised.
Lauren’s Metacognitive Strategies

Lauren chose to “design a giant panda enrichment toy” incorporating the favorite food of a panda—bamboo. She designed a giant spherical ball with a logical set of features: She wanted it to be lightweight, small enough to fit in a tree (but large enough for a giant panda), brightly colored, and big enough to put bamboo in. Her only constraint was that the ball needed to be made out of safe materials. She was unique among the participants in that she sketched her design from two perspectives: afar (in the tree as a zoo patron would see it) and close-up (with detail) as a giant panda would see it (Figure 44, top).

During redesign, Lauren independently made three design changes, one of which was an interesting, contrary reaction to feedback from her partner, Zoe. In response to the prompt in which Lauren asked Zoe for feedback on improving her design, Zoe deliberated for a long time—about a minute—before finally saying that Lauren’s design should not be hollow (Figure 45). Lauren explicitly wrote the word hollow as one of the criteria in her design brief during the redesign phase. Her other two changes—enlarging the top hole in the ball so that it was big enough for a panda paw and adjusting the overall size of the design (Figure 44, bottom)—appeared to have arisen from her own internal reflection, as there was no discussion of those two changes between the pair.
Figure 44. Lauren’s initial (top) and revised (bottom) sketches from afar and close-up.
3 DESIGN REVISIONS

1. Adjusted size so big enough for panda, but small enough to fit in tree (unknown impetus).
2. Increased hole size at top, so that it was big enough for panda paw (unknown impetus).
3. Explicitly made the toy hollow.

Figure 45. How Lauren’s design was revised.
Interaction Pattern Four: The Olympian and the Coach

One male student pair had a unique dynamic. They were close friends and had worked together previously. Each was highly verbal and had an excellent ability to simulate how the user would interact with the design. One of the students, however, had significantly more technical knowledge than the other. The uneven technical knowledge led to a “big brother-little brother” dynamic in which the “little brother” greatly admired the “big brother” and was in awe of his technical knowledge, and his design. Consequently, nearly all of the boys’ redesign energy went into the “big brother’s” redesign. The “little brother” became like a coach to an Olympian, cheering the “big brother” on and offering lots of feedback for improvements—both solicited and unsolicited. The Olympian’s resulting redesign was far more technical, complicated, and advanced than any of the other student participants, but the downside was that the Coach—the little brother—\textit{never explicitly implemented} his redesign ideas. So, the redesign outcomes were uneven. The Olympian made a challenging climb to the top of an extremely steep mountain with the support of the Coach, but the Coach remained halfway down the mountainside and never fully made it to the top, as illustrated in Figure 46. Details of the Olympian and Coach case are now presented.
Carl and Max: Olympian and Coach

Carl and Max (pseudonyms) were the one pair of students placed together *deliberately* because of their observed friendship during the initial design phase. Max, who described himself as “a small boy,” was exuberant and positive about the design challenge, eager to tell the researcher about his chosen animal—a penguin. He sought out the advice of his nearby peers during the initial design phase, probing them for ideas. One peer suggested designing a looped, circular ice track studded with fish. After much discussion, though, Max turned to music, a
subject he loved and excelled at, for inspiration. With a grin, he exclaimed to the researcher, “I’ve got it! I’ll make a penguin dance party mat!” For the design of the mat, he turned to a different friend, Carl, a boy whom Max clearly admired and looked up to. He moved to where Carl was sitting and asked for help in designing the mat.

Carl spoke and behaved very maturely for his age. During the first-day classroom discussion on engineering careers, he was comfortable questioning and challenging the researcher, appearing to enjoy the art of debating ideas. He had more advanced knowledge than the other students of science and technology, and had won a regional science fair competition. Carl interacted with Max patiently and compassionately, as if he were a younger brother.

The researcher was hesitant to place the boys together for the redesign phase, concerned that Carl might completely dominate the pair because of his advanced knowledge. Indeed, during the redesign phase, the boys’ interactions were almost completely focused on Carl’s design. Consequently, Max failed to explicitly implement any redesign ideas.

On the other hand, the boys were happy to discover that they had been made partners. Max exclaimed with surprise, “Oh, wow! How lucky is that?” To which Carl replied, “Sweet!” And their strong friendship made space for Max to consider Carl’s design, and offer ample constructive feedback. Carl listened carefully to Max’s ideas and feedback, responded to them, and expressed gratitude. The scripts initiated conversation between the boys, but the researcher believes that their existing friendship was key to enabling intense and extensive interaction about Carl’s design that went far beyond the scripts. Indeed, the transcript of their interactions was the lengthiest of all the pairs.
Carl’s Metacognitive Strategies

Carl chose to design a remote-controlled “Mars rover for a Belgian Malinois”—a large, high energy dog. He wanted his rover to “stimulate [the dog’s] sense of smell for tracking,” thereby making it hunt and run. His constraints were that the design be under one hundred dollars and that it be safe with no choking hazards. Although not explicitly written in his initial design brief, Carl sketched numerous features on his rover, including a ball launcher, treads for all-terrain driving, a camera, and a smell release mechanism (Figure 47, top). Some of these features were then explicitly called out in his revised design brief.

Carl made twelve design changes (Figure 47, bottom). Only four of the changes came about directly as a result of prompts. One of the prompts that incited change was not the typical “negative” or “neutral” prompts that other participants reacted to. Instead it was a “positive” prompt asking his partner for feedback on the best part of his design. Carl’s reflection on his partner’s feedback in reaction to this prompt was unusual among the participants. (Only one other participant, the “guide,” Jade, had a similar, but minor reflective response.) Carl’s remaining design changes came about during the redesign phase through extensive, unscripted feedback from his partner, Max, and through his own detailed explanations about how the user would interact with the design (Figures 48-51).

It is notable that some feedback from Max was not ultimately implemented (e.g., mud flaps, covered treads) although Max’s ideas were initially well-received from Carl. The failure to implement the feedback may have been because Carl had so many other ideas and forgot, or because of a lack of time. Feedback from Max that tended to be implemented immediately was not the unsolicited kind. Instead it was the feedback that arose from Carl’s spontaneous (unscripted) questions, directly requesting help.
Figure 47. Carl’s initial sketch (top) of a remote-controlled, “Mars rover” for a large dog, and his revised sketch (bottom) showing refined details and added attachments.
CARL: What do you like best about the design?
MAX: I think the best part is that it will help the dog with what you said, the nine hours of.
CARL: Exercise is a bit much.
MAX: Exercise, yeah. That will help it out a lot. And you won’t have to be running about 30 miles per hour.
CARL: Yeah.
MAX: Which is humanly impossible.
CARL: Hussein Bolt’s fastest speed is like 24....
MAX: ...And it has like a fetch component, so you like run it off and then shoot the ball back.
MAX: Like one of those tennis things that shoots tennis balls?
CARL: Yeah, it’d be spring-loaded.

MAX: What is the weakest part [of your design] do you think?
CARL: Probably the weakest physically is going to be the motors powering the treads because they are going to have to move really fast.
MAX: Probably needs a really big gear system.
CARL: Yeah, probably, if not individual motors for each track because this is going to have to work like a tank. These dogs are...they’re bred to work and when you don’t work them properly, they get ballistic.
MAX: No wonder tanks have about a three times bigger engine than cars.
CARL: Yeah, so this is going to be run on, like I said, a 12-S LIPO which have about 45.53 Volts. Um, and so, I connect that up and I would run it on at least about 30 mile an hour motors. I think that would be almost 250 or maybe 180’s or 250 rpm motors. RPS, excuse me. Rotations per second versus rotations per minute. And so, probably the treads might get knocked out of alignment.
MAX: Um huh.
CARL: And I’m also worried it might be too heavy to practically carry.
MAX: Yeah.

Figure 48. How Carl’s design was revised.
**Figure 49.** How Carl’s design was revised (continued).
**Figure 50.** How Carl’s design was revised (continued).
Figure 51. How Carl’s design was revised (continued).
Max’s Metacognitive Strategies

Max chose to design a dance party mat for a penguin which he describe as a “floating penguin dance floor” with “buttons that hit strings when stepped on.” Max did not create an initial design sketch on his own. Instead, when he asked his partner, Carl, for help in designing the mat, Carl drew for him an internal magnetic mechanism (described by Carl as “a mallet wrapped in a magnet”) that would strike a string tuned to a certain note when pressed. Max used the sketch drawn by Carl for his “initial design” (Figure 52, top).

During the interaction, Max discussed four design problems that might need fixing with his partner, Carl (Figure 53). Two of the discussed changes were his own ideas brought about through the prompt, “What do you think is the weakest part of your design?” Max expressed concern that if a user was “too light” or stepped on “two or more buttons at once,” the design would not function properly.

The third discussed change arose from Carl’s feedback to the prompt, “How does your design work?” Max began to answer the question, but then Carl interrupted him and discussed the issue of a note getting “stuck” if the design were purely mechanical. So, his solution was to move to electromagnets.

The fourth design change that was discussed was about the stability of the raft in response to: Is there any part of my design that you think could be improved? Carl flagged the stability of the raft as an issue and Max agreed with his feedback that it needed to be fixed.

Max’s “revised sketch” (Figure 52, bottom) and design brief, though, do not explicitly identify or highlight any of the design changes that were discussed. The drawing is instead a high-level sketch of the design he envisioned (more like an initial design). The researcher could not then count Max as having made any design changes, since none were explicitly implemented
in either the final design brief or the final solution sketch.

Figure 52. Max’s “initial” sketch (top, drawn by his partner, Carl) and his “revised” sketch (bottom, drawn by himself, Max).
**Figure 53.** How Max’s design was revised.
Quantitative and Qualitative Analysis of Student Designs

Three research propositions were developed in advance of the comparative case study to predict the design change outcomes:

1. The designs created after the intervention had a greater number of criteria, or more refined criteria, than those created before the intervention.
2. The solution sketches made after the intervention were more detailed than those made before the intervention.
3. The solution sketches made after the intervention more explicitly identified the criteria than those made before the intervention.

To answer the research propositions, the differences between the initial and revised designs were analyzed both quantitatively and qualitatively for each student participant. Table 3 was used to code changes to the criteria (features) in each design, while Table 4 was used to code changes in the level of detail and labeling. Summaries of the coded changes are presented below.

Table 3 provides a plan for categorizing a change in a criteria (between the initial and revised designs) for each participant. For example, if a student changed a dimension that enhanced the design (was nice to have), but wasn’t necessarily critical to its function, that was coded as altering an existing criteria. If a student modified a feature of the design that was critical to making the design work properly, that was coded as a critical change to an already existing criteria. If a student created a completely new feature that had not existed before, that change was coded as a new criteria to enhance the design. If that new criteria was critical to the operation of the design, the change was coded as new and critical. A summary of the design criteria changes for all the participants is presented in Table 6.
Table 6

*Frequency counts of coded design changes for each participant*

<table>
<thead>
<tr>
<th>Name</th>
<th>Group</th>
<th>Altered existing criteria</th>
<th>Altered and critical existing criteria</th>
<th>New criteria</th>
<th>New and critical criteria</th>
<th>Total number of changes</th>
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<tbody>
<tr>
<td>Leo</td>
<td>Guide</td>
<td>3</td>
<td>2</td>
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<td>7</td>
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<tr>
<td>Javier</td>
<td>Aspirant</td>
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<td>8</td>
<td>0</td>
<td>8</td>
</tr>
<tr>
<td>Jade</td>
<td>Guide</td>
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<td>0</td>
<td>0</td>
<td>6</td>
</tr>
<tr>
<td>Luisa</td>
<td>Aspirant</td>
<td>5</td>
<td>0</td>
<td>2</td>
<td>0</td>
<td>7</td>
</tr>
<tr>
<td>Elise</td>
<td>Supporter</td>
<td>1</td>
<td>0</td>
<td>0</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Naomi</td>
<td>Supporter</td>
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<td>0</td>
<td>0</td>
<td>2</td>
</tr>
<tr>
<td>Franco</td>
<td>Supporter</td>
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<td>0</td>
<td>4</td>
</tr>
<tr>
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<td>0</td>
<td>0</td>
<td>3</td>
</tr>
<tr>
<td>Terence</td>
<td>Soloist</td>
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<td>1</td>
<td>0</td>
<td>1</td>
<td>4</td>
</tr>
<tr>
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<td>Soloist</td>
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<td>0</td>
<td>3</td>
</tr>
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<td>Soloist</td>
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<td>0</td>
<td>0</td>
<td>3</td>
</tr>
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<td>Lauren</td>
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<td>3</td>
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<tr>
<td>Carl</td>
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<td>6</td>
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<td>0</td>
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</table>

All participants, except Max, had greater criteria, or more refined criteria, in their designs after the intervention, which supports research proposition number one. Note that if a participant discussed changing a criteria, but did not *explicitly* implement the change in either the design briefs or solution sketches, then the change was not counted. For example, four design changes (Figure 53) were discussed by the participant, Max, during his interaction with his partner, Carl, but none of those design changes were explicitly implemented or called out in his brief or sketches, so were therefore not counted. Also note that the “Guide and Aspirant” pairs were very dynamic and had the most design changes *per pair*, while the male “Aspirant” and “Olympian” had the most *new* criteria.

Table 4 provides a plan to answer the second and third research propositions by asking
questions about the detail and labeling of each design. A summary of the answers for each participant is shown in Table 7. Note that the second and third research propositions (positing the there would be more details and labeling in the revised sketches than the initial) were only true simultaneously for the “Guide and Aspirant” pairs and one of the soloists. The second research proposition (positing that there would be more details in the revised sketch than the initial) was also true for one of the “Supporters.” For all other participants, the second and third research propositions were not true.

Table 7

Summary of detail and labeling changes between initial and revised sketches

<table>
<thead>
<tr>
<th>Students</th>
<th>Detail (Was there an increase in sketch detail in going from the initial to the revised sketch?)</th>
<th>Labeling (Was there an increase in sketch labeling in going from the initial to the revised sketch?)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leo</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Javier</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Jade</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Luisa</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Elise</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Naomi</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Franco</td>
<td>Yes</td>
<td>No</td>
</tr>
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<td>Manuel</td>
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<td>No</td>
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<td>Kate</td>
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<td>No</td>
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<tr>
<td>Terence</td>
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<td>No</td>
</tr>
<tr>
<td>Bryce</td>
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<td>No</td>
</tr>
<tr>
<td>Zoe</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Lauren</td>
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<td>No</td>
</tr>
<tr>
<td>Carl</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>Max</td>
<td>N/A</td>
<td>N/A</td>
</tr>
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</table>

Analysis of Coded Pair Interactions

Verbal interactions between each student pair were audio-recorded as the students read and responded to the metacognitive prompt scripts, and as they redesigned. The researcher
created transcripts of the audio-recordings, which were then coded with a co-researcher (using the codebook definitions from Table 3). The co-researcher was a Collaborative Institutional Training Initiative (CITI) certified, secondary math teacher and former engineer.

The researcher and co-researcher engaged in rounds of coding and codebook modifications until an intercoder or intrarater reliability statistic (Cohen’s kappa) greater than 0.85 was achieved (Wilson et al., 2014). Because Cohen’s kappa can sometimes show a paradoxically low value (due to the distribution of the data), Gwet (2014) recommended computing other intrarater reliability statistics as well, e.g., Scott’s Pi (Scott, 1955), Brennan-Prediger Coefficient (Brennan & Prediger, 1981), Krippendorff’s Alpha (Krippendorff, 2004), and Gwet’s AC1 (Gwet, 2014).

The final Cohen’s kappa computed for the full, coded data set is shown in Table 8, along with the alternative statistics recommended by Gwet (2014) for two raters. All statistics were calculated using R, open-source statistical code, and the agreement coefficients were all very similar (0.855, 0.855, 0.861, 0.855, and 0.862).

Table 8

<table>
<thead>
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<th></th>
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<tr>
<td>Agreement Coefficient</td>
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<td>95% Confidence Interval</td>
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</tbody>
</table>
The frequency counts for each type of code in the codebook of Table 3 are presented in Table 9 for each participant. Note that the Guides (both male and female) and the Olympian have the highest frequency counts for the simple and total explanations, while the male Guide and Olympian have the most user-centered explanations. Similar highest (and lowest) frequency counts of Table 9 are summarized in Table 10 for each of the verbal phenomena.

Table 9

Frequency counts of coded text fragments for each participant

<table>
<thead>
<tr>
<th>Students</th>
<th>Explanations</th>
<th>Feedback</th>
<th>Affirmations</th>
<th>Questions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Name</td>
<td>Group</td>
<td>Simple</td>
<td>User-centered</td>
<td>Total</td>
</tr>
<tr>
<td>Leo</td>
<td>Guide</td>
<td>35</td>
<td>19</td>
<td>54</td>
</tr>
<tr>
<td>Javier</td>
<td>Aspirant</td>
<td>12</td>
<td>4</td>
<td>16</td>
</tr>
<tr>
<td>Jade</td>
<td>Guide</td>
<td>17</td>
<td>5</td>
<td>22</td>
</tr>
<tr>
<td>Luisa</td>
<td>Aspirant</td>
<td>7</td>
<td>5</td>
<td>12</td>
</tr>
<tr>
<td>Elise</td>
<td>Supporter</td>
<td>1</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>Naomi</td>
<td>Supporter</td>
<td>2</td>
<td>4</td>
<td>6</td>
</tr>
<tr>
<td>Franco</td>
<td>Supporter</td>
<td>6</td>
<td>5</td>
<td>11</td>
</tr>
<tr>
<td>Manuel</td>
<td>Supporter</td>
<td>10</td>
<td>6</td>
<td>16</td>
</tr>
<tr>
<td>Terence</td>
<td>Soloist</td>
<td>6</td>
<td>8</td>
<td>14</td>
</tr>
<tr>
<td>Bryce</td>
<td>Soloist</td>
<td>10</td>
<td>3</td>
<td>13</td>
</tr>
<tr>
<td>Zoe</td>
<td>Soloist</td>
<td>6</td>
<td>4</td>
<td>10</td>
</tr>
<tr>
<td>Lauren</td>
<td>Soloist</td>
<td>7</td>
<td>1</td>
<td>8</td>
</tr>
<tr>
<td>Carl</td>
<td>Olympian</td>
<td>32</td>
<td>15</td>
<td>47</td>
</tr>
<tr>
<td>Max</td>
<td>Coach</td>
<td>8</td>
<td>1</td>
<td>9</td>
</tr>
</tbody>
</table>
Table 10

**Summary of participants with the highest and lowest frequency counts of verbal phenomena**

<table>
<thead>
<tr>
<th>Verbal Phenomena</th>
<th>Highest Frequency Counts</th>
<th>Lowest Frequency Counts</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simple Explanations</td>
<td>Male Olympian, Male Guide, Female Guide</td>
<td>Pair of female Supporters</td>
</tr>
<tr>
<td>User-centered Explanations</td>
<td>Male Guide, Male Olympian</td>
<td>Female Soloist, Coach</td>
</tr>
<tr>
<td>Total Explanations</td>
<td>Male Olympian, Male Guide, Female Guide</td>
<td>Pair of female Supporters</td>
</tr>
<tr>
<td>Feedback Given</td>
<td>Male Coach, Male Guide</td>
<td>Male Supporter, Male Soloist, Female Soloist</td>
</tr>
<tr>
<td>Feedback Received</td>
<td>Male Olympian Male Aspirant</td>
<td>Male Supporter, Male Soloist, Female Soloist</td>
</tr>
<tr>
<td>Affirmations Given</td>
<td>Male Coach</td>
<td>Female Supporter, Male Soloist, Female Soloist</td>
</tr>
<tr>
<td>Affirmations Received</td>
<td>Male Olympian</td>
<td>Female Supporter, Male Soloist, Female Soloist</td>
</tr>
<tr>
<td>Questions Asked</td>
<td>Male Aspirant, Male Olympian, Male Coach</td>
<td>Female Aspirant, Pair of female Supporters, Male Soloist, Female Soloist</td>
</tr>
</tbody>
</table>

Scatter plots of the frequency counts for each of the codes are shown in Figures 54-61. With the exception of the “Olympian and Coach” pair, the data points are grouped together to make identification of pairs easier.
Discussion of Coded Pair Interactions

Explanations

Explanations were defined by the researcher as a student’s description of his or her own design or chosen user (animal). If a description was straightforward, without any user-centered perspective, then the explanation was coded as “simple.” If a description was more elaborate with the student taking the user’s perspective by visualizing or simulating the user playing with the design, or imagining the user’s experiences, thoughts, or feelings, then the explanation was coded as “user-centered.” The sum of a participant’s simple and user-centered explanations was defined as “total explanations.”

As shown in Table 9 and Figures 54-56, the “Olympian” and “Guides” (both male and female) had the most simple and total explanations, while the most user-centered explanation fell to the Olympian and the male Guide. For the simple and total explanations with the Coach outlier excluded, there was a weak, positive relationship between the frequency counts of explanations and the number of design changes. Of course, the quantity of explanations—simple, user-centered, or total—says nothing about the quality of the explanations or their power to incite change. An explanation’s quality is revealed only if the explanation leads to greater peer interactions or incites an actual design change.
Figure 54. Frequency counts of simple explanations versus design changes for each participant.
Figure 55. Frequency counts of user-centered explanations versus design changes.
Figure 56. Frequency counts of total explanations versus design changes.
Feedback

The researcher observed two broad types of feedback that were given by the participants to their peer partners: Technical feedback and social feedback. Technical feedback could be

- an imperative (e.g., “Put it on better!”),
- a directive (e.g., “You should add a nap area.”),
- a question (e.g., “I think that it maybe could be…a little bit bigger?”), or
- a critical evaluation (e.g., “…the stability of the raft….you might want support lines.”).

Social feedback could be encouraging or affirming (e.g., “Oh, that’s nice! I like that it can be an underwater toy.”) The researcher observed that social feedback served to enhance rapport between a pair and often led to reciprocal social feedback or affirmations.

Out of all the participants, the “Coach” and the male “Guide” gave the most feedback to their partners (see Max and Leo in Table 9 and Figure 57). Correspondingly, the “Olympian” (Carl) and the male “Aspirant” (Javier) were the greatest recipients of feedback. The Olympian and male Aspirant also had the most design changes of all the participants. With the exception of the student participant, Max, that there is a strong, positive relationship between feedback received and the number of design changes a participant makes (Figure 58).
Figure 57. Frequency counts of feedback given versus design changes.
Figure 58. Frequency counts of feedback received versus design changes.
Affirmations

Affirmations were simple, positive responses to something a partner said (e.g., yeah, yes, uh-Uh, okay) that helped to bolster or confirm a partner’s thought. The researcher believes that affirmations can signal that a pair is working well together and having a good interchange of ideas, or that they are offering social support.

By far the greatest number of affirmations given fell to the “Coach” (see Max in Table 9 and Figure 59), but the two Aspirants (both male and female) also had a significant number of affirmations. Correspondingly, the “Olympian” was the greatest recipient of affirmations (see Carl, Table 9 and Figure 60). The lowest exchange of affirmations was among the Soloists pairs (both male and female).

Questions

Questions were student-generated queries that were obviously not feedback. (Prompts were teacher-generated queries.) The male “Aspirant” and the “Olympian” and “Coach” asked the most questions (see Javier, Carl, and Max in Table 9 and Figure 61), while five participants failed to generate any questions at all (a male and female Soloist, a female Aspirant, and two female Supporters, Elise and Naomi). There does not appear to be a strong relationship between the number of questions a participant asks and the number of design changes he or she makes.
Figure 59. Frequency counts of affirmations given versus design changes.
Figure 60. Frequency counts of affirmations received versus design changes.
Figure 61. Frequency counts of questions asked versus design changes.
Combinations of Codes: The Expressiveness Index and the Stimulus Index

An “Expressiveness Index” was defined by the researcher as the sum of all verbal utterances from a participant (not including the reading of the metacognitive prompts). A participant’s “Expressiveness Index” is therefore the sum of his or her total explanations, feedback given, affirmations given, and questions asked.

Likewise, a “Stimulus Index” was defined by the researcher as the sum of all the self or partner stimuli given to a participant about his or her design. A participant’s “Stimulus Index” is therefore the sum of his or her total explanations, feedback received, affirmations received, and questions asked about his or her own design. Table 11 shows the frequency counts for combinations of codes for each participant. Scatter plots of the Expressiveness and Stimulus Indices versus the number of design changes made by each participant are shown in Figures 62 and 63, respectively.
Table 11

*Frequency counts for combinations of codes*

<table>
<thead>
<tr>
<th>Students</th>
<th>Group</th>
<th>“Expressiveness Index”</th>
<th>“Stimulus Index”</th>
</tr>
</thead>
<tbody>
<tr>
<td>Leo</td>
<td>Guide</td>
<td>80</td>
<td>79</td>
</tr>
<tr>
<td>Javier</td>
<td>Aspirant</td>
<td>49</td>
<td>40</td>
</tr>
<tr>
<td>Jade</td>
<td>Guide</td>
<td>41</td>
<td>49</td>
</tr>
<tr>
<td>Luisa</td>
<td>Aspirant</td>
<td>33</td>
<td>25</td>
</tr>
<tr>
<td>Elise</td>
<td>Supporter</td>
<td>14</td>
<td>11</td>
</tr>
<tr>
<td>Naomi</td>
<td>Supporter</td>
<td>11</td>
<td>14</td>
</tr>
<tr>
<td>Franco</td>
<td>Supporter</td>
<td>22</td>
<td>19</td>
</tr>
<tr>
<td>Manuel</td>
<td>Supporter</td>
<td>26</td>
<td>22</td>
</tr>
<tr>
<td>Terence</td>
<td>Soloist</td>
<td>16</td>
<td>19</td>
</tr>
<tr>
<td>Bryce</td>
<td>Soloist</td>
<td>19</td>
<td>16</td>
</tr>
<tr>
<td>Zoe</td>
<td>Soloist</td>
<td>14</td>
<td>16</td>
</tr>
<tr>
<td>Lauren</td>
<td>Soloist</td>
<td>13</td>
<td>10</td>
</tr>
<tr>
<td>Carl</td>
<td>Olympian</td>
<td>76</td>
<td>106</td>
</tr>
<tr>
<td>Max</td>
<td>Coach</td>
<td>69</td>
<td>28</td>
</tr>
</tbody>
</table>
Figure 62. Frequency counts of a participant’s “Expressiveness Index” versus design changes.
Figure 63. Frequency counts of a participant’s “Stimulus Index” versus design changes.
Discussion of Combinations of Codes: The Expressiveness Index and the Stimulus Index

The “Olympian and Coach” pair and the male “Guide and Aspirant” pair were the most expressive, followed by the female “Guide and Aspirant” pair (see Carl and Max, Leo and Javier, and Jade and Luisa in Table 10 and Figure 62). With the exception of the “Coach” participant, Max, there is positive relationship between the Expressiveness Index and the number of design changes.

The Olympian and male and female “Guides” received the greatest stimulus followed by the male and female “Aspirants” and “Coach” (see Carl, Leo, Jade, Javier, Luisa, and Max in Table 10 and Figure 63). With the exception of the “Coach,” Max, there is a positive relationship between the Stimulus Index and the number of design changes.

Summary of Prompts that Incited Reflection

Two scripts containing metacognitive prompts were used in the research: One script prompted a student designer for explanations (Appendix K) and the other script prompted a student designer’s partner to provide feedback (Appendix K). The researcher determined which of the prompts incited reflection, as evidenced by design brief or sketches changes, or by verbal discussion of a change. The frequency counts and names of the students who were impacted by a metacognitive prompt from the scripts are presented in Figures 64 (prompts for explanations) and Figure 65 (prompts for feedback).

Note that for both sets of prompts, it was the “negative” prompts that incited the most reflection in the greatest number of students. “Negative” prompts are defined as those prompts which ask a student designer or his or her partner about design weaknesses or features which could be improved. However, “neutral” prompts were also widely effective. Neutral prompts
did not use words like “best” or “worst,” but simply asked for explanations about how the design worked, or tried to get a student to think about how the user would interact with the design.

“Positive” prompts, which used words like “best,” and asked for explanations or feedback about positive features of the design, were less effective overall for students. However, the researcher believes positive prompts should be kept as they appear to enhance rapport between pairs, thereby opening pathways for more critical discussions.

Figure 64. Counts and names of student participants who reflected upon their own designs when asked a metacognitive prompt from their partner requesting an explanation.
Case Evidence for the Tutor Learning Effect

The development of this comparative case study was guided by several metacognitive learning theories about the tutor learning effect, the phenomenon of tutor learning gains or knowledge-building during peer tutoring. The case study findings demonstrate evidence for the tutor learning effect most strongly in the Guide and Aspirant pairs, where the act of guiding helped not only the Aspirants, but the Guides as well. The Guide and the Aspirant interaction...
pattern had the most design changes per pair, making it the most dynamic and effective style of interaction for instigating changes in both partners.

**Findings for the Partially Studied Pairs**

There were three pairs who were only partially studied due to consent or absence issues: Two female pairs and one mixed-gender pair. One of the female pairs was presented in the Supporters section (see Kate and Partner) under Interaction Pattern Two. The second female pair (who were absent on Day 2, the day the students created their initial designs) is presented below (see Leilani and Morgan: Dynamic Supporters and Negotiators). It is an example of a unique case in which a highly interactive pair worked together from the beginning to create designs. Even though they did not have scripts to guide them, they naturally asked each other many questions, deliberately seeking affirmations, feedback, clarification, or resolution of “cognitive dissonances” (Chin & Osborne, 2010; Festinger, 1957). In addition, they naturally explained their designs to their partners as they developed—what they were doing and why. They both designed for the same animal, yet came up with strikingly different designs.

The third pair was one of two mixed-gender pairs in the classroom. They had a Supporter interaction style in that they had about the same level in their technical and metacognitive skills, and provided feedback when prompted by the script. The only observed difference between the mixed-gender and same-gendered Supporter pairs was a smaller socio-emotional component (less praise, less teasing, less mirroring of behavior). However, this could also have been because the students in the mixed-gendered pair did not seem to know each other as friends or even acquaintances, so their interactions were not extensive.
Leilani and Morgan: Dynamic Supporters and Negotiators

Leilani and Morgan (pseudonyms) had an exceptionally dynamic and interactive style reminiscent of the Olympian and Coach pair, Carl and Max, but with an important difference—they were well-matched in both their technical and metacognitive skills. Both girls were excellent students, having achieved 4.0 grade point averages, and both preferred working in groups (Morgan liked small; Leilani liked any size). They stated that they enjoyed receiving new and “multiple ideas from different minds.” Both could see themselves in a medical career as a doctor with Morgan adding that she could see herself as a dentist or teacher as well. Each struggled with one of the STEM subjects—Leilani with science; Morgan with math, which she stated she was good at, but did not enjoy. Interestingly, they each wished they knew something more about the STEM subject that the other found the most difficult.

Unfortunately, the girls were both absent for Day 2, the day in which the students at the research site completed their initial designs. Consequently, when they arrived on Day 3, they did not have an initial design to work with. The researcher instructed them to work together on Day 3 to create their “initial” designs.

They designed as a pair naturalistically. Even without scripts to guide them, they spontaneously asked each other many questions, seeking affirmations or feedback about their own designs, or, most surprisingly, questioning and challenging elements of the other’s designs. Leilani, especially, would frequently probe Morgan: “Wait, so how do they get into that?” “Do you think they are strong enough to pull that apart?” “So, what are you going to make that out of?” Neither girl was afraid to challenge or disagree with the other if something seemed amiss in their partner’s explanation. In addition, they “thought out loud”—not with verbalized, “private speech” like the male Guide, Leo—but simply to explain design elements to their partner as their
designs were being created, negotiated, and redesigned.

Both girls chose to design for the same animal (user), yet came up with distinctly different designs (Figures 66). Near the end of the class period, they read the metacognitive prompts to one another, but by then the scripts were superfluous. The girls had already negotiated and redesigned nearly every element of their designs. So, in effect, their designs at the end of the day were their revised ones. There was not an initial sketch or brief to compare with, but through the transcript, one can imagine what their initial briefs and sketches would have looked like.
Figure 66. Leilani’s single sketch (top) and Morgan’s single sketch (revised dynamically).
While it is unfortunate that the girls were not able to complete the full curriculum in the same way as the other pairs, the researcher feels grateful that this accidental case provides a blueprint for another way to structure the design learning activity: Have a pair of adolescent friends work together from the beginning to create their own designs for the same user without teacher-generated scripts. Metacognitive prompts may be invoked naturally as was seen repeatedly in this case. Moreover, the student-generated metacognitive prompts may be design-specific, possessing deeper and greater “epistemic-probing” power (Chin & Osborne, 2010) than the teacher-generated prompts. As “epistemic probes,” a student’s questions can sort out what a peer partner knows and doesn’t know, and can make visible a partner’s knowledge and reasoning. They can also act as a “heuristic tool” (Chin & Osborne, 2010), helping a student develop logical arguments. Student-generated prompts can therefore set the stage for peers to co-construct knowledge and solutions by offering confirmations, corrections of knowledge, or the filling in of gaps. Indeed, the girls provided all these benefits to one another. In one interchange, Leilani asked Morgan a series of probing questions (bolded below) that stimulated her to explain and redesign, and helped the girls co-construct a design solution:

LEILANI: Oh, and then the nose…the dolphin’s nose. Does it go right there?
MORGAN: It goes between them.

LEILANI: Yeah, yeah. So wait, so how do they get into that?
MORGAN: So the string has to be big enough so they can bite onto the string because they can smell the food.
LEILANI: Yeah.
MORGAN: So they’ll bite onto the string and then they’ll swim apart and they’ll pull it and then the fish will come out.

LEILANI: Oh. So, what are you going to make that out of?
MORGAN: Like…[whispers] PC pipe. [Means PVC pipe.]
LEILANI: A what?
MORGAN: PC pipe. [PVC pipe.]
LEILANI: Oh, yeah, yeah. Do you think they are strong enough to pull that apart?
MORGAN: PC pipe and this is probably just going to be like a cap.

LEILANI: Oh wait, doesn’t that [cap] have to be like a…kind of like a float?
MORGAN: Yeah.
LEILANI: So it has to be like a…
MORGAN: [Both girls excitedly talking at the same time.] Oh, because like…if it’s rubber, that will float.
LEILANI: What if you do a…
MORGAN: A hard plastic. A really hard plastic.
LEILANI: Yeah, or…
MORGAN: But it has to be big enough that they can’t eat it.
Leilani: Something that floats...something like a tube, you know? Kind of like that. [Shows her something.] So, you would put it on the ends?
MORGAN: No, it can’t be metal.
LEILANI: Yeah, yeah.
MORGAN: Could be wood, but that’ll be hard.
LEILANI: Yeah, that would. And they’d probably scratch on it or something.
MORGAN: Maybe whatever those chairs are made of.
LEILANI: They’ll float?
LEILANI: You can’t put a ton of fish in there or it will sink.
MORGAN: True. And we can’t fill it up with water.
LEILANI: I say a little bit of water fill it up with.
MORGAN: Yeah. Just a little bit of water so they don’t…

LEILANI: How tall is it?
MORGAN: It’s like…oh, tall? It’s two feet tall. Oh, you mean this way?
LEILANI: Yeah. No, this way.
MORGAN: This way, that’s…the width’s two feet.
LEILANI: Okay.
MORGAN: But this…
LEILANI: Ok, what if you only do half a foot of water?
MORGAN: Probably, that might work…but this right here…from here to here is…that’s going to make three feet actually.
LEILANI: Yeah, yeah.
MORGAN: Because it has to be big enough that they can’t eat it.

In another interchange, Leilani does not know the name for the float in her design, so Morgan fills in the gap and then stimulates her to redesign the tether:

LEILANI: So, mine’s going to be at the bottom of the pool. Like at the aquarium, you know? And it’s going to have these strings that come up so then it’s…you know, like one of those balls that float in the ocean or something? Not the ocean, but a lake.
MORGAN: Like the buoys?
LEILANI: [Laughs.] Buoys, yeah buoys. So it will be kind of like a buoy, but it will be attached to a string. But it will be underwater. I guess I should make some above water, too.
MORGAN: Shouldn’t it be like a stick though?
LEILANI: A stick?
MORGAN: Instead of string?
LEILANI: No, I’m thinking like a wire.
MORGAN: Okay.
LEILANI: So, it doesn’t come detached, you know?
MORGAN: I was going to say if it’s a string, it might come detached more easily.
LEILANI: No, I mean, this is going to be made out of wire. And then this is going to be the buoy at the top of the wire. Or we could do a chain.
MORGAN: Yeah.
LEILANI: Yeah.
MORGAN: We should probably do a chain just in case.
LEILANI: Like a light chain.
MORGAN: Yeah.
LEILANI: And then so, it’s going to have a buoy. How do you spell buoy?
MORGAN: Uh, sixth grade vocabulary. [Laughs and then the girls ask their peers at the next table how to spell it.]

Regarding the co-construction of knowledge, it was fascinating to observe the girls’ pronouns shift occasionally when they talked about their designs. Several times, the “I” pronoun shifted to “we.” It is seen twice in the interchange above (bolded), e.g., “We should probably do a chain just in case.” Or in another interchange, Morgan says, “…if we need to we can put a fish spray on them.” Although the girls thought of their designs as their own (e.g., they talked about a design being “mine” and used the pronoun, I, when describing their own work), they also seemed to acknowledge some degree of joint ownership and co-construction of the designs when they shifted to the “we” pronoun. The frequency counts for each type of pronoun in the transcript for Leilani and Morgan are shown in Table 12.
The researcher can envision, however, that the structure of this learning activity (having friends work together from the beginning on their own single designs without scripts) might not work for students who are quieter, or for pairs who do not have good rapport, or for students who are not equal in their technical or metacognitive skills. What if one student is a significantly stronger designer than the other? Would unequal pairs be able to interact as these girls do, questioning and challenging features and offering ample feedback? It is unknown, but one can imagine an unsure student trying to compete with an advanced one and becoming unmotivated or giving up.

The beauty of the *teacher-generated* metacognitive prompts is that students need only *read* them aloud. The personalities, rapport, designing skills, or interaction style of a pair are less of a factor in stimulating reflection and revision. Virtually every student responds and revises upon hearing the teacher-generated prompts from a peer. The downside is that teacher-generated prompts are more general (less design-specific), so they may not probe as deeply or generate “in-the-moment” or “just in time” feedback and critical thinking. In other words, when
a designer is struggling with a particular design element, a deep question or feedback from a partner about that design-specific element can help resolve or advance the struggle. With student-generated metacognitive prompts, as were observed in this case pair, redesign was done not as a separate activity, but “on the fly.” The metacognitive prompts came as needed and were highly salient to the designer.

Because this case pair did not have the usual initial and revised designs, the researcher decided to analyze how each design element was negotiated and redesigned. The results are presented in Tables 13 and 14. Note that some of the design elements (e.g., the tether, the buoy attractant, and the material for the caps) went through lengthy evolutions with up to nine design iterations.

Table 13.

*How design elements in Leilani’s design evolved.*

<table>
<thead>
<tr>
<th>Design Element</th>
<th>Evolution</th>
<th>How element evolved?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tether</td>
<td>string→pole→string→stick→wire→chain→light chain</td>
<td>Explanations, questions, feedback, affirmations</td>
</tr>
<tr>
<td>Tether lengths</td>
<td>3 feet→3 ½ feet</td>
<td>Explanations, Questions, Affirmation</td>
</tr>
<tr>
<td></td>
<td>6 feet→10 feet→9 ½ feet</td>
<td></td>
</tr>
<tr>
<td>Buoy weight</td>
<td>2 pounds</td>
<td>Explanation, questions, affirmation</td>
</tr>
<tr>
<td></td>
<td>3 ½ pounds</td>
<td></td>
</tr>
<tr>
<td></td>
<td>6 pounds→6 or 7 pounds→6 pounds</td>
<td></td>
</tr>
<tr>
<td>Buoy dimensions</td>
<td>3 feet→all about the same size</td>
<td>Explanation, question</td>
</tr>
<tr>
<td>Buoy attractant</td>
<td>nothing→live fish→dead fish→meat of fish→nothing→fish coat or fish spray→fish spray→coat of a bad-smelling substance→fish spray</td>
<td>Questions, explanations, feedback, affirmations</td>
</tr>
</tbody>
</table>
Table 14.

*How design elements in Morgan’s design evolved.*

<table>
<thead>
<tr>
<th>Design Element</th>
<th>Evolution</th>
<th>How element evolved?</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filling</td>
<td>live fish → dead fish</td>
<td>Question, explanations</td>
</tr>
<tr>
<td>Handles on capped ends</td>
<td>string → thick rope</td>
<td>Explanations question, affirmation</td>
</tr>
<tr>
<td>Material for tube body</td>
<td>“PC” pipe → PVC pipe</td>
<td>Computer inquiry (example of self-regulated learning)</td>
</tr>
<tr>
<td>Dimensions of the tube</td>
<td>2 feet → 3 feet, 3 feet → 5 feet</td>
<td>Explanations, question</td>
</tr>
<tr>
<td>Size of fish</td>
<td>Small fish (2 ounces)</td>
<td>Explanations, affirmation</td>
</tr>
<tr>
<td>Weight of the fish</td>
<td>6 pounds → 6 or 7 pounds</td>
<td>Explanations, question, feedback, affirmation</td>
</tr>
<tr>
<td>Amount of water to add to body</td>
<td>one-half foot → one-fourth gallon</td>
<td>Feedback, question, explanations, affirmation</td>
</tr>
<tr>
<td>Material for caps</td>
<td>rubber → hard plastic → metal → wood → Same material as plastic chairs in the room</td>
<td>Explanations, questions, feedback, affirmations</td>
</tr>
<tr>
<td>Cap attractant</td>
<td>little hole in caps so scent of fish inside the body tube will attract the dolphins → fish spray</td>
<td>Explanation, questions, feedback, affirmations</td>
</tr>
</tbody>
</table>
CHAPTER VI

CONCLUSIONS, LESSONS LEARNED, RECOMMENDATIONS FOR FUTURE STUDY, and SIGNIFICANCE

The final chapter is divided into four sections. In the first section, conclusions are presented for the research questions, research propositions, design change relationships, the metacognitive prompts used in the study, and a partially studied case. In the second section, pragmatic lessons learned from implementing the curriculum in a large, public, middle school classroom are detailed. In the third section, unknown and unexplored aspects of the findings are described to suggest recommendations for future study. Finally, the significance of the findings to adolescent educators and designers of curriculum and instruction are summarized.

Conclusions

The conclusions drawn from the study’s findings are presented below for the research questions and research propositions. Additionally, observations made about design change relationships, the metacognitive prompts used in the study, and a partially studied case are summarized.

Research Questions

A comparative case study was conducted to answer research questions about how alterations in adolescent designs occur in the context of peer-delivered metacognitive prompts:
1. How do metacognitive prompts delivered in a reciprocal and structured peer tutoring environment alter adolescent design briefs (the explicit task interpretation) of an engineering design problem?

2. How do metacognitive prompts delivered in a reciprocal and structured peer tutoring environment alter adolescent solution sketches (the design problem solution space) of an engineering design problem?

Based on the data gathered from the seven-pair, comparative case study, how design alterations occur depends upon the interaction pattern of the pair:

- **Guide and Aspirant Interaction Pattern.** For pairs in which there is a “guide,” a student with strong and evident metacognitive skills and an “aspirant,” an unsure but motivated-to-improve student, alterations are numerous for both students and come about through a combination of simple explanations, user-centered explanations, feedback, and guide-generated questions.

- **Supporters Interaction Pattern.** For pairs in which the students are well-matched (with similar levels of technical and metacognitive knowledge), and well-connected (displaying strong social, emotional, and cognitive support to their partners), alterations occur mostly through a combination of simple and user-centered explanations, and feedback.

- **Soloists Interaction Pattern.** For pairs in which the students are well-matched (with similar levels of technical and metacognitive knowledge), but not “well-connected” (showing no evidence of willingness to offer social, emotional, or cognitive support to their partners), alterations occur mostly through simple explanations, a few user-center explanations, and internal (unexpressed) reflection.
• **Olympian and Coach Interaction Pattern.** For pairs in which the students are not well-matched (with one student having greater technical knowledge than the other), but well-connected (displaying strong social, emotional, and cognitive support to their partners), alterations occur for the “Olympian” through a combination of simple and user-centered explanations, extensive feedback from the “Coach,” and Olympian and Coach-generated questions. Alterations are limited to discussions for the “Coach” and may not be explicitly evident in the revised design.

In addition to the verbal phenomena (of explanations, feedback, affirmations, and questions), for all interaction patterns except the Soloists, there is a *socio-emotional component* to the alterations. Guides, for example, may boast or direct all impromptu discussions, leaving Aspirants feeling frustrated or dissatisfied with their own designs. Or alternatively, Aspirants may feel bolstered and reassured by following the Guides’ leads. Supporters may heavily praise or affirm their partners, giving partners pride in their creations and reassuring them that their design is sound, or that their design change ideas are sound. Olympians may transmit tremendous energy and excitement about their own designs, leading Coaches to forego their own designs and invest heavy mental energy and enthusiasm into the Olympians’.

**Research Propositions**

The comparative case study also tested three research propositions that were developed in advance to predict the outcomes:

1. The designs created after the intervention had a greater number of criteria, or more refined criteria, than those written before the intervention.
2. The solution sketches made after the intervention were more detailed than those made before the intervention.

3. The solution sketches made after the intervention more explicitly identified the criteria than those made before the intervention.

The outcomes for the research propositions were mixed. The first research proposition was true for thirteen out of fourteen research participants. Only the Coach failed to explicitly implement more design criteria or more refined criteria in the final design (although he did discuss new criteria and refinement). Both the second and third research propositions (on increased detail and labeling) were simultaneously true for the Guide and Aspirant participants and for one of the Soloists. In addition, the second research proposition (on increased detail), but not the third (on increased labeling), was true for one of the Supporters. However, for eight of the fourteen research participants, neither the second nor the third research propositions were true.

Design Change Relationships

This section summarizes relationships that were observed between peer-to-peer verbal phenomena (feedback, explanations, the Expressiveness Index, the Stimulus Index, and questions) and the number of design changes. With the exception of the “Coach” participant, that there was a strong, positive relationship between the amount of feedback a participant received and the number of design changes he or she made. There were also positive relationships, with that same exception, between the Expressiveness and Stimulus Indices and the number of design changes participants made. For the simple and total explanations with the Coach outlier excluded, there was a weak, positive relationship between the frequency counts of
explanations and the number of design changes. There was no relationship observed between the frequency counts of questions asked and the number of design changes made by a participant.

**Metacognitive Prompts**

This section summarizes the metacognitive prompts that elicited the most design changes as the students worked in pairs. For both the explanation and feedback-provoking scripts, the “negative” metacognitive prompts (ones which asked about design weaknesses) were the most effective at inciting changes. However, “neutral” prompts (which asked about how the design worked or how the user would interact with the design without any value-laden words like “weakness” or “best”) were only slightly less effective than the negative prompts. “Positive” prompts (which asked about “best” parts of the design) were less effective than negative or neutral prompts, but enhanced student rapport by generating praise in most cases.

**Partially Studied Case**

Based on the findings of one accidental and partially studied case pair, metacognitive prompts may be invoked *naturally* if the learning activity is restructured. Whereas the comparative case study had students in a pair work first independently to develop an initial design, and then together with scripts for the redesign, the accidental case had students in a pair work together from the beginning on their own designs for the same user, without teacher-generated scripts for guidance on redesign. The restructuring of the learning activity offered five advantages:

1. Metacognitive prompts were invoked naturally (with no script).
2. The student-generated metacognitive prompts were more design-specific (less general) than the teacher-generated prompts.
3. The student-generated metacognitive prompts appeared to have greater “epistemic-probing” power than the teacher-generated prompts, and were used as a “heuristic tool” to engender logical arguments between the students (Chin & Osborne, 2010).

4. The student-generated prompts were more “timely” than the teacher-generated prompts because they were generated “in the moment” when a student was considering or struggling with a design element.

5. Pairs exhibited signs of co-construction and co-ownership of the designs (pronouns changed occasionally from I to we).

**Lessons Learned**

Implementing the intervention in a classroom environment over three class periods revealed pragmatic issues that were not evident during the single-day pilot study, as detailed below:

1. **Class size.** The case study was conducted in a 32-student (16-pair) classroom by a solo researcher. Because of space limitations in the classroom, the students were spread out into two adjoining rooms for the learning activity. The researcher believes that a lower student-to-teacher ratio (approximately ten pairs) would enable the instructor to give more attention to each pair, so that all individual questions or concerns about the design process could be answered.

2. **Time.** Some students were frustrated because they were not able to finish either their initial or revised designs in class. They voiced their dissatisfaction with not being finished and requested to take the designs home to work on them. The partnering teacher advised against this because her experience with seventh graders was that “…work that is
taken home does not always come back the next day.” For the comparative case study, all work was done inside the classroom during the three class periods, but the researcher believes that allowing students to have more time outside of class would help slower students not feel rushed and allow everyone to complete the designs to their full satisfaction.

3. **Learning activity instructions.** The researcher believes there is a need for a short video or demonstration of the process of the pairs presenting their designs to each other and reading and responding to the scripts. Although instructions were given to the class slowly and methodically, it quickly become obvious through the students’ questions that some of the students had not listened to, or did not fully comprehend, the instructions. The researcher believes that having the students observe the process, in conjunction with verbal instructions, would resolve the issue. An observation activity could be as simple as having two students come to the front of the class and have the teacher walk them through a quick, mock reading of the scripts. The researcher believes that receiving the instructions both visually and aurally would help all students understand the task, but especially those who are English language learners, those who are anxious, or those who do not process auditory instructions well. In addition, the researcher recommends that a Spanish-language version of the scripts be made available to those students who are Spanish-speaking, English language learners. One side of the script could be printed in English and the other side in Spanish, eliminating the need for extra papers.

4. **Partner selection.** The researcher observed that participant expressiveness and willingness to interact with a partner was greater when the student participants in a pair were friends rather than acquaintances or completely unfamiliar with each other.
Azmitia & Montgomery (1993) also concluded that scientific discussions between adolescent friends were enhanced beyond those of adolescent acquaintances with friends showing higher level dialogues like evaluations, critiques, justifications and transactive discussions. For the comparative case study, the researcher was forced by the limitations of informed consent and gender to pair students without knowing whether they were friends or even acquaintances. The researcher believes that a better approach would be to allow all students to choose their own partner, and in an odd-number classroom, have one group of three.

**Recommendations for Future Study**

While this comparative case study has shown that metacognitive prompts can incite adolescents to reflect and make design changes, it is unknown the degree to which the *messenger* (a student’s peer who delivers the prompts) is important. Would a computer “avatar” be just as effective as a peer? Would an adult teacher? Would reading a metacognitive prompt and writing or verbalizing the response work as well?

It is unknown as well the degree to which the *environment* in which the prompts are delivered is important. Pairs have been shown to work. Would small groups of three to five students be equally effective? Would a computer environment be successful? Or would the loss of the socio-emotional component reduce motivation to create, share, and change the designs? Does the effect of the environment depend on the student’s personality with some students more dynamic in a pair or small group, and others more successful in a computer environment? Does adding an “avatar” to the computer environment create a peer-like experience that is more motivating?
The data collected in this study suggests that there is a socio-emotional component to the peer-to-peer interactions that impacts design changes for all the interaction patterns except for those of the “Soloists.” Could a Soloist participant be incited to make even more changes if partnered with a friend or acquaintance who was willing to give feedback or praise? Or does that depend upon the student’s intrinsic personality? Would a Soloist student like Zoe or Terence become more dynamic with a supportive partner? Would a Soloist student like Lauren remain staunchly a soloist with all her changes internally derived, or coming from her own explanations? Along these same lines of thought, it is unknown if “optimal pairing” or “optimal partnering” can make any student a more dynamic designer.

What constitutes optimal partnering? Research suggests (Azmitia & Montgomery, 1993) that friendship is one component. This comparative case study suggests that partnering a student with strong metacognitive skills to an unsure student who is highly motivated to improve (i.e., the Guide and Aspirant pairs) can form a dynamic alliance that benefits both students. What other components make for an optimal design pair?

Is a pair’s interaction style stable? Or, will a pair become more dynamic over time if the same partners are paired together for multiple design challenges, thereby becoming accustomed to each other and the process of design? If the teacher-generated metacognitive prompts are withdrawn after multiple design challenges, will that cause students to generate their own prompts when given a new design challenge? Are the findings applicable to other educational problems besides design, like the large class of problems involving problem solving (Royer, 1986)?

Finally, while this study was developed to support adolescent designers, it is unknown whether it could also support designers with more mature metacognition as well, such as
undergraduate engineering students. Could metacognitive prompts help more mature designers avoid design fixation?

**Significance for Adolescent Educators**

Design is a challenging, creative endeavor. It is a difficult subject to teach because there is no simple algorithm that can encompass the open-endedness of design problems, which are often ill-defined and poorly structured. Nor can any simple algorithm handle the non-linear processes that arise during design, during which a designer must reiterate back to earlier stages. Designing requires considerable metacognitive skills to manipulate knowledge—skills which can be immature in adolescence (Casey et al., 2008; Choudhury et al., 2006; Choudhury et al., 2008; Lawanto et al., 2013a, 2013b; Petanjek et al., 2011; Wilson, Smith, & Householder, 2014).

This comparative case study has demonstrated a pragmatic learning activity for enhancing adolescent designs during their earliest phases through guided peer interactions with metacognitive prompts. Design revision is stimulated through verbal phenomena (explanations, feedback, questions, and affirmations), and through socio-emotional means. Which verbal phenomena contribute to revisions and the degree to which the socio-emotional component plays a role depends upon the interaction style of the peer pairs. Regardless of their interaction style, though, the learning activity helps adolescents avoid design fixation. Students are stimulated and motivated to alter their designs primarily by creating new criteria, or refining or eliminating existing criteria.

The metacognitive prompts used in this comparative case study can be adapted to fit any design challenge. Teachers or designers of curriculum and instruction need only first develop prompts that ask about the “user”—the one who will be using the design—and what the user’s
characteristics and needs are. Prompts can then be developed that ask about how the user will interact with the design, and why the students think their designs will meet the user’s needs. Finally, students can be prompted to evaluate a design’s strengths and weaknesses—their own and a partner’s.

An alternative to the metacognitive prompts (used in the comparative case study) is to set-up the learning activity as was done (by chance) in the last case of the Findings. Students can create their own designs for the same user while working in a pair without any scripts (teacher-generated metacognitive prompts). If the pairs are well-matched (technically and metacognitively), have an existing friendship, and are highly interactive, they may themselves generate metacognitive prompts for one another—prompts that are more design-specific (less general) than the teacher-generated prompts. Moreover, student-generated prompts may be delivered “in the moment,” when an adolescent designer is struggling with a design element. The caveat, though, is that this approach may not work for students who are introverted, or for pairs who are not well-matched.

The learning activity used in this study meets the Next Generation Science Standards (2013) for middle school students which requires sixth through eighth graders to be able to define a problem by specifying criteria and constraints (as was done in the design briefs), develop solutions (as was done in the sketches), and revise. The metacognitive prompts delivered by a peer to a partner during the learning activity create an environment in which revision is supported both metacognitively and socially. Revision is enabled.
REFERENCES


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learning interventions with elementary school students: a meta-analytic review.


APPENDICES
Appendix A

Permission Request Letter for Pilot Study and Approval Letter (School District)

TO: Dr. [redacted], Superintendent of the [redacted] School District

FROM: Kristin Strong, Graduate Student
Dept. of Engineering Education

DATE: May 26, 2015

RE: Request for permission to conduct research within the [redacted] School District

Dear Dr. Garrett:

I am a graduate student at [redacted] working with Dr. Oenardi Lawanto in the Dept. of Engineering Education. We are conducting a pilot study (in preparation for a larger study in the fall) to explore how peer tutoring at the secondary level invokes higher order thinking skills during a design activity.

In the pilot study, one pair of students interested in science, technology, engineering, or mathematics will work together in a peer tutoring session. The students will then redesign a project they have completed outside of school. It is anticipated that the peer tutoring session will take less than 1 hour. We would like to request permission to conduct this research at a secondary school within the [redacted] School District.

Please find attached a concise research proposal detailing the background, merit, goals, and procedures of this research as well as a review copy of the student/parent informed consent. I am happy to address any questions or concerns you may have.

Best regards,
Kristin Strong
June 8, 2015

To Whom It May Concern:

On behalf of the [Redacted] School District, I give consent for Kristin Strong to conduct a pilot study at [Redacted] Middle School and [Redacted] High School. The study will explore how peer tutoring at the secondary level invokes higher order thinking skills during a design activity. I have received a concise research proposal as well as a copy of the student/parent informed consent.

Please contact me if you have any questions, concerns, or require further documentation from me in regards to this consent.

Sincerely,

[Redacted]

Superintendent
Appendix B

Permission Request Letter for Pilot Study and Approval Letter (Middle School)

TO:                Dr. [Redacted] Principal of [Redacted] Middle School

FROM:         Kristin Strong, Graduate Student
             Dept. of Engineering Education
             [Redacted]

DATE:         May 18, 2015

RE:             Request for permission to conduct research at [Redacted] and use a conference room for one hour

Dear Dr. Monson:

I am a graduate student at [Redacted] working with Dr. Oenardi Lawanto in the Dept. of Engineering Education. We are conducting a pilot study (in preparation for a larger study in the fall) to explore how peer tutoring invokes higher order thinking skills during a design activity.

In the pilot study, one pair of students interested in science, technology, engineering, or mathematics will work together in a peer tutoring session. The students will then redesign a project they have completed outside of school. It is anticipated that the peer tutoring session will take less than 1 hour. We would like to request permission to conduct this research at [Redacted] and use a conference room for the peer tutoring session.

Please find attached a concise research proposal detailing the background, merit, goals, and procedures of this research as well as a review copy of the student/parent informed consent. I am happy to address any questions or concerns you may have.

Best regards,
Kristin Strong
May 28, 2015

RE: Kristen Strong, USU Graduate Student
    Research Study

To Whom It May Concern:

    I have had the chance to review the research proposal of Kristen Strong, working
    with Dr. Oenardi Lawanto in the Department of Engineering at [redacted].

    As I have read through the pilot study that is proposed with a pair of students from
    [redacted] Middle School, I feel the research would be of minimal risk to the students
    and their families. Therefore, I would offer the necessary support for the research to be
    conducted at [redacted] Middle School. Please let me know if I can provide further
    assurances from my end.

Sincerely,

Dr. [redacted]
Principal
[redacted] Middle School
Appendix C

Institutional Review Board Letter of Approval for Pilot Study

Institutional Review Board
USU Assurance: FWA#00003308

Expedite #6 & #7

Letter of Approval

FROM:
Melanie Domenech Rodriguez, IRB Chair
Nicole Vouvalis, IRB Administrator

To: Oenardi Lawanto, Kristin Strong
Date: June 18, 2015
Protocol #: 6637
Title: A Pilot Study To Assess Protocol And Data Analysis For A Multiple Case Study Of Design In Secondary Education
Risk: Minimal risk

Your proposal has been reviewed by the Institutional Review Board and is approved under expedite procedure #6 & #7 (based on the Department of Health and Human Services (DHHS) regulations for the protection of human research subjects, 45 CFR Part 46, as amended to include provisions of the Federal Policy for the Protection of Human Subjects, November 9, 1998):

#6: Collection of data from voice, video, digital, or image recordings made for research purposes.
#7: Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies.

This approval applies only to the proposal currently on file for the period of one year. If your study extends beyond this approval period, you must contact this office to request an annual review of this research. Any change affecting human subjects must be approved by the Board prior to implementation. Injuries or any unanticipated problems involving risk to subjects or to others must be reported immediately to the Chair of the Institutional Review Board.

Prior to involving human subjects, properly executed informed consent must be obtained from each subject or from an authorized representative, and documentation of informed consent must be kept on file for at least three years after the project ends. Each subject must be furnished with a copy of the informed consent document for their personal records.
Appendix D

Letter of Informed Consent for Pilot Study

INTRODUCED CONSENT
A Pilot Study to Assess Protocol and Data Analysis for a Multiple Case Study of Design in Secondary Education

*Introduction/Purpose: Dr. Oenardi Lawanto in the Department of Engineering Education at Utah State University is conducting a research study to find out how peer tutoring affects higher thinking skills in design problems. Your student has been asked to take part because he/she is of an appropriate grade level for this research and has shown an interest in science, technology, engineering, or mathematics. There will be 2 participants at this school. There will be 2 total participants in this research. Kristin Strong will be the graduate student collecting the data for this research.

*Funding: This is not an externally funded study.

*Procedures: If you agree to allow your student to participate in this research study, he or she will be asked to complete some activities first at home: (1) take a survey of interests; (2) read a short presentation on design; (3) take a survey about understanding of design (4) watch two short videos about making the lives of zoo animals more interesting; (5) research the play habits of a favorite animal; and (6) complete a design (with guidance). These activities are expected to take about 60 min.

Your student will then be asked to attend an after-school session at his or her school that will last approximately 60 minutes. During the session, your student will work with another student. (Your student can choose a friend, if desired, or can be assigned a partner to work with.) With guidance, each student in a pair will present his or her design to the other student in a pair. Presentations will be recorded (audio only). Students will then be asked to revise their designs after peer feedback.

*Risks: There is a small risk of loss of confidentiality, yet we will take the following steps to reduce this risk: (1) no names of participants will be used (a pseudonym will be created for your student and used in research reports); (2) the location (city, state, and school) of the study will not be revealed, nor any information that could lead to the specific identity of the participants; (3) through the use of an identification key (number), the researcher will be able to link data collected to the student’s identity; (4) only the student researcher will have access to the identification key; and (5) all audio transcripts will be password protected and kept on a Box.com account at Utah State University for security and protection of confidential data.

*Benefits: This research is not designed to help your student specifically, although he or she may gain an understanding of the engineering design process through participation. We hope that the research results will help investigators better understand how to teach design at the middle school and high school levels; it may therefore benefit future students.

Explanation & offer to answer questions. Kristin Strong has explained this research study to you and answered your questions. If you have other questions or research-related problems, you may reach (PI) Dr. Oenardi Lawanto at (435) 797-8699 or olawanto@usu.edu.

V7 06/15/2011
INFORMED CONSENT
A Pilot Study to Assess Protocol and Data Analysis
for a Multiple Case Study of Design in Secondary Education

*Payment/Compensation: Your student will be paid $20 for participation in this study. The Internal Revenue Service (IRS) has determined that if the amount your student gets from this study, plus any prior amounts your student received from participating in research studies at USU since January of this year, total $600 or more, USU must report this income to the federal government.

*Voluntary nature of participation and right to withdraw without consequence: Participation in research is entirely voluntary. You may refuse to participate or withdraw at any time without consequence or loss of benefits. If you decide to withdraw from the study at any time, please contact Kristin Strong, student researcher at [redacted]. You may be withdrawn from this study without your consent by the investigator if your student is unable to complete the home activities or participate in the after-school session.

*Confidentiality: Research records will be kept confidential, consistent with federal and state regulations. Only the investigator, Oenardi Lavanto, and student researcher, Kristin Strong, will have access to the data which will be kept on a password protected computer in a locked room. To protect your privacy, personal, identifiable information will be removed from study documents and replaced with a study identifier. Identifying information will be stored separately from data and will be destroyed as soon as data analysis is concluded (within one year). Digital audio recordings will be destroyed once transcription is complete.

Because your student will be interacting with a peer in this study, we will ask that students maintain the confidentiality of any information they may learn about others in this research study.

*IRB Approval Statement The Institutional Review Board for the protection of human participants at Utah State University has approved this research study. If you have any questions or concerns about your rights or a research-related injury and would like to contact someone other than the research team, you may contact the IRB Administrator at (435) 797-0567 or email irb@usu.edu to obtain information or to offer input.

*Copy of consent You have been given two copies of this Informed Consent. Please sign both copies and keep one copy for your files.

*Investigator Statement “I certify that the research study has been explained to the individual, by me or my research staff, and that the individual understands the nature and purpose, the possible risks and
INFORMED CONSENT
A Pilot Study to Assess Protocol and Data Analysis
for a Multiple Case Study of Design in Secondary Education

benefits associated with taking part in this research study. Any questions that have been raised have been answered.

*Signature of Researcher(s)*

Oenardi Lawanto, PhD
Principal Investigator
(435-797-8699)
(olawanto@usu.edu)

Kristin Strong
Student Researcher

Signature of Parent or Guardian: By signing below, I agree to allow my student to participate.

______________________________  ______________________________
Parent/Guardian’s signature       Date

Child/Youth Assent: I understand that my parent(s) or guardian(s) are aware of this research study and that they have given permission for me to participate. I understand that it is up to me to participate even if they say yes. If I do not want to be in this study, I do not have to and no one will be upset if I don’t want to participate or if I change my mind later and want to stop. I can ask any questions that I have about this study now or later. By signing below, I agree to participate.

______________________________  ______________________________
Student Name/Signature           Date
Appendix E

Student Interest Survey

Student Interests

1. What is your favorite class or activity in school and why?

2. What is your least favorite class or activity in school and why?

3. What careers can you picture yourself in?

4. Do you prefer to work alone, in small groups, or in large groups? Why?

5. Describe yourself using 3 words

6. If you could learn more about any subject, what would it be? Why are you curious about this subject?

7. Do you have a special talent or interest that you know a lot about? If so, what is it?

8. Tell me about a past accomplishment that made you feel proud of yourself.
Appendix F

Design Brief Curriculum

What is a Design Brief?

A design is a PLAN to make something, like a new...

- Video game
- Apple peeler
- Two dog leash
- Cat brush
**Brief** means the design plan is short.
(Usually just one page.)

What are the **PARTS** of a design brief?

1. Goal
2. Criteria
3. Constraints
The **GOAL** is what you are trying to design or make. For example:

My Design Brief

2. Criteria
3. Constraints

![Sketch of a dog feeder]

The **CRITERIA** are the special features or characteristics of what you are trying to make. For example:

My Design Brief

2. Criteria:
   - 20 inches (50 cm) high
   - Can see through it
   - Releases 1 cup of food each time you turn the wheel
   - Easy to fill with dog food
   - Handle to carry
   - Won't tip over easily
   - Washable
3. Constraints

![Additional details on the sketch]
The **CONSTRAINTS** are the limitations—the things that stop you from making anything you want. For example:

---

**My Design Brief**

1. **Goal:** Make a dog feeder.

2. **Criteria:**
   - 20 inches (50 cm) high
   - Can see through it
   - Releases 1 cup of food each time you turn wheel
   - Easy to fill with dog food
   - Handle to carry
   - Won’t tip over easily
   - Washable

3. **Constraints:**
   - Not too expensive (less than $20)
   - Made out of a material that is safe for storing food.

---

**What will you design today?**
Appendix G

Design Brief Survey

1. What do you think design briefs are used for?

2. What are the 3 parts of a design brief? What is each part used for?
Appendix H

Design Challenge and Advance Organizer

Design Challenge: Design an Animal Enrichment Toy!

Introduction

What helps keep an animal healthy? Just like people, animals need the right food, clean water, grooming, rest, and exercise. The exercise is best when it uses the animal's natural skills and instincts like climbing, swimming, hunting, fetching, or digging, because exercise in this form conditions the animal's brain, as well as its body.

Figure 1. These photos show animals at play using their natural instincts, like pouncing and fetching.

Animals kept in zoos have special challenges staying healthy, even if their environments are kept as close to their natural habitat as possible. Many zoo animals don't have to work for their food since it is given to them by the zoo-keepers. Without the challenges of finding food, guarding territory, or avoiding predators, some zoo animals may become bored and even depressed. Zoos try to combat this boredom with enrichment toys. Enrichment means making something richer, fuller, or more interesting. The goal of an enrichment toy is to provide a stimulating activity that exercises both the brain and the body of the animal.
How to Design an Animal Enrichment Toy

1. **Choose an animal.** You can choose a favorite house pet or a zoo animal.

2. **Find out about your animal’s senses.** You can use the internet for research or a book. Does your animal have a good sense of vision? Hearing? Smell? If hearing is good, what frequencies (pitches) are best? High, squeaky pitches or low, rumbling ones? If the sense of smell is sharp, what kinds of odors get your animal very excited? Your toy should appeal to one or more of your animal’s strongest senses.

3. **Find out about your animal’s natural skills and activities.** For example, when your animal is awake, what is he or she doing? Running, digging, kneading, nesting, jumping, swimming, sniffing, climbing, marking, pouncing, vocalizing (making noises), or hiding? How can your toy encourage those activities?

4. **Think about safety.** You certainly don't want a toy to hurt an animal, so when you design a toy, you must think about what would happen if the toy broke, or if an animal ate a piece of it. Toys must always be designed from **non-toxic** (safe or not poisonous) materials.

5. **Write a design brief** on the attached page called **My Design Brief**.

6. **Sketch (draw) your design** on a fresh, blank sheet of paper. Don’t worry about making it perfect—it’s a sketch!
Appendix H (continued)

Design Challenge and Advance Organizer

Information about My Animal

<table>
<thead>
<tr>
<th>Animal I chose:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>What does my animal like to eat?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>What are my animal’s strongest senses (vision, hearing, smell, touch, etc.)?</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>What are my animal’s natural skills (running, digging, jumping, swimming, hunting, hiding, making noises, climbing, etc.)?</th>
</tr>
</thead>
</table>
Appendix I

Design Brief Template

My Design Brief

1. Goal (what you are planning to make):

2. Criteria (special features or characteristics you want in your design):

3. Constraints (limitations, things that hold you back from designing anything you want):
Appendix J

Tutoring Scripts for Pilot Study Containing Metacognitive Prompts for Explanations

Questions You Can Ask Your Partner

1. What animal did you choose?

2. How does your animal play or hunt?

3. What senses does your animal use when it plays or hunts?

4. How does your design work?

5. Why do you think your design will make the animal playful?

6. What do you think is the best part of your design?

7. What do you think is the weakest part of your design?
Appendix J (continued)

Tutoring Scripts for Pilot Study Containing Metacognitive Prompts for Feedback

Questions You Can Ask Your Partner

1. What do you like the best about my design?

2. Is there any part of my design that you think could be improved? If so, how would you change it?
1. Ask your partner: “What animal did you choose?”

2. Ask your partner: “How does your animal play or hunt?”

3. Ask your partner: “What senses does your animal use to play or hunt?”

4. Ask your partner: “How does your design work?”

5. Ask your partner: “Why do you think your design will make the animal playful?”

6. Ask your partner: “What do you think is the best part of your design?”

7. Ask your partner: “What do you think is the weakest part of your design?”
Appendix K (continued)

Revised Tutoring Scripts for Comparative Case Study
Containing Metacognitive Prompts for Feedback

1. Ask your partner: “What do you like the best about my design?”

2. Ask your partner: “Is there any part of my design that you think could be improved? If so, how would you change it?”

When your partner is done answering these questions, exchange papers and start over:

- Give this orange paper to your partner.
- Take the blue paper from your partner.
- Start again with the blue paper first.
- Have your partner read the orange paper second.
- You and your partner can then redesign your design brief and sketch on fresh sheets of paper.
Appendix L

Letters of Approval (School and District)

August 9, 2017

ATTENTION: Institutional Review Board
Utah State University
8200 Old Main Hill
Logan, UT 84321-8200

Re: Ms. Kristin Strong’s 7th Grade STEM Research Proposal
“How Middle School Students Can Be Supported in Design by Working in Pairs”

Dear IRB Members:

I have read over Kristin Strong’s research proposal on how middle school students can be supported in design by working in pairs to be carried out at [redacted] Middle School. I understand that Ms. Strong is conducting her research as part of her university requirements and will have the opportunity to present her findings in other venues.

I understand that the Utah State Institutional Review Board is concerned with protecting the confidentiality, privacy, and well-being of research participants. Ms. Strong will be working closely with our 7th grade Career and Technical Education (CTE) faculty as she works with our 7th grade students.

After reviewing Ms. Strong’s proposal, I do not have any concerns regarding this project. As Principal of [redacted] Middle School, I support and approve this research project including recruitment of participants and data collection.

Should you have additional questions or concerns, you may contact me via email [redacted]

Sincerely,

[Redacted]
Principal
Middle School
Dear Ms. Strong:

It is my understanding that you would like to conduct your study entitled “Supporting Adolescent Metacognition in Engineering Design Through Scripted Prompts from Peer Tutors: A Comparative Case Study” with students at Mount Logan Middle School in Logan City School District. We support this effort and understand that parental/student consent forms will be secured by your research team before the study begins.

There has been a change in responsibilities at Logan City School District. Jed Grunig, Director of Elementary Schools, and Melissa Richardson, Director of Secondary Schools will now be responsible for approving these studies. If you have any questions, please do not hesitate to contact them at ed.Grunig@loganschools.org or Melisa.richardson@loganschools.org. You may also contact either of them at the phone number listed above.

Sincerely,

David Long
Education, Technical, and Student Services Director
Appendix M
Informed Consent for Comparative Case Study

Supporting Adolescent Metacognition in Engineering Design
Through Scripted Prompts from Peer Tutors: A Comparative Case Study

Introduction
Your student is invited to participate in a research study conducted by Dr. Denardi Lawanto, a professor in the Department of Engineering Education at Utah State University, and Kristin Strong, a student researcher at Utah State University. The purpose of this research is to find out if the designs of middle school students can be improved by working in pairs.

This form includes detailed information on the research to help you decide whether to participate in this study. Please read it carefully and ask any questions you have before you agree to participate.

Procedures
If you agree to allow your student to participate in this research study, he or she will be asked to: (1) take a survey of school interests; (2) participate in a design brief lesson; (3) watch two short videos about animal enrichment in zoos; (4) research the diet and play skills of a favorite animal; (5) read a design challenge; (6) write a one-page design brief and draw a sketch (with guidance); (7) ask and answer questions about the designs (with guidance) while working in a pair; and (8) redesign the design brief and sketch.

Student pair interactions will be recorded (audio only). These activities are expected to take about two hours over a three-day period. We anticipate that 20 students will participate in this research study at your school.

Risks
This is a minimal risk research study. That means that the risks of participating are no more likely or serious than those you encounter in everyday activities. The foreseeable risk includes a small risk of loss of confidentiality. In order to minimize this risk, the researchers (1) will not use the names of participants; (2) will not reveal the location (city, state, and school) of the study, nor any information that could lead to identifying the participant; (3) will use an identification key (number) to link data collected to the student's identity; (4) will allow only the student researcher and Dr. Lawanto to have access to the identification key; and (5) will keep all digital data on a Box.com account at Utah State University for security and protection of confidential data.

Benefits
Participation in this study may directly benefit your student by helping him or her to learn about engineering careers and understand the engineering design process. More broadly, this study will help the researchers learn more about how to teach design at the middle-school level, and may help future adolescent students.

Confidentiality
The researchers will make every effort to ensure that the information your student provides as part of this study remains confidential. Your student's identity will not be revealed in any publications, presentations, or reports resulting from this research study. While we will ask all students in the class to keep the information they hear from others confidential, we cannot guarantee that everyone will do so.

We will collect your student's data through digital audio recordings and digital photographs of his or her design and survey. This data will be securely stored in a restricted-access folder on Box.com, an encrypted, cloud-based storage system. To protect your student's privacy, personal identifiable information will be removed from data and replaced with an identifier. Identifiers will be stored separately from the data and destroyed as soon as data analysis is concluded (within one year). Digital audio recordings will be destroyed once transcription is complete.
(within two to three months). This informed consent form will be kept for three years after the study is complete, and then it will be destroyed.

It is unlikely, but possible, that others (Utah State University, or state or federal officials) may require us to share your student’s data from the study to ensure that the research was conducted safely and appropriately. We will only share your information if law or policy requires us to do so. If the researchers learn that your student is going to engage in self-harm, or intends to harm another, state law requires that the researchers report these intentions to the authorities.

Voluntary Participation & Withdrawal
Your student’s participation in this research is completely voluntary. If you agree to allow your student to participate now and change your mind later, you may withdraw at any time by contacting Kristin Strong, student researcher, at [redacted].

If you choose to withdraw after we have already collected data about your student, we will destroy your student’s data and not use it for the study. The researchers may choose to terminate your student’s participation in this research study if he or she is unable to participate in all three class periods. The researcher or teacher will verbally inform the student of his or her withdrawal from the study.

Payment
For your student’s participation in this research study, he or she will receive $10. Payment will occur even if his or her participation in the study is incomplete.

IRB Review
The Institutional Review Board (IRB) for the protection of human research participants at Utah State University has reviewed and approved this study. If you have questions about the research study itself, please contact the Principal Investigator at (435) 797-8699 or oenardi.lawanto@usu.edu. For questions in Spanish, please contact the translator, Mr. Jorge Acosta-Feliz, at [redacted]. If you have questions about your rights or would simply like to speak with someone other than the research team about questions or concerns, please contact the IRB Director at (435) 797-0567 or irb@usu.edu.

Oenardi Lawanto, PhD
Principal Investigator
(435) 797-8699; olawanto@usu.edu

Kristin M. Strong
Student Investigator

Informed Consent
By signing below, you agree to allow your student to participate in this study. You indicate that you understand the risks and benefits of participation, and that you know what your student will be asked to do. You also agree that you have asked any questions you might have, and are clear on how to stop your participation in the study if you choose to do so. Please be sure to retain a copy of this form for your records.

__________________________  ___________________________  ____________________
Parent/Guardian’s Signature  Student Participant’s Name, Printed  Date

Engineering Education Dept.  |  (435) 797-2758  |  4160 Old Main Hill  |  Logan, UT 84322
Youth As sent
We are doing a research study about how to teach design in middle school. Research studies help us learn more about people. If you would like to be a part of this research study, we will ask you a few questions about your school interests and you will learn how engineers make designs. You will then learn how people make toys for animals in zoos. Next we will ask you to choose a favorite animal—like a pet, or an animal in a zoo—and design a toy for that animal. Then you'll work with a partner in class and share your designs with each other. Finally, you'll redesign your toy. We will take photographs of your designs, and when you work with your partner, we will audio record your conversations. These activities will take about three class periods (about two hours).

Before you agree to do these things, we need to tell you a little more. First, when the researchers take pictures of your designs and record your conversations, there is a small risk that your identity could be revealed. But we will take steps to avoid this by removing your name from your work and replacing it with a number. Also, while we will tell other people about what we learned from doing this study with you and the 19 other students who are in the study, we won't tell anyone your name, your school's name, or that you were in the study.

If you are in this study, there are also some things that you may like, such as learning about engineering careers, the engineering design process, and how to care for animals. You will receive $10 payment for participating in this study.

If this sounds like something you would like to do, we will ask you to say that you understand what we talked about, and that you do want to participate. You do not have to be in this study if you do not want to be. If you decide to stop after we begin learning about designs and designing toys for animals, that's okay, too. No one will be upset if you don't want to do this, or change your mind later.

You can ask any questions you have, now or later. Your parents know about this research study, and they have said you can participate, if you want.

If you would like to be in this study, please sign your name and write the date.

_________________________________________  ________________________________
Student's Name                                Date
Tutoría de pares con preguntas guiadas para apoyar la metacognición de los adolescentes en el diseño de ingeniería: un estudio de caso comparativo

Introducción

Su estudiante es invitado a participar en un estudio de investigación realizado por la Dra. Celene Camacho, profesor del Departamento de Educación en Ingeniería de la Universidad Estatal de Utah, y Krishie Strong, investigadora estudiantil en la Universidad Estatal de Utah. El propósito de este estudio es aminorar si los diseños de los estudiantes de secundaria se pueden mejorar trabajando en parejas.

Este formulario incluye información detallada sobre la investigación para ayudarlo a decidir si participar en este estudio. Por favor, lea cuidadosamente y haga cualquier pregunta que tenga antes de aceptar su participación.

Procedimientos

Si usted acepta permitir que su estudiante participe en este estudio de investigación, se le pedirá que: (1) tome una encuesta de los intereses de la escuela; (2) participar en una lección breve de diseño; (3) ver dos vídeos cortos sobre enriquecimiento de animales en zoológicos; (4) investigar la dieta y hábitos de juego de un animal favorito; (5) leer un diseño de diseño; (6) escribir un resumen de diseño de una página y dibujar un bosquejo (con guía); (7) preguntar y responder preguntas sobre los diseños (con guía) mientras trabaja en un par; y (8) rediseñar el diseño y el bosquejo.

Las interacciones del par de estudiantes se grabarán (sólo audio). Se espera que estas actividades tomen alrededor de dos horas durante un período de tres días. Proveemos que 20 estudiantes participarán en este estudio de investigación en su escuela.

Riesgos

Este es un estudio de investigación de riesgo mínimo. Esto significa que los riesgos de participar no son más probables o serios que los que se encuentran en las actividades cotidianas. El riesgo previsible incluye un pequeño riesgo de pérdida de confidencialidad. Con el fin de minimizar este riesgo, los investigadores (1) no utilizarán los nombres de los participantes; (2) no revelarán la ubicación (ciudad, estado y escuela) del estudiante; (3) no utilizarán la clave de identificación (numerosas) para vincular los datos recopilados con el identidad del estudiante; (4) permitirá que el estudiante investigador y el Dr. Camacho tengan acceso a la clave de identificación; y (5) mantendrán todos los datos digitales en una cuenta de Box.com en la Universidad Estatal de Utah para la seguridad y protección de datos confidenciales.

Beneficios

La participación en este estudio puede beneficiar directamente a su estudiante ayudándolo a aprender sobre las carreras de ingeniería y entender el proceso de diseño de ingeniería. Más ampliamente, este estudio ayudará a los estudiantes a aprender más acerca de cómo ensayar el diseño en el nivel de la escuela intermedia, y puede ayudar a futuros estudiantes adolescentes.

Confidencialidad

Los investigadores harán todo lo posible para asegurar que la información que su estudiante proporciona como parte de este estudio permanezca confidencial. La identidad de su estudiante no será revelada en ninguna publicación, presentación o informe resultante de este estudio de investigación. Si bien pediremos a todos los
estudiantes de la clase que mantengan confidencial la información que escuchan de los demás, no podemos garantizar que todos lo hagan.

Recogeremos los datos de su estudiante a través de grabaciones de audio digital y fotografías digitales de su diseño y encuesta. Estos datos se almacenarán de forma segura en una carpeta de acceso restringido en Box.com, un sistema de almacenamiento encriptado basado en la nube. Para proteger la privacidad de su estudiante, la información personal identificable será eliminada de los datos y reemplazada con un identificador. Los identificadores se almacenarán por separado de los datos y se destruirán tan pronto como se concluya el análisis de los datos (dentro de un año). Las grabaciones de audio digital se destruirán una vez que la transcripción esté completa (dentro de dos a tres meses). Este formulario de consentimiento informado se mantendrá durante tres años después de que el estudio esté completo y luego será destruido.

Es poco probable, pero posible, que otros (Utah State University, o funcionarios estatales o federales) puedan requerir que compartamos los datos de su estudiante del estudio para asegurar que la investigación se llevó a cabo de manera segura y apropiada. Solo compartiremos su información si la ley o la política nos obliga a hacerlo. Si los investigadores aprenden que su estudiante va a comprometerse en uno mismo-daño, o piensa dañar otro, la ley estatal requiere que los investigadores divulguen estas intenciones a las autoridades.

Participación voluntaria y retirada
La participación de su estudiante en esta investigación es completamente voluntaria. Si está de acuerdo en permitir que su estudiante participe ahora y cambie de opinión más tarde, puede retirarse en cualquier momento poniéndose en contacto con Kristin Strong, investigadora al.

Si decide retirarse después de haber recopilado datos sobre su estudiante, destruiremos los datos de su estudiante y no los usaremos para el estudio. Los investigadores pueden optar por terminar la participación de su estudiante en este estudio de investigación si él o ella es incapaz de participar en los tres periodos de clase. El investigador o maestro informará verbalmente al estudiante de su retiro del estudio.

Pago
Para la participación de su estudiante en este estudio de investigación, él o ella recibirá $10. El pago ocurrirá incluso si su participación en el estudio es incompleta.

Revisión del IRB
La Junta de Revisión Institucional (IRB) para la protección de los participantes humanos de la investigación en la Universidad Estatal de Utah ha revisado y aprobado este estudio. Si tiene preguntas sobre el propio estudio de investigación, comuníquese con el investigador principal al (435) 797-8699 o oenardi.lawanto@usu.edu. Si tiene preguntas en español, comuníquese con el traductor, el Sr. Jorge Acosta-Feliz, al.

Si tiene preguntas sobre sus derechos o simplemente desea hablar con alguien que no sea el equipo de investigación sobre preguntas o preocupaciones, comuníquese con el Director del IRB al (435) 797-0567 o irb@usu.edu.

Oenardi Lawanto, PhD
Investigador principal
(435) 797-8699; olawanto@usu.edu

Kristin M. Strong
Investigadora Estudiantil
Consentimiento informado

Al firmar a continuación, usted acepta permitir que su estudiante participe en este estudio. Usted indica que entiende los riesgos y beneficios de la participación y que sabe lo que se le pedirá a su estudiante. Usted también está de acuerdo en que ha hecho cualquier pregunta que pueda tener y tiene claro cómo obtener su participación en el estudio si decide hacerlo. Por favor asegúrese de conservar una copia de este formulario para sus registros.

Firma del padre o de la madre o tutor legal: __________________________
Nombre del Participante en la Investigación (en letra de imprenta): __________________________
Fecha: __________________________

Asentimiento de los jóvenes

Estamos haciendo un estudio de investigación sobre cómo enseñar el diseño en la escuela secundaria. Los estudios de investigación nos ayudan a aprender más acerca de las personas. Si desea ser parte de este estudio de investigación, le haremos algunas preguntas sobre sus intereses escolares y aprenderá cómo hacen los ingenieros los diseños. A continuación, aprenderá cómo el gato juega a los animales en los zoológicos. A continuación, pediremos que elija un animal favorito como una mascota o un animal en un zoológico y diseñe un juguete para ese animal. Luego trabajará con un compañero en clase y compartirá sus diseños entre sí.

Finalmente, usted recibirá un juguete. Tomaremos fotografías de sus diseños, y cuando trabaje con su pareja, grabaremos sus conversaciones. Estas actividades tomarán alrededor de tres períodos de clase (aproximadamente dos horas)

Antes de que aceptes hacer estas cosas, necesitamos discutir un poco más. En primer lugar, cuando los investigadores toman fotografías de sus diseños y graban sus conversaciones, hay un pequeño riesgo de que su identidad pueda ser revelada. Pero tomaremos medidas para evitar esto, eliminando su nombre de su trabajo y reemplazándolo con un número. Ademá, mientras le diremos a otras personas sobre lo que aprendimos al hacer este estudio con usted y con los otros 13 estudiantes que están en el estudio, no le diremos a nadie su nombre, el nombre de su escuela o qué estudió en el estudio.

Si usted está en este estudio, también hay algunas cosas que le pueden gustar, como aprender sobre carreras de ingeniería, el proceso de diseño de ingeniería y cómo cuidar a los animales. Usted recibirá un pago de $10 por participar en este estudio.

Si esto suena como algo que le gustaría hacer, le pediremos que diga que entiendo lo que hablamos y que quiere participar. No tienes que estar en este estudio si no quieres estarlo. Si deciden detenerse después de que comenzamos a aprender sobre los diseños y el diseño de juguetes para los animales, también está bien. Nadie se molestará si no quiere hacer esto, o cambiar de opinión más tarde.

Puede hacer cualquier pregunta que tenga, ahora o después. Sus padres saben sobre este estudio de investigación, y han dicho que usted puede participar, si lo desea.

Si desea participar en este estudio, firmé su nombre y escriba la fecha.

________________________
El nombre del estudiante

________________________
Fecha
Appendix N

Institutional Review Board Letter of Approval for Comparative Case Study

Institutional Review Board
Utah State University
Office of Research and Graduate Studies

Expedite #6 & #7
Letter of Approval

FROM:
Melanie Domenich Rodriguez, IRB Chair
Nicole Vouvalis, IRB Administrator

To: Denardi Lawanto, Kristin Strong
Date: November 02, 2017
Protocol #: 8675
Title: Supporting Adolescent Metacognition In Engineering Design Through Scripted Prompts From Peer Tutors: A Comparative Case Study
Risk: Minimal risk

Your proposal has been reviewed by the Institutional Review Board and is approved under expedite procedure #6 & #7 (based on the Department of Health and Human Services (DHHS) regulations for the protection of human research subjects, 45 CFR Part 46, as amended to include provisions of the Federal Policy for the Protection of Human Subjects, November 9, 1988):

#6: Collection of data from voice, video, digital, or image recordings made for research purposes.
#7: Research on individual or group characteristics or behavior (including, but not limited to, research on perception, cognition, motivation, identity, language, communication, cultural beliefs or practices, and social behavior) or research employing survey, interview, oral history, focus group, program evaluation, human factors evaluation, or quality assurance methodologies.

This approval applies only to the proposal currently on file for the period of one year. If your study extends beyond this approval period, you must contact this office to request an annual review of this research. Any change affecting human subjects must be approved by the Board prior to implementation. Injuries or any unanticipated problems involving risk to subjects or to others must be reported immediately to the Chair of the Institutional Review Board.

Prior to involving human subjects, properly executed informed consent must be obtained from each subject or from an authorized representative, and documentation of informed consent must be kept on file for at least three years after the project ends. Each subject must be furnished with a copy of the informed consent document for their personal records.
CURRICULUM VITAE

Kristin M. Strong
kristin.strong@aggiemail.usu.edu

Education
- 2018 PhD  Engineering Education, Utah State University, Logan, UT
- 1993 MS  Bioengineering, University of Utah, Salt Lake City, UT
- 1986 BS  Electrical Engineering, magna cum laude, Utah State University, Logan, UT

Professional Experience
- 2016 Research Assistant, Utah State University, Teacher Education and Leadership
  - Curriculum development for middle and high school engineering and technology education
  - Qualitative analysis of engineering ethics research at the high school level
  - Outreach for USU’s Science and Engineering Day, grades 4-8
- 2008-2010 Staff Scientist for non-profit organization, Science Buddies, SF Bay Area
  - Web content development of science fair project ideas for students, grades K-12 (approximately 75 online publications)
  - Content development of science and engineering career profiles (approximately 50 online publications) intended to motivate young adults to pursue STEM careers
  - Embedded real-time programming
  - Control system analysis
  - Hardware-in-the-loop simulation
  - Software verification and validation
  - Six degree-of-freedom simulation and modeling
- 1990-1993 Research Asst., Univ. Hospital, Dept. of Anesthesiology, Salt Lake City, UT
  - Neural network detection and quantification of venous air embolism using Doppler ultrasound (1 publication)
  - Digital signal processing
  - Algorithm development
  - Presentations to colleagues and physicians
- 1987-1990 Research Engineer, Lockheed Missiles and Space Co., Sunnyvale, CA
  - Control of flexible structures research and algorithm development (3 publications)
  - Presentations to management
  - Proposal writing
  - User service manual development
Computer Languages, Operating Systems, and Software Experience

- C, FORTRAN, BASIC, PASCAL, HTML/CSS
- UNIX, VxWorks (real-time operating system)
- MATLAB, Excel, Word, PowerPoint, SPSS, Canvas Learning Management System

Publications


Recent Volunteer Activities

2016 Outreach for USU’s Science and Engineering Day, grades 4-8
2012 Tutor for graduate students taking statistics
2011 Judge for regional VEX robotics student competition at Utah State University.

Awards

2010 Utah State University Presidential Fellowship
1990 Becton-Dickinson Fellowship