CROSS CASE STUDY OF AN ELEMENTARY ENGINEERING TASK

A Dissertation Presented

by

JOHN HEFFERNAN

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
of the requirements for the degree of

DOCTOR OF PHILOSOPHY

May 2017

College of Education

Mathematics, Science, and Learning Technologies

CROSS CASE STUDY OF AN ELEMENTARY ENGINEERING TASK

A Dissertation Presented

by

JOHN HEFFERNAN

Approved as to style and content by:

____
Florence Sullivan, Chair

____
W. Richards Adrion, Member

____
Darrell Earnest, Member

____

Joseph B. Berger, Senior Associate Dean
College of Education

ABSTRACT

CROSS CASE STUDY OF AN ELEMENTARY ENGINEERING TASK

MAY 2017

JOHN HEFFERNAN, B.S.E.E., TUFTS UNIVERSITY

M.S.E.E., TUFTS UNIVERSITY

M.Ed., LESLEY UNIVERSITY

Ed.S., UNIVERSITY OF MASSACHUSETTS AMHERST

Ph.D., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Professor Florence Sullivan

Designerly play has been identified as a fundamental component of childhood learning (Baynes, 1994; Petroski, 2003). However, as students enter grade one and beyond, the increasing academic focus has resulted in the loss of opportunities for designerly play (Zhao, 2012). At the same time, there are increasing calls to increase the number, skill, and diversity of STEM workers (Brophy, Portsmore, Klein, & Rogers, 2008). The robotics based Elementary Engineering Curriculum (Heffernan, 2013) - used by students in this study - and other similar projects have the potential to increase the STEM pipeline but elementary engineering is not well-understood. Research is needed to understand how to teach engineering to students as their cognitive, motor, and social skills rapidly develop in elementary school (Alimisis, 2012; Crismond & Adams, 2012; Mead, Thomas, & Weinberg, 2012; Penner, Giles, Lehrer, & Schauble, 1997; Roth, 1996;

Schunn, 2009; Wagner, 1999). The literature review and theoretical frameworks chapters of this study determined the most relevant theoretical frameworks, engineering design process models, and existing research that is relevant to a cross-sectional case study of six grade 2 and six grade 6 elementary robotics students in the context of established K-6 elementary robotics curriculum (Heffernan, 2013). Students were videotaped doing an open-ended engineering task based on LEGO robotics using talk-aloud (Ericsson & Simon, 1993) and clinical interview (Ginsburg, 1997) techniques. The engineering design processes were analyzed and compared by age and gender. Significant differences were found in final projects and engineering design process. However, the differences were not, for the most part, related to development or gender, but were related to the complexity of the ride they tried to build and the skills and structural knowledge they brought to the task. The key factors identified consisted of three executive function process skills of cognitive flexibility, causal reasoning, and planning ability, three domain specific process skills of application of mathematics and science, engineering design process skills, and design principles of stability, scale, and the structural knowledge they had of LEGO robotics, most pointedly, LEGO connection knowledge. Implications of these findings for teachers are given.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Figure Page

CHAPTER 1

PROBLEM STATEMENT

> Exposure to technological concepts and hands-on, design-related activities in the elementary and secondary grades are the most likely ways to help children acquire the kinds of knowledge, ways of thinking and acting, and capabilities consistent with being technologically literate. Unfortunately, there is very little information about how children or adults learn concepts in technology and how, or whether, that learning differs from other types of cognition.
>
> - National Academy of Engineering, Committee on Technological Literacy, & National Research Council (U.S.), 2002 (p. 57)

> It was hard so it made us jump up and down when it finally worked.
> - Grade 5 Girl

> We don't usually build things. It's just fun building things and getting things to work and then it does something good at the end. You feel good about what you made.
> - Grade 6 Boy

> It teaches us to keep trying. Even if you fail, you can succeed if you keep trying.
> - Grade 6 Boy

> It's also about working together to make these crazy, awesome things.
> - Grade 6 Boy

> It's more fun to actually be building something. If you took a class in robots and just learned about things, if the teacher just drilled information into your head, it would not be as fun as building and experiencing it to learn.
> - Grade 6 Boy

In my robotics class at Williamsburg elementary, a second grader has a difficult time at school due to severe Attention Deficit Disorder with Hyperactivity (ADHD). No matter how patient and understanding his teachers were, he experiences school as a difficult place with lots of negative feedback. The classroom teacher and I looked on in amazement as he gave an extremely cogent, deep, and enthusiastic explanation of how gears work and how the teeth function to transfer the energy. He was literally bursting at the seams to share this knowledge and we complimented him on his explanation. With robotics, he was shining in front of teachers and peers for the first time, helping his peers rather than being helped.

Problem Statement

Designerly play - children's play that involves design and building - has been identified as a fundamental component of childhood learning (Baynes, 1994; Petroski, 2003). Designerly play is supported in typical preschool and kindergarten classes with sand tables, water tables, blocks, LEGO blocks, art, and dramatic play areas. Petroski connects designerly play with engineering: "Design is rooted in choice and imagination and play. Thus the essential idea of engineering can readily be explained to and understood by children" (p. 206).

As students enter grade one and beyond, the increasing academic focus has resulted in the loss of opportunities for designerly play (Zhao, 2012). At the same time, there are increasing calls to increase the number, skill, and diversity of STEM workers (Brophy et al., 2008). The new Next Generation Science Standards in the United States, in recognition of this problem, require the use of engineering as a way to teach science ("Next Generation Science Standards," 2012).

The lack of opportunities for designerly play (which includes engineering) in elementary schools (Schunn, 2009) may be causing a reduction in the number and diversity of students interested in the STEM fields (especially engineering and computer science) in middle and high school as natural STEM interest atrophies due to the lack of authentic experiences (Schunn, 2009). Mead, Thomas, & Weinberg (2012) suggest that a

STEM pipeline - that feeds a large and diverse workforce - start at the ages of six to eight by initially engaging student interest and moving to more structured actives at grades three to five.

Robotics has resulted in increases in STEM self-efficacy and attitudes (Nugent, Barker, Grandgenett, & Adamchuk, 2009; Nugent et al., 2009) for middle school students in informal settings. Similarly, positive gains in self-efficacy and STEM career interest were shown for middle and high school girls in an informal setting (Weinberg, Pettibone, Thomas, Stephen, & Stein, 2007). Further gains can be expected if STEM education is started at the elementary level though a long term study is needed to validate this hypothesis (Mead et al., 2012). Increases in STEM self-efficacy and interest resulting from early STEM experiences could be particularly advantageous for girls since STEM attitudes are largely set by middle school (Stein, Nickerson, & Schools, 2004).

Other reasons for introducing engineering at the elementary level were clearly elucidated by Cunningham & Hester (2007):

1. Engineering builds on young children's natural interests in building and taking things apart,
2. Engineering is a motivating context for integrating mathematics and science content,
3. Engineering develops iterative problem solving skills,
4. Engineering develops the ability to work on projects and build 3-D models,
5. Engineering at an early age helps increase interest in STEM fields and helps increase the diversity of STEM workers,

6. Engineering and technological literacy are needed for citizens now and in the future.

Elementary engineering curriculum such as the robotics based Elementary Engineering Curriculum (Heffernan, 2013) and more general Engineering Is Elementary (Ernst & Bottomley, 2011) have the potential to fill the current gap in elementary engineering. Robotics offers specific affordances (such as the natural integration of science, mathematics, technology, and creative and collaborative skills) that make it an especially attractive educational technology (Brophy et al., 2008; Gura, 2011).

Levy & Mioduser (2010) showed that complex and advanced cognition could occur in young children's interpretation of robot rules and behaviors. Similar understandings need to be uncovered for the construction and programming of educational robots. Also, ill structured problems such as open-ended engineering design tasks have the potential to help develop executive function skills such as causal reasoning, planning, and cognitive flexibility (Cutting, Apperly, & Beck, 2011; Cutting, Apperly, Chappell, & Beck, 2014; Jonassen & Ionas, 2008). Research that helps teachers and curriculum developers understand elementary engineering design processes has timely relevance in light of the Next Generation Science Standards ("Next Generation Science Standards," 2012), which incorporates engineering design as a way to teach science and engineering and to develop 21st century skills such as collaboration, communication, and creativity. This research should also help elementary teachers understand the roles of: development, gender, domain specific knowledge and skills, and general cognitive development in the form of executive function.

Project Background

After working as a software engineer and then a third grade classroom teacher, I became a technology teacher. I inherited a robotics program, which worked well for sixth graders. However, I wondered what would happen if the program started in kindergarten with students getting engineering experiences every year. I saw amazing motivation and problems solving in my students. Students were working collaboratively. Certain students were being successful who were not successful in school before. Robotics was reaching girls who previously were not interested in programming and engineering. Boys who had difficulty in other areas of school such as reading, writing, and attention were the "shining stars" in robotics.

I developed, mostly by trial and error, a sequence of yearly units that combined structured and open-ended robotics activity, which culminated in a curriculum book for teachers because no such sequence existed before (Heffernan, 2013). I did two informal teacher action research projects that 1) interviewed robotics students, 2) tracked the same students every year doing the same open ended robotics tasks. A subsequent pilot study for this research showed significant differences in engineering design processes and causal reasoning between a grade 2 and a grade 6 student. But many questions remained in my mind.

- What is known about engineering and robotics particularly as it relates to student learning and development? What studies specific to elementary students exist?
- I observed interesting changes in student responses to open ended engineering challenges by looking at the same students every year. Had

anyone else done that before? Were there cross-sectional or longitudinal research results that could help PK-6 teachers?

- How could my work contribute to the knowledge base of elementary engineering education?

Conclusion

I set out on a multiyear effort to read every paper I could find on educational robotics, which also led me to other areas (such and design education, engineering education, and cognition) that I found were needed for a comprehensive understanding of elementary robotics. The literature review in the next chap will synthesize the results of that search and present the research questions I have developed as a result of my pilot study that could be a contribution to our understanding of elementary robotics.

CHAPTER 2

REVIEW OF THE LITERATURE

Literature Review Methodology

I have collected and read many papers on engineering and robotics education. This list grew over time by using the citations in papers read to find more papers (Brunton, Stansfield, & Thomas, 2012). I also compared my list with two published robotics literature reviews (Benitti, 2012; Sullivan & Heffernan, 2016) and two currently unpublished robotics literature reviews obtained through professional contacts (Carberry, Klassner, Schafer, & Varnado, 2014; Torok, 2012). I checked reference lists (Brunton et al., 2012) noting studies that were cited frequently or seemed important. I also retrieved and read every paper listed on the Tufts Center of Engineering Education and Outreach (CEEO) website ("CEEO: Home," n.d.). As part of the a literature review of robotics as computational manipulatives (Sullivan & Heffernan, 2016) I did an extensive search for papers on robotics. Reading the robotics papers also led me to a series of papers that discuss the broader topic of research on the processes of design, engineering education, developmental psychology, and causal reasoning.

Cognitive flexibility (or lack thereof) was identified in the pilot study as a potentially significant development factor in elementary engineering processes. A significant body of research was found that investigated cognitive flexibility as one of many possible executive function skills (such as planning, inhibition, task-switching) that are key to solving both open-ended design problems such as tool innovation (Cutting et al., 2011, 2014) and also more structured problems such as the Tower of Hanoi problem (McCormack & Atance, 2011). Executive function (or control) is defined by Cutting et al. (2011) as "an umbrella term for psychological processes involved in the conscious control of thought and action" that are "is needed for novel tasks or situations that require concentration, planning, strategy development, coordination, and/or choosing between alternative options" (p. 499). Open-ended engineering problems such as the tasks in this study are clearly "novel tasks or situations" so the executive function literature was very important in understanding the engineering design processes of elementary students.

Most papers relevant to this study fell into the categories of design, engineering, and robotics. Design is defined as "to plan and make (something) for a specific use or purpose". Examples of this broadest category of design could include architecture, engineering, or even crafts such as knitting. Engineering is a subset of design that is commonly defined as the application of math and science to create something new within defined constraints to address a human need (Brophy et al., 2008; Crismond & Adams, 2012). Robotics, as used in school settings, is a further subset of engineering where students design, build, and program robots for specific tasks. Robots are typically defined as machines that can accomplish intelligent, complex tasks in an autonomous fashion. Figure 1 illustrates this taxonomy of studies.

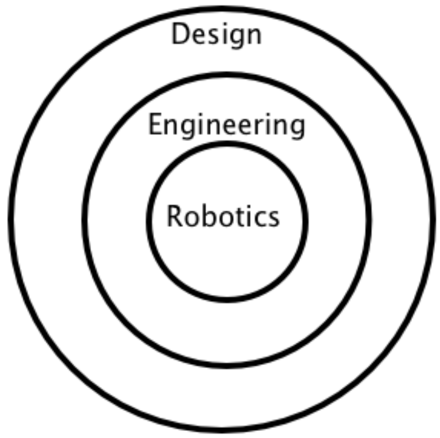


Figure 1. Taxonomy of design studies.

The literature review was first written as a paper-by-paper summary. Later, the papers were synthesized by using techniques of grounded theory to first organize and synthesize the results by categories (Charmaz, 2014; Galman, 2013; Glaser & Strauss, 2009). The categories that are directly relevant to the concerns of this proposed study are:

- The efficacy of robotics and engineering design as a way of teaching STEM content, improving STEM process skills, and increasing STEM interest,
- The engineering design process - how engineering is a form of problem solving and research on the engineering design process,

- General aspects of the design process specifically the use of mathematics and science in engineering and designerly play that cut across the various phases of the engineering design process,
- Executive function - research on executive functions as it relates to engineering design problems, specifically casual reasoning, planning, and cognitive flexibility,
- Gender - results from examining engineering design or robotics by comparing different ages, genders, or expertise levels,

Engineering Design and Robotics for Teaching STEM Content and STEM Process Skills and Increasing STEM Interest

In my own experience, robotics seems to a motivating, high-interest way to teach STEM to elementary students. But is this conclusion backed up by research? Is an-depth look at elementary engineering processes even justified? In this section, the efficacy of engineering design and robotics as a way of teaching STEM content, improving STEM process skills, and increasing STEM interest is examined. In general, positive results were found. In some cases, the short-term nature of the robotics or engineering experience was suggested as the reason for non-significant results. Another common conclusion is that teacher scaffolding is needed to successfully realize STEM content gains, especially in the application of science in engineering tasks.

Mehalik, Doplet, & Schunn (2008) asked how science concept learning compares when using design based versus scripted approaches in middle school students. They found that students using the systems design approach showed significant gains compared to the scripted inquiry approach, especially low achieving African-American students. Fortus et al. (2005) in a quantitative study of grade 9 students found that design based science (DBS) was effective in teaching science concepts. Their data also suggested that DBS was also helpful in knowledge transfer to different science topics. Kolodner et al. (2003) also had a strong focus on knowledge transfer used design based science for middle school students in an approach they call Learning by Design (LBD). The student data was positive but there were challenges in terms of teachers being willing to be more of a facilitator than a lecturer.

Leonard & Derry (2011) also found that middle school design based science was effective but that there are many complex and challenging changes required for students and teachers to combine scientific and engineering approaches. Puntambekar & Kolodner (2005) looked for methods to help middle school teachers teach science concepts and processes using design. They found that students need different types of classroom scaffolding to fully use science process and content in the context of design based science activities.

Mitnik, Recabarren, Nussbaum, & Soto (2009) explored the use of computer supported collaborative learning with robotics to increase understanding of kinematics and graphing in grade 10 students. Students who used a robot as means to teach kinematics and graphing did much better in content learning, interest, and collaboration than a control group that used a simulation. In this case, the robots and mobile devices were an effective means to teach physics and mathematics. As with other studies, the use of robotics supports science learning with appropriate curriculum and teacher scaffolding.

Williams, Ma, Lai, Prejean, & Ford (2007) evaluated physics content knowledge and scientific inquiry skills gains using robotics for middle school robotics summer camp students. The study found science content gains but did not find an increase in science process skills in this two-week program and suggested that longer-term experiences are needed to realize process gains. Adamchuk et al. (2012) found STEM learning, attitude, and self-efficacy gains in an out-of-school robotics experience that incorporated Global Information System (GIS) and related technologies. Robotics also has resulted in increases STEM self-efficacy and attitudes (Nugent et al., 2009, 2009) for middle school students in informal settings. In one of the few controlled studies of robotics, Barker & Ansorge (2007) showed strong gains for the control group of nine to eleven year olds in an after-school robotics program. However, their test was very specific to robotics and the control group received no robotics training. McGrath et al. (2012) designed, implemented, and tested a middle and high school underwater robotics curriculum that mixed formal and informal learning. Their study found gains in learning, attitudes, and process skills. Positive gains in self-efficacy and STEM career interest were shown for middle and high school girls in an informal setting (Weinberg et al., 2007).

Sullivan (2008) asked if robotics provides affordances for increasing thinking skills, science process skills, and systems understanding for middle school students. She found that robotics instruction, with proper inquiry based pedagogy, could improve content knowledge, thinking skills, science process skills, and systems understanding. Sullivan says that, “these outcomes are a result of both the affordances of the robotics environment itself and a pedagogical approach that emphasizes open-ended, extended inquiry” (p. 390).

In summary, results show that engineering design experiences including robotics, given sufficient time, appropriate pedagogy, and teacher scaffolding, result in STEM content and process skills increases and STEM interest and self-efficacy gains. Now that generally positive results have been shown overall, a more specific examination about student design processes during the robotics and engineering design experiences is justified. In other words, what might be occurring that might explain the positive effects of robotics?

The Engineering Design Process

In this section, research specific to the overall design process is reviewed. What is known about how elementary students use the engineering design process? Other ages? Does this change over time as they pass the many developmental milestones of this age?

Engineering design as a form of problem solving. Problem solving research is examined first since the engineering design process is an example of problem solving in the specific domain of engineering. Only problem solving research as it relates to engineering design and robotics is reviewed here. A more general discussion of problem solving models and frameworks is part of the theoretical frameworks chapter.

Roden (1997, 1999) looked at changes in the design processes from the equivalent of prekindergarten to kindergarten in Great Britain over a period of two years with a focus on collaborative problem solving strategies. He classified the collaborative problem solving strategies students used as: personalization, identification of wants and needs, negotiation and reposing the task, focusing on the task, tools, and materials, practice and planning, identifying difficulties, talking self through problems, tackling obstacles, sharing and cooperating, panic or persistence, showing and evaluating. Each strategy was judged as: declining, emerging, developing, and changing over time. Roden (1997, 1999) showed that collaborative problem solving strategies do change over time and he suggests that teachers both need to understand them and to help children make them explicit. This study shows changes over relatively short (yearly) longitudinal time frames. The strategies Roden identified are a mix of cognitive, social, and affective strategies.

McRobbie, Stein, & Ginns (2001) found a three level hierarchy of problems that adult learners solved in a design problem: macro (high level), meso (intermediate), and micro (small, specific). This suggests that similar hierarchies of problem solving might be found in children's design processes.

Some studies look at how different factors influence problem solving in the context of robotics. Norton, McRobbie, & Ginns (2007) reported better and more holistic problem solving when students were required to use flow charts before programming LEGO robots to do a complex task. Also, teacher goals and beliefs heavily influenced student processes and outcomes in their activity theory based study of two middle school robotics classes. Sullivan & Lin (2012) found that students' perceptions of an ideal science student influenced their problem solving strategy use. Students with a process oriented, rather than a static, traits oriented view of a scientist, used more flexible and successful domain specific problem solving strategies.

Barak & Zadok (2009) found that middle school students intuitively used heuristic search to find solutions to robotics based design problems but could not necessarily articulate their strategies. Students moved from trial and error to a more sophisticated heuristic approaches, which means that more promising possible solutions were picked. The authors define two classes of heuristics as proximity methods (using backward and forward chaining to hone in on a solutions) and planning methods by using modeling, abstraction, and analogies. Specific examples in the context of their robotics study were: eliminating components for troubleshooting, reusing an existing function for a new purpose, and examining available parts. Some of the heuristics described such as modeling, planning, and examining part (research) might also be considered actual Engineering Design Process (EDP) phases. The authors concluded that students could have benefited from specific, in-context, math, science, technology, and problem solving instruction.

Lindh & Holgersson (2007) attempted to ascertain the effect of LEGO materials on problem solving ability in Sweden with grade 5 and grade 9 students using LEGO materials as compared to a control group. The results were mixed at best. However, there was no curriculum or common professional development so it is unclear how a positive result could be expected.

In summary, researchers have found evidence that problem solving strategies used in design and robotics:

- change with age and experience,
- can be affected by the tools and materials used,
- are affected by student perceptions of scientists (and presumably engineers),
- can reveal embedded hierarchies of problems such as macro, meso, and micro levels,

- many heuristic strategies for problem solving are already known by students.

All these findings reveal the value of problem solving in a design context and also suggest some behaviors to look for in this study.

EDP research. The engineering design process is an example of problem solving in the specific domain of engineering. What is known about the engineering design process that could shed light on elementary student's behavior in the context of open-ended robotics engineering challenges?

One common finding is that students (and even expert engineers) do not follow theorized, idealized, linear processes (Crismond, 2001; Johnsey, 1993; McRobbie et al., 2001; Welch, 1999). Welch (1999) provided timelines that show the theorized and actual design processes (see Figure 2 and Figure 3). He found that grade 7 students did not follow an idealized, theoretical design process. They evaluated their design much more frequently than the theorized EDP model would predict, tried one idea at a time instead of evaluating alternatives, and preferred 3-dimensional materials to 2-dimensional sketches.

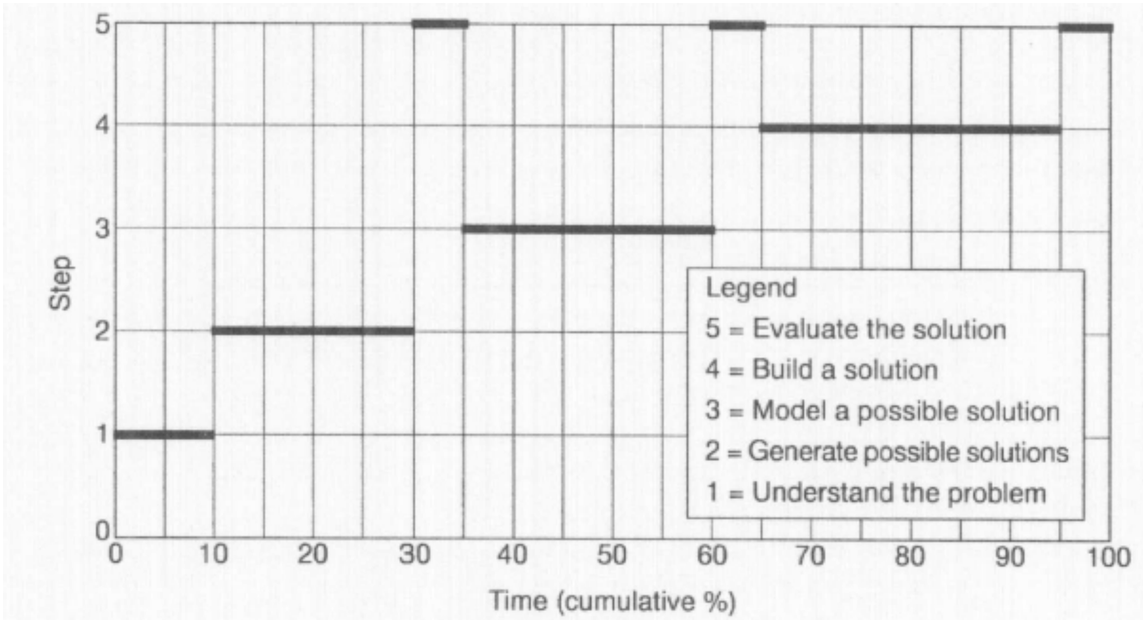


Figure 2. Predicted theoretical design process. From “Analyzing the Tacit Strategies of Novice Designers” by M. Welch, M., 1999, *Research in Science & Technological Education*, *17*(1), p. 28. Copyright 1999 Taylor and Francis Ltd.

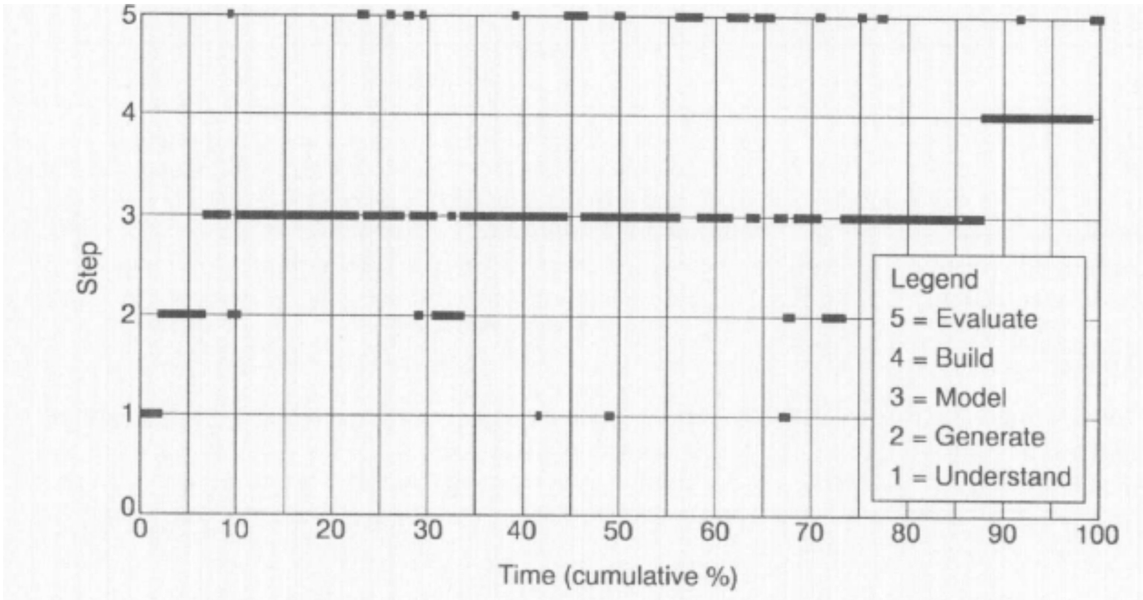


Figure 3. Actual design process. From "Analyzing the Tacit Strategies of Novice Designers" by M. Welch, M., 1999, Research in Science & Technological Education, 17(1), p. 28. Copyright 1999 Taylor and Francis Ltd.

Johnsey's (1993) early study looked at year 4 (grade 3) children's design processes as compared to early, theorized, and idealized models of the design process. The children worked in pairs on an hour-long design task. The study revealed that design process was far different than what was predicted from idealized, theorized models. Students jumped back across design and these younger students jumped into making prematurely. Teacher intervention was allowed and counted as research in the results, which would distort the results from what students would do on their own. Only part of one graph of one student was shown. A more thorough analysis is needed to gain a better understanding of elementary student engineering design processes.

There has been a thorough analysis of college student engineering design process that compare freshman and seniors in series of students by Atman and her colleagues. Cardella, Atman, Turns, & Adams (2008) performed a small case study looking at different college engineering majors in depth - students that made progress freshman to senior - low to high, low-to-low, high to high, etc. They compared their EDP graphs as freshman and seniors and also rated the designs using a rubric. They used a talk-aloud protocol and recoded transcripts with less than 70% agreement. They rated quality of solution and measured transitions between phases of the design process. In general, skilled designers used content knowledge and also utilized more steps of the EDP. Experienced designers spent more time in evaluating alternatives, and making and communicating design decisions. Many seniors considered the end user more than freshman and were judged as more innovative. The seniors did better than freshman students in terms of design quality, spent more time on the activity, had more transitions between phases, and also did better on the final stages of the design process, which they call project realization. Note that other studies show that experts spend more time on a design task (Atman et al., 2007).

In a related study, Atman et al. (2007) looked at freshman (n=26) and seniors (n=24) engineering students and compared them to expert engineers (n=19) on a task that was outside of the experts' area of expertize. Using video and a talk aloud protocol, EDP graphs and solution quality were compared. Requests for further information were allowed and coded as such. The researchers quantitatively tested various hypotheses about design process and quality using quantitative methods. A number of findings resulted from the analysis:

- The number of alternative considered correlated with solution quality for seniors.
- Problem definition improves as possible solutions are explored.
- Experts spent more time on the problems especially on problem scoping.
- Experts considered more alternatives.

- Experts were more consistent in their process than college students. This pattern was described as a cascading pattern (see Figure 88) with three characteristics: initial time with problem definition and scoping, modeling possible solutions, and time spent throughout the process to gather more information and further scope the problem.

The authors recommend that engineering education include: encourage up-front design scoping, gather information throughout design process, and attend to project realization.

Atman, Cardella, Turns, & Adams (2005) found that college engineering seniors had better designs than freshmen. Most students, but not all, improved from freshmen to senior year, though that varied by problem type. Performance and behavior also varied by problem type. Freshman need to spent more time on problem scoping and developing alternate solutions. Both groups did not spend enough time on evaluation and project realization. The authors suggest providing more variety of problems and encouraging more focus on latter design stages.

Crismond (2001) compared novice and expert high school and adult designers as they tried to redesign some common household tools. Each teams' activities was coded and analyzed in terms of a cognitive model Crismond calls the Cognitive Design Framework (CDF). In the CDF, there are three pillars with these horizontal bases: design space, process skills, and content knowledge. Each pillar goes from the concrete level to the abstract level vertically. His thesis was that expert designers make connections both between the three pillars and also vertically from concrete to abstract. The CDF suggested a design process model with these design activities: handling materials, big picture thinking, generating ideas, making vertical CDF connections, making horizontal CDF connections, analyzing, suggesting solutions, questioning, deciding, sketching, and reflecting. The study then analyzed and compared how much time each expert and novice teams spend in each design activity (see Figure 4).

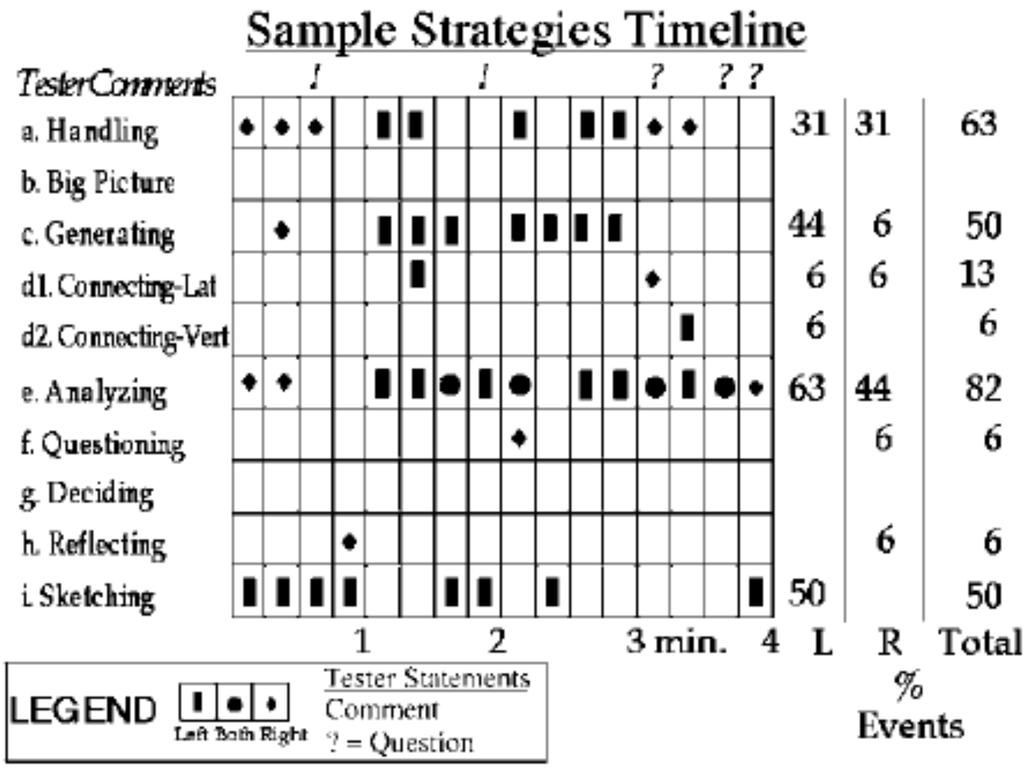


Figure 4. Design process analysis of a redesign task. From "Learning and Using Science Ideas When Doing Investigate-and-Redesign tasks: A Study of Naive, Novice, and Expert designers doing constrained and scaffolded design work" by D. Crismond, 2001, Journal of Research in Science Teaching, 38(7), p. 813. Copyright 2001 John Wiley & Sons, Inc.

Crismond found that only the expert designers used general design principles and they also used connections to science concepts to help their design process. The former general design principles were "rules of thumb for good design" (p. 796) that connected the abstract to the concrete. In the realm of elementary engineering, these could be the design principles of scale, symmetry, and stability that were seen in the pilot study.

Symmetry, in particular, has been noted as an important aspect of building for children (Portsmore, 2009). Crismond (2001) concluded that teachers must scaffold design tasks to help students make these connections that experts but not novices make.

What conclusions can be drawn from the college engineering and EDP studies as as whole?

- Actual design processes differ from theorized, idealized, linear models. Actual novice and expert design both go back and forth across the design process.
- More experienced designers spend more time up front on problem scoping and continue to do so throughout the process.
- The number of alternative solutions considered generally correlates with solution quality.
- Time spent correlates positively with design quality.
- Experts use more content knowledge.
- Experts use general design principles.
- Experts use the EDP more effectively.
- Teachers need to provide instruction and scaffolding for students in the application of: science and general problem solving, design processes knowledge, and design principles.
- Significant changes can be seen in engineering processes over time.

In summary, while much is known about the design processes of older students and experts, there has not been a thorough and in-depth study of elementary student design processes and it is unknown if and how the conclusions and recommendations of these studies apply at the elementary level. Now that problem solving process research - and specifically the engineering design process research - has been reviewed, results pertaining to general aspects of the design process such as the application of mathematics and science and designerly play are examined and synthesized. A full examination of the EDP phases of different models will be deferred until the Theoretical Frameworks chapter.

General Aspects of Design Process

In this section, research related to the design process in general and not to specific phases of the EDP as relevant to a study of elementary robotics is examined. Not all possible topics were found. For example, it is widely reported that robotics is highly motivating but no research on interest and motivation and robotics in particular was found (except as tool for generating STEM interest). Research was found that relates to designerly play and connecting mathematics and science to engineering.

Designerly play. In this section, findings that discuss the role of designerly play in the context of engineering design or robotics is examined. Children come to school with lots of natural experience and processes in place for design (Outterside, 1993). Fleer (1999), in a study of five and eleven year olds, found that older students still engaged in fantasy play associated with the design task but in a more subdued and socially acceptable way. However, fantasy play was an integral part of the kindergarten students' design activities. Note that Vygotsky (1986) theorized that the fading of fantasy play, especially in the form of language, gradually faded as this internal dialogue becomes internalized as rational thought.

Designerly play still plays a role when students get older but it changes from the fantasy play of younger children. In a study of middle school robotics students, Sullivan (2011) found that play and bricolage (tinkering) are important aspects of fostering creativity. Furthermore, teachers can scaffold creativity by providing open-ended, goal-oriented tasks, by modeling play and bricolage, and by providing a collaborative and creative environment.

Mioduser, Levy, & Talis (2007) found that kindergarten children first engaged in planful play when asked to determine the underlying rules observing moving robots. This was a critical aspect of their cognitive processes. Children can take a technological or psychological approach in explaining intelligence machine behavior. The researchers thought of children's psychological explanations, which were frequently anthropomorphic, of robot behavior as a starting point for more scientific explanations. As children gained experience and understanding of robotic technology, they moved from psychological to technological viewpoints with experience and adult intervention. Furthermore, they saw evidence connecting the psychological to technological through what they termed bridging. In other words, the technical did not replace the psychological in an unrelated fashion but children made a connection from one to the other. Levy & Mioduser (2008) also state that "the robot's reactivity to the environment, and its endowment with decision-making abilities, distinguish the robot as a psychological artifact. Its programmability sets it apart as a computational-technological artifact" (p. 347). The combination of young children's developmental tendency to anthropomorphize and robot's special capacities to interact with its environment is one likely cause of the special motivation robotics provides. In other words, robots have a special capacity to engage designerly play.

Slangen, Keulen, & Gravemeijer (2010) looked at children's (age 10-12) conceptual understanding of robots. They defined an ordered taxonomy of cognitive levels related to robotics: psychological, technological, functional, and controlled system with controlled system being the most sophisticated understanding. Like Levy and Mioduser, they see more playful, psychological mode as the starting point for a deeper understanding of robots.

In summary, research on children's understanding of robots suggests that the interactive and autonomous characteristics of robots make them especially efficacious for engaging the designerly play instincts of children and that this play changes from fantasy play to a more subdued form of play as children progress through elementary school.

Connecting math and science to engineering. Engineering is often defined as the application of mathematics and science to create something new that meets a human need (Brophy et al., 2008). Therefore, the application of mathematics and science is an important part of engineering education. An example of the application of science in the context of elementary robotics is the use of gearing up to increase robotic vehicle speed. Does the ability to apply mathematics and science knowledge to engineering challenges increase as students develop? What is known about how this skill operates at the elementary level?

Research exists on both the application of science in design tasks and the use of engineering design, including robotics, to teach science. Crismond found that expert designers used connections to science concepts to help their design process while novice high school designers did not. Crismond (2001) concluded that teachers must scaffold the application of science in design tasks for this reason. Other design-based science studies also report positive results on the use of design to teach science come to the same conclusion regarding the importance of teacher scaffolding to connect science to engineering (Fortus et al., 2005; Leonard & Derry, 2011; Mitnik et al., 2009; Puntambekar & Kolodner, 2005).

Leonard & Derry (2011) sum the problem up this way:

> Seldom in a design context does a science concept appear in an isolated form that allows it to be studied discretely—it operates in concert with multiple, intersecting science and technological concepts. (p. 45)

There is much less research on the use of mathematics in engineering design tasks. However, Mitnik, Recabarren, Nussbaum, & Soto (2009) found that the use the robots and mobile devices were an effective means to teach physics and mathematics. While the application of mathematics and science to engineering tasks is important and researchers have found that teacher scaffolding plays an important role, it is not known if how this skill that operates at the elementary level.

In summary, research on the application of mathematics and science in engineering shows:

- expert designers apply science more than novice designers,
- design based science creates affordances for the application and understanding of science concepts and practices with teacher scaffolding.

It is not known how the application of mathematics and science works at the elementary level and how it might change with development.

Executive Function and Engineering

Executive function is typically defined as ‘‘a collection of inter-related processes responsible for purposeful, goal-directed behavior,’’ such as ‘‘anticipation, goal selection, planning, initiation of activity, self-regulation, mental flexibility, deployment of attention, and utilization of feedback’’ (Davidson, Amso, Anderson, & Diamond, 2006, p. 71). Three executive function skills in particular seem the most relevant to open-ended engineering design problems: cognitive flexibility, planning, and causal reasoning. Let’s examine research on each one in turn.

Cognitive flexibility. In both my dissertation pilot study and in my teaching, I have observed students (especially younger students) both struggling to project out the consequences of design decisions and resisting rethinking non-optimal design decisions and starting over. The latter I called non-optimal persistence.

Some research that relates to this subject was found in a new book called *Engaging Young Engineers: Teaching Problem Solving Skills Through STEM* (Stone-Macdonald, Wendell, Douglass, Love, & Hyson, *2015)*. In their theoretical framework, they posit that there are five kinds of thinking developed by teaching problem solving via STEM for early learners.

- Curious thinking
- Persistent thinking
- Flexible thinking
- Reflective thinking
- Collaborative thinking

In the framework, persistence is viewed as wholly positive. However, the non-optimal persistence I have been seeing can be thought of as a lack of flexible thinking both in the framework above and in the cognitive science literature. Cognitive flexibility (or flexible thinking) is typically defined as part of executive function (Davidson et al., 2006).

Cognitive flexibility (CF) in particular, is defined as "the ability to consider multiple bits of information or ideas at one time and actively switch between them when engaging in a task" (Cartwright, 2012, p. 26). Cognitive flexibility (flexible thinking) has been shown to have a slow developmental trajectory course (Cartwright, 2012; Davidson et al., 2006) so it is a good candidate for explaining differences between second and sixth grade students.

Cognitive flexibility is seen as a key component of solving ill-structured problems, that is, problems where students have "information about the start and goal states but lack information about how to get from one to the other" (Cutting et al., 2011, p. 500). Open-ended engineering problems are an example of ill-structured problems (Stone-Macdonald et al., 2015). Cognitive flexibility is also considered a key part of the creativity needed to invent new things or solve problems (Sternberg, 2003; Stone-Macdonald et al., 2015).

Given the definitions and context above, two questions emerge in terms of elementary engineering.

1. What does existing research say about the non-optimal persistence (or cognitive inflexibility) I have been seeing in second grade students?
2. Could existing cognitive science research on executive function and cognitive flexibility shed light on the engineering process of elementary

aged children in terms of coding or a model of elementary engineering as it relates to underlying cognitive development?

Now that I have defined the terms and questions, let's examine the research.

Executive function (EF) and cognitive flexibility in particular (CF) play critical roles in the development of academic tasks. Engineering is no exception (Stone-Macdonald et al., 2015). Results in specific domains point to the importance of CF. For example, being cognitively flexible (CF), part of EF, by attending to both sound and meaning in a reading task helps reading comprehension (Cartwright, 2012). Specific environmental factors, which could also include school experiences, have positive influence on CF. For example, bilingual children show more CF than monolingual children (Adi-Japha, Berberich-Artzi, & Libnawi, 2010). However, previous experience can sometimes negatively influence cognitive flexibility (Barrett, Davis, & Needham, 2007). While CF is a positive cognitive factor, how does it operate in a specific domain?

In a study of cognitive flexibility in children's drawing, Karmiloff-Smith (1990) found significant changes between ages four and eleven when asked to draw a house, man, and animal that does not exist. Children changed from deleting standard elements and changing size and shape to adding elements from other categories. Representational change is first seen at a basic level of simple changes. For example, younger children deleted at the end of their already developed procedure of drawing a figure while older children deleted anytime suggesting the younger children could run the procedure only as is and then change it after (Karmiloff-Smith, 1990). Then, as a process of internal change, a higher-level reorganization becomes possible. In other words, once the procedure is established, at which time simple changes to the sequence can be made, the procedure itself is available as data to the older children so that can be modified in a process called redescription (Karmiloff-Smith, 1995). If the same process were operating in the domain of elementary engineering, we would expect to see children mastering specific sequences of tasks but having difficulty in the more open-ended, ill-structured problems that require a redescription of domain knowledge.

Ill-structured problems. Given that ill-structured problems are difficult, especially to younger students who have less developed cognitive flexibility, are there scaffolds that teachers can use to help children? Instructor generated question prompts were the best type of prompt to use in an ill-structured undergraduate education project as compared to student generated and student generated with instructor feedback (Byun, Lee, & Cerreto, 2014). This result is consistent with the pilot study where asking simple question helped the student start a process of tracing back a wiring path to solve an issue with his robot car.

Knowledge integration prompts were most successful in solving ill-structured problems (rather than conceptual knowledge prompts or both). Knowledge integration prompts helped social studies undergraduates form structural knowledge, which is defined by Chen & Bradshaw (2007) as “the knowledge of integrating domain knowledge into useful procedural knowledge for solving domain problems” (p. 361-362). They helped students explain and understand concepts and the relationships between them (Chen & Bradshaw). Although it is not clear if similar conclusions can be drawn for elementary engineering, the detection of structural knowledge in the dissertation research will be added to analysis process of the ill-structured, open-ended engineering problem. For example, it could be that meta-knowledge of key LEGO connector pieces and how to use them could be a key factor in the construction of student-designed LEGO robots in open-ended engineering challenges, an example of an ill-structured problem. Tool innovation, an ill-structured engineering problem, has been studied in young children.

Tool innovation. According to Cutting et al. (2011), younger children aged four to five (and some animals such as crows and primates) can manufacture tools after having seen an example. However, children are not as good at tool innovation until they are nine to ten years old. This is true even after they are given instruction and a warm-up with the materials. The authors proposed that this difficulty is due to one of three possible causes: mental inflexibility, aspects of the particular task they used, or the developmental difficulty of ill-structured problems. Has the mental inflexibility seen in the pilot study (which I termed non-optimal persistence) has been seen in other ill-structured tasks and what else is known about it? Before that question can be answered, some terms need definition and some context needs to be established.

Executive function (also called executive control in the literature) could be a key cognitive factor in tool innovation "needed for novel tasks or situations that require concentration, planning, strategy development, coordination, and/or choosing between alternative options" (Cutting et al., 2011, p. 499). The difficulty with tool innovation in young children could be due to mental inflexibility, which Cutting et al. say is a function of executive control, the latter defined as "conscious control of thought and action" (p. 449). The authors cite a number of sources that have shown that cognitive flexibility is very developmental with increases between three and five years of age and additional gains with complex tasks, speed, and accuracy between five and eleven years of age. Task switching, another component of executive function, could also be a factor. Cutting et al. state that, “It seems plausible that difficulty in switching between alternatives might contribute to children’s difficulty with tool innovation" (p. 499).

They tested the mental inflexibility explanation by first having the children succeed in one task and then had them try a task that had an "opposite" solution. If the mental inflexibility theory was correct, then children should find the second task more difficult because they have to switch to a new perspective. The authors found that perseveration (or non-optimal persistence), though seen, was not a significant factor in the first experiment and that success on on task did not cause problems with a second, "opposite" task.

However, the four and five year olds did show significant levels of task perseverance as compared to six and seven year olds in the second experiment. They also suggested that the warm up task used in the first experiment may have helped the younger children avoid perseverance behaviors. With regard to perseverance, Cutting et al. (2011) conclude that:

> Nevertheless, although the current studies suggest that overcoming such perseveration is not the limiting step for tool innovation success, the data do suggest that it may be a necessary condition for success; if children initially use an unsuccessful tool and then fail to stop using it, they can never go on to succeed in innovating a tool. (p. 508)

Perseverance was coded if the children persisted with their first, unsuccessful tool for the whole time period of one minute. So, this coding scheme would not work in the context of a more open-ended task. However, the concept of persistence as an idea that is not working *is* valid for my research. In general, although the results for perseverance were mixed in this research in terms of how much it affects the final results, a non-optimal perseverance was seen to have some significant effects and will be examined carefully in my research to further unpack its significance for second grade students.

The second possibility they tested was that even though children could innovate tools, aspects of the particular task makes innovation difficult; they may persevere with unmodified materials. They reduced the possibility of this in their second experiment. The research showed that aspects of the particular task, which involves bending pipe cleaners to make a new tool, were not a factor in the lack of tool innovation. However, age continued to be a significant factor in success at tool innovation.

Possibility three was that a further development of executive function is needed for tool innovation because it is a difficult, cognitively challenging, ill-structured problem. Cutting, Apperly, & Beck (2011) relate tool innovation and ill-structured tasks as follows.

> Tool innovation is an excellent example of an ill-structured task. Participants have information about the start and goal states but lack information about how to get from one to the other. They must devise and hold in mind a solution to the problem, inhibit irrelevant actions, and plan a sequence of actions to achieve their goal. (p. 500)

The authors suggest, through what seems to be a process of elimination rather than an actual experiment, that a better developed executive function is needed to solve ill-structured problems like tool innovation.

Cutting, Apperly, Chappell, & Beck (2014) sought to better understand the reasons why tool innovation is so difficult for young children in a second set of experiments. Specifically, by highlighting different parts of the solution in turn, they sought to determine what knowledge (or lack thereof), if any, was the cause of the difficulty. Alternatively, were the difficulties the result of an executive function issue of integrating different knowledge in an ill-structured problem?

Their thesis is that experts possess structural knowledge that allows them to successfully integrate different pieces of domain specific knowledge into a solution. Novices, even though they may possess the required domain specific knowledge, lack the structural knowledge to integrate the domain specific knowledge into a solution. The researchers sought to find out if "children's difficulty in these tool innovation studies may lie with bringing to mind the required pieces of information from memory, coordinating these different pieces of knowledge, or a combination of both" (Cutting et al., 2014, p. 112).

Cutting, Apperly, Chappell, & Beck (2014) controlled two necessary pieces of domain specific knowledge: the material properties and the target state. They found that older children were able to integrate the domain knowledge but that younger children were not, even when both pieces of required domain specific knowledge was highlighted for them. Cutting et al. conclude that, "that without this structural knowledge, young children lacked the flexibility needed to retrieve their knowledge from memory and then coordinate it in order to solve these tool innovation tasks" (p. 115). Furthermore, the main issue for both age groups was knowledge retrieval with knowledge integration being a big issue for the younger children. The lack of structural knowledge could have explanatory power for differences between second and sixth grade students in open-ended engineering problems. Note that Cutting et al. (2014) did not suggest how students can be helped to solve ill-structured problems.

Planning in young children. The pilot study revealed significant differences in the ability of one second and one sixth grader to anticipate the consequences of their design decisions. How might this result relate to children's general ability to plan (as opposed to the specific aspect of the plan phase of the EDP) as reported in the research base? McCormack & Atance (2011) review of research on planning for young children could illuminate the planning issues seen in the pilot study.

McCormack & Atance (2011) define planning this way:

> "Critically, planning is a key way in which flexibility of thought can be exploited to enable behavior to adapt not just to the current state of the world, but to anticipated states of the world in the immediate or distant future." (p. 3)

For McCormack & Atance (2011), planning is seen as possibly related to three different aspects of cognitive flexibility: event-independent representations of time, executive function, and self-projection.

Planning and the ability to mentally represent temporal events. The authors (McCormack & Atance, 2011) conclude that the development of planning in young children (which they define as three to five years old generally) is related to their ability to mentally represent temporal events independently of the actual events. The authors emphasize that this ability is not the same as the ability to reproduce event order in a story read to them, which is called sequencing (Kazakoff & Bers, 2012). (Presumably, however, sequencing is a prerequisite cognitive skill to the mental representation of temporal events independent of the actual events.) This mental representation is done when children envision empty slots in a future sequence of actions that could be filled in different ways. The authors suggest that this ability has been shown by research to be important in preschool children's success in different types of planning tasks such as Tower of Hanoi, Tower of London, route planning, and real world planning tasks. Are children using the same cognitive process when predicting the effects of their design decisions in an open-ended engineering task?

Planning and executive function. McCormack & Atance (2011) examine what research has revealed about how various subcomponents of executive function (EF) influence success in planning tasks. First, the authors argue that the research shows that a general EF ability is not responsible for planning but that the subcomponents of EF of working memory, inhibitory control, and task switching may be. Their review of research suggests that only inhibitory control only may be a significant factor in planning for young children. Could the better-developed inhibitory control of sixth graders explain some of the difference in planning seen in the pilot study?

Planning and self-projection. Lastly, the authors discuss the role of self-projection in planning for young children. Self-projection is defined as the ability to shift personal perspectives in the form of alternative scenarios (McCormack & Atance, 2011). Two types of self-projection are discussed: future thinking and theory of mind (TOM) (Buckner & Carroll, 2007).

Future thinking - as contrasted with meeting present goals - is defined as projecting the self into future goals and scenarios. Under this definition, open-ended engineering tasks are defined as meeting present goals and not as future thinking. However, it is not clear to me how there can be a clear-cut difference as both involve mental projection into the future. In any case, research showed similar development in future thinking as in other planning tasks during the age span of three to five years old (although research is sparse).

Theory of Mind (TOM) is defined as the ability to know that one has a mental state and that others have different mental states for the purpose of explaining present and anticipate future behavior for the individual ("Theory of Mind | Internet Encyclopedia of Philosophy," n.d.). Evidence linking TOM to planning ability is mixed (McCormack & Atance, 2011). In summary, as presently defined and with the current state of research, self-projection is of questionable value in explaining elementary engineering processes because: 1) it is defined as having an image of self which is not necessarily present in the domain of engineering and 2) because research results linking self-projection to planning are not clear.

Planning and drawing in the context of design. Planning is an early stage in the engineering design process typically put after problem definition and research. Although I could only find a limited number of studies that look at planning in design, both were for elementary students, including one cross-sectional study, so they are particularly relevant for this literature review. Drawing is a common way for students to plan their designs and results specific to drawing are reviewed after results for planning.

Portsmore (2011) looked at preplanning for grade one students and found that even first grade students could sometimes use effective preplanning in a design task with familiar materials. She used a clinical interview format with a precisely defined design task which was to retrieve a set of keys on a key ring from a tall container using a set collection of materials (such as tape, magnets, spoons, and pipe cleaners) with a twenty-minute time limit. Portsmore provided a very precise and structured task with concise rubrics for drawings of their plans and for their completed student designs. Many first graders were able to plan ahead successful designs and materials choices in the familiar and constrained domain. However, they did not necessarily build what they drew indicating that first graders may not have used these drawings as planning as adults would. The results of this research seem to indicate the planning can occur with younger children with familiar materials and tasks that are not too cognitively demanding (Gardner & Rogoff, 1990).

In a cross-sectional study of planning comparing five and thirteen years olds, Gustafson & Rowell (1998) asked students to say what their course of action would be and why when presented with an open ended design task. The choices were: research with book, put together model, draw picture, talk to friend, or think/reflect. The initial course of action was determined by their initial idea of successful solution and there were two approaches, inside and outside of head. If students had an idea of the solution already (inside head), they tended to choose modeling, imaging, or reflecting. If the students did not have an idea, they choose the outside of head approaches of research or social (talk to a friend). There were gender and age differences. Many girls aged eight to ten chose a social approach. Research, imaging, and modeling were the most popular choices - modeling with younger students and research with older students. Their conclusion was that teachers should be aware of and allow for different approaches to planning. One conjecture was that students that chose reflection might be more cognitively advanced and capable of metacognition. The age and gender differences they found in the elementary range suggest for planning that similar differences exist for the more general engineering design process.

Fleer (1999) found that planning drawings were not always used by kindergarten and grade 5 and 6 students in a cross-sectional case student of design processes. However, post-make drawings, especially by the older students provided good documentation of design choices. The younger children especially showed a preference for using 3-D models (i.e., the actual materials) to solve design problems rather than drawings. She also noted the importance of "tacit doing knowledge", that is, children expressed knowledge by acting on materials rather than discourse or drawings. This study suggests that older elementary students utilize planning drawings more often that younger students.

Anning (1994) found that drawing ahead of time was frequently not meaningful in a case study that primarily focused on implementation issues with the inclusion of design in English primary schools. She theorized that this is because drawing is not as valued as reading and writing in school and that there may be developmental constraints on drawing as planning for younger students. She cites research that suggested that at age nine, children can make accurate planning drawings for blocks (Anning, 1994; Banta, 1980).

In summary, the findings on planning and drawing that may be relevant to elementary open-ended robotics engineering tasks are:

- Results are mixed as to the utility of drawing and the capability of younger students to plan. Some positive results were found in tightly constrained problems with familiar materials (M. D. Portsmore & Brizuela, 2011). However, other studies find that young students largely skip the planning phase and the reason for this are developmental constraints (Anning, 1994; Fleer, 1999). It is possible that children can accomplish tasks ahead of projected developmental milestones in constrained tasks with familiar materials. My pilot study data suggests that this may not be the case in the more general case of open-ended engineering challenges where knowledge transfer must occur.

- Planning strategies may depend on variety of factors such as the problem itself, student age, gender, and whether or not the student has an initial solution to the problem.

Causal reasoning. Causal reasoning theory and research could shed light on the increasing ability of elementary students to plan and to project out the effects of their design decisions shown in my pilot study, which involves causal reasoning.

Piaget defined a progression of causality from magical-phenomenalist (which Piaget called realism - different than how realism is usually defined in philosophy) to an eventual scientific viewpoint (Fuson, 1976; Piaget & Inhelder, 1969). Fuson (1976) summarized Piaget's theory of causal reasoning as follows. Infants do not have a delimitation of self and the outside world, attribute cause to the temporal proximity of events, and attribute events to them without consideration of physical proximity. From three to eleven, a progression of causality occurs from the realism of infants to objectivity, reciprocity, and relativity. In the realism stage, perceptions and feelings are directly experienced (real) without additional thought or mental representation and without a notion of self and other. In the objectivity stage, there is an understanding of self and other. With reciprocity, the child places equal value on the views of him or her and other. With relativity, the child perceives the relationships between different objects. In early stages of causal reasoning, children may give animistic, finalistic, participatory, and artificial explanations of phenomenon. An example of animism from robotics is when children attribute causation in robots or machines to an anthropomorphic conception of machine itself (Mioduser et al., 2007). Finalistic explanations are the result of the belief that everything has an explanation and any explanation suffices regardless of its plausibility. Participatory explanations result from children's belief that they participate causally in natural phenomenon (magical thinking). Finally, artificial explanations attribute all causality to its benefit to humans (Fuson, 1976). Others have since built on Piaget's theories of causality.

Jonassen & Ionas (2008) provide a complex model (see) of causal reasoning and then suggest different ways to support the learning of causal reasoning. In this model, problem solving and conceptual change support predictions, implications, inferences, and explanations, which, in turn, enable causal reasoning. Predictions are defined as anticipating an outcome based on the initial state of a system and plausible causal relationships. Prediction in the model is defined in terms of either the scientific method, namely hypothesis, or forecasting events such as weather or economic performance. (Implication is defined as the same process as prediction but with more probabilistic causal relationships.) Inference is defined as the opposite process as prediction, that is, positing events and initial conditions based on a final set of conditions and plausible causal relationships. Explanation is defined as the ability to describe a system's components, functions, and causal relationships. The authors see causal reasoning being engaged by direct instruction, simulations, question prompts, and learner modeling.

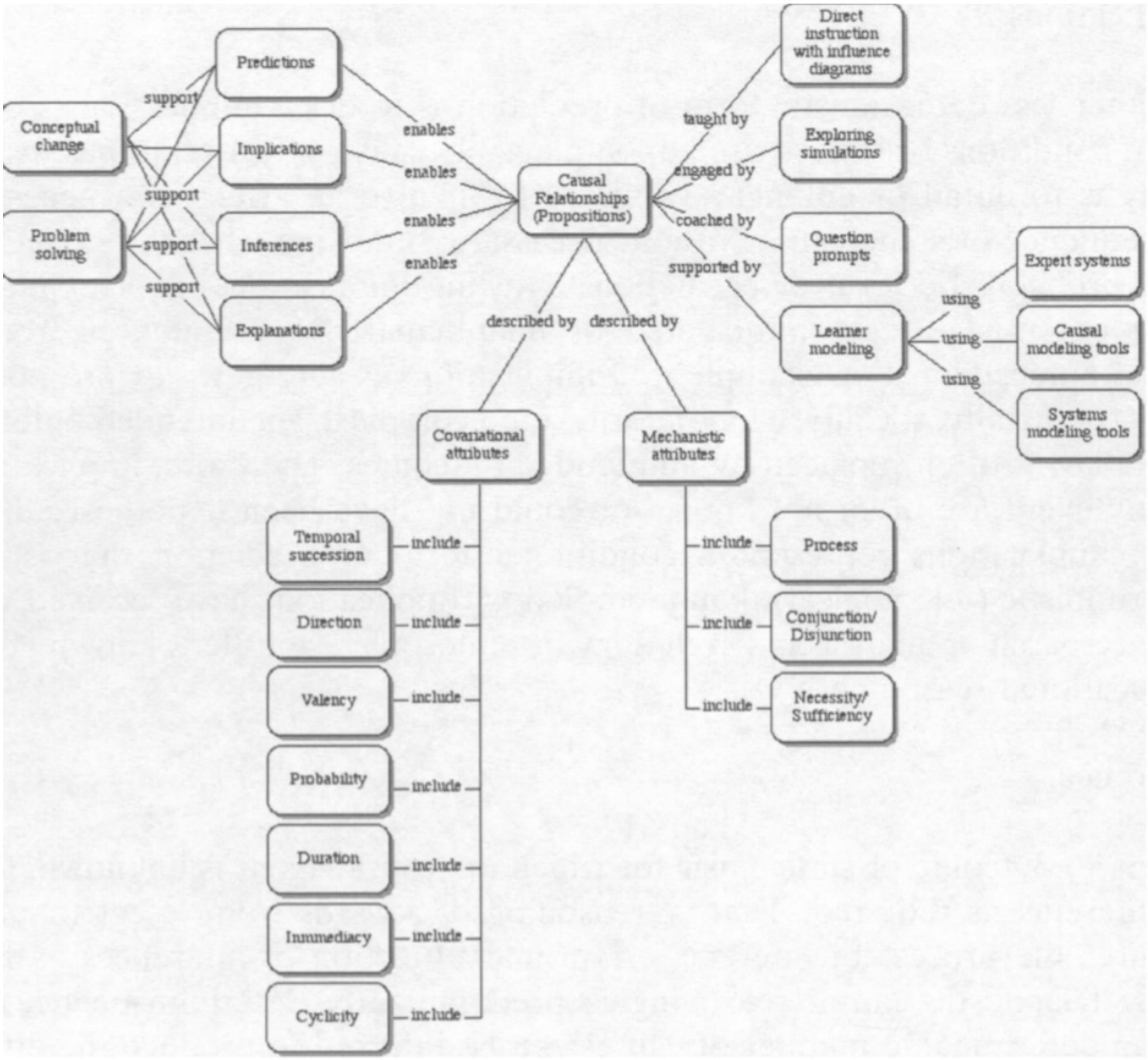


Figure 5. This figure shows a general framework for causal reasoning. From "Designing effective supports for causal reasoning" by D.H. Jonassen & I.G. Ionas, 2008, Educational Technology Research and Development, 56(3), p. 289. Copyright 2008 Association for Educational Communications and Technology.

Engineering education provides problem-solving affordances for learning causal reasoning. Although I was unable to locate any research on causality specifically in the context of engineering design, all four enablers of causal reasoning in this model are part of engineering - predictions, inferences, explanations, and implications - but prediction and inference are the most relevant. Engineers predict how a design, process, or software program will actually function in the physical world. Inference is used when troubleshooting a model or prototype to determine design or prototype build issues to understand why a prototype did not work so the design can be improved.

Casual reasoning and causal inference research typically centers on *a posteriori evaluation* of data to determine causes. Engineers make *a priori* predictions of the performance of their designed systems. The predictions may be supported with simulations, models, and prototypes. In the context of LEGO robotics, students are expected to design and then build a prototype with a prediction of performance in mind and then evaluate the actual performance with respect to predicted performance. Since prediction is usually associated with science, I use the term mental projection to describe this cognitive skill in the domain of engineering. The ability to mentally project the impact of design decisions turned out to be an important difference between the second and sixth grade students in my pilot study. A fourth grade student of mine was able to articulate the importance of causal reasoning in robotics this way:

> You have to think in a different way. This would make this - would make this - happen. Each step is connected.

While the literature on causal reasoning does not consider the domain of engineering, there are some principles and findings that may inform the study of causal reasoning in the context of engineering. Kuhn, Schauble, & Garcia-Mlia (1992) found that successful causal reasoning depends on: 1) students being able to realize that their existing theory could be wrong and 2) students refraining from only including data that supports their theories. I theorize that these factors may be impacted by development; specifically, ego-centrism (only seeing their own point of view) may make casual reasoning difficult for younger children (Piaget & Inhelder, 1969). Ego-centrism manifested in my pilot study for the second grade subject as 1) difficulty predicting the effects of non-functional design decisions and 2) difficulty reworking designs with problems. See Chapter 3 for a more in-depth discussion of Piagetian concepts such as ego-centrism.

The authors (Kuhn et al., 1992) also found that self-directed practice alone (such as open-ended engineering challenges) was sufficient to cause gains in scientific and causal reasoning. Finally, the authors suggest that the development of scientific reasoning - of which causal reasoning is an important component - is gradual, continuous, and not a discrete developmental milestone like Piagetian conservation.

Kuhn (2007) studied fourth grade students who received instruction in the control of variables (COV) strategy for understanding cause and effect. COV is the systemic manipulation of one variable at a time to pinpoint cause and effect. Even when they had mastered the COV strategy, students did not necessarily transfer it to the domain under study. She suggests that curriculum is needed to help students apply COV and other scientific reasoning skills. Engineering education could be one such domain.

Legare, Gelman, & Wellman (2010) found in their study of preschool children that inconsistent (rather than consistent) conditions triggered explanations which, in turn, triggered causal reasoning. The evaluation phase of engineering is rife with results that differ from the predicted outcome and therefore provides a rich experience for improving causal reasoning.

Kuhn & Dean (2004) report that research on causality is split into two camps. Causal reasoning can be described as utilizing either mechanism based (explanations), covariance based information (data), or both. Multivariate inference (MVI) researchers look at how college students attribute causes from multiple variables based on data. Scientific Reasoning (SR) researchers look at how children use knowledge of underlying mechanisms to attribute cause in the scientific realm. Kuhn & Dean (2004) argue that both approaches have merit. They conclude that research from both camps can be combined and causal reasoning should combine both data and underlying mechanisms. In the context of LEGO robotics based engineering challenges, students optimally use data from prototype evaluation and knowledge of underlying causal mechanisms.

Other studies attempt to show how causal reasoning manifests in young children. Buchanan & Sobel (2011) showed marked jumps in causal reasoning from age three to age four in experiments centered around changing battery and light configurations, which demonstrated that causal reasoning does have developmental characteristics. Their experiments also showed that this cognitive developmental was domain specific and not general (in contrast to Piaget's general and universal stages). Finally, the children needed to see and understand the underlying causal mechanism to successfully determine cause and effect.

In summary, research on causal reasoning has the following importance for a study of elementary engineering:

- elementary robotics curriculum and instruction should teach both data based and mechanism based approaches to troubleshooting,

- curriculum is needed to help students apply control of variables and other scientific reasoning skills,
- the development of scientific reasoning - of which causal reasoning is an important component - is gradual, continuous, and not a discrete developmental milestone like Piagetian conservation,
- self-directed practice alone (such as open-ended engineering challenges) is sufficient to cause gains in scientific and causal reasoning,
- engineers use both prediction and inference in their design processes and elementary engineering challenges create affordances to teach these skills.

Limitations of existing research. It is not clear how these different underlying executive function mechanisms and skills may overlap or be interrelated (McCormack & Atance, 2011). Although causal reasoning must be closely related to planning, there is no mention of causal reasoning in the review. Research in planning relies heavily on Tower of Hanoi and Tower of London tasks, which may differ significantly from the open-ended robotics engineering tasks in this study. Preliminary results from the pilot study indicate that milestones in these tasks may lag behind simpler, more well-defined tasks studied by educational psychology and other researchers (McCormack & Atance, 2011; Portsmore & Brizuela, 2011).

Summary of executive function as it relates to engineering. My thesis is that developmental, underlying cognitive mechanisms change significantly from second to sixth grade, especially causal reasoning, which affects the ability of students to solve open-ended engineering challenges specifically in the ability to predict the consequences of their design decisions. Furthermore, scaffolding in the form of teacher prompts can benefit students. The literature review of executive function, cognitive flexibility, and engineering and suggests a complex variety of related factors that may be at work in this domain. Some are functional such as problem solving (shown in blue) and some are underlying cognitive factors (shown in yellow) such as inhibitory control. The diagram below (see Figure 6) shows the relationships between these possible factors, ill-structured problems, and open-ended engineering problems as established by a synthesis of research, inference, and the pilot study. The diagram was used to guide the coding and analysis of the research data of second and sixth graders undertaking the same open-ended engineering problem (although not all factors may be detectable in this particular study).

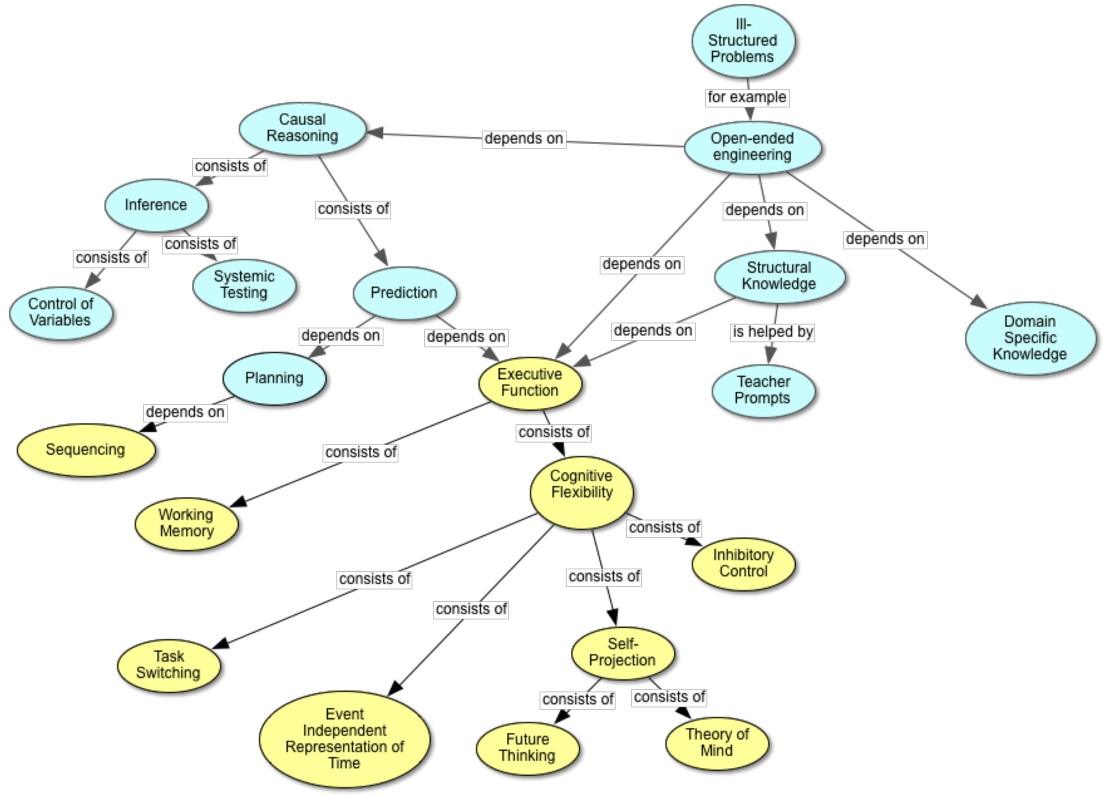


Figure 6. Relationships between engineering, functional, and cognitive factors.

Robotics and Gender

The lower numbers of women pursing STEM and, in particular computer science careers, is well-documented (Margolis & Fisher, 2003; National Science Foundation, National Center for Science and Engineering Statistics, 2013). For older students, there are indications that females have preferences for relational activities or programs with a social context although they can be attracted to traditional programs with prior exposure (Hynes, 2007; Melchior, Cutter, & Cohen, 2004; Nourbakhsh et al., 2005; Rosen, Stillwell, & Usselman, 2012; Skorinko, Doyle, & Tryggvason, 2012; Stein et al., 2004; Voyles, Fossum, & Haller, 2008). What are the other gender differences researchers have found in robotics programs? For the differences researchers and theorists have identified, do they operate at the age of elementary students, who may not yet have strong, internalized, socio-cultural gender expectations related to STEM learning?

A short discussion on what is meant by gender is appropriate. None of the studies reviewed here specified how gender was determined. Furthermore, researchers assumed a binary definition of gender as either male or female though non-binary instances of gender are certainly in use by many (Butler, 2011). In most cases, it was likely that gender was self-reported since questionnaires were used as the data source for demographic information. In one case, researchers recorded unspecified gender (Skorinko, Doyle, & Tryggvason, 2012) presumably by offering a non-specified gender option in their questionnaire. However, that class of gender was not included in their data analysis. In some cases, gender may have been assigned by teachers and researchers without regard to self-reported gender identify.

Most robotics studies show equal achievement for females (Hynes, 2007; Milto et al., 2002; Nourbakhsh et al., 2005; Nugent et al., 2010; Sullivan & Bers, 2013; Varnado, 2005) while two studies showed higher gains for males in some aspects of robotics programs (Nugent et al., 2010; A. Sullivan & Bers, 2013). For example, Sullivan & Bers (2013) found positive achievement results for kindergarten girls overall (in a curriculum that included art materials) but that boys did better in handing robotics materials and using IF statements. They suggested that stereotype threat (Committee on Maximizing the Potential of Women in Academic Science and Engineering (U.S.), Committee on Science, National Academy of Sciences (U.S.), National Academy of Engineering, & Institute of Medicine (U.S.), 2007) may be operating even for students as young as five and six. Stereotype threat is defined by Sullivan & Bers (2013) as the "the anxiety that one's performance on a task or activity will be seen through the lens of a negative stereotype" (p. 693). In these cases, females still showed gains but they were less than male achievement gains.

Voyles et al. (2008) also found marked differences in the way teachers responded to males and females in the context of a traditional robotics activity. While teachers felt that they were being sensitive to and supportive of both genders, some of their results could result in decreased self-efficacy and independence for females. For example, teachers thought for girls or did work for them more than for boys.

Turkle & Papert (1991) developed the theoretical notion of epistemological pluralism, which states that "hard" and "soft" approaches to computer programming are equally valuable. The "hard" approach is top-down, abstract, and distanced from computational artifacts while the "soft" approach is bottom-up, concrete, and characterized by closeness to computational artifacts. However, the "soft" approach is not valued in schools and in the field so this discourages women, who tend to take a "soft" approach. They say that, "sources of exclusion [are] determined not by rules that keep women out, but by ways of thinking that make them reluctant to join in" (p. 1). They propose that a thinking style that views computers as concrete, close, and transparent as an equally valid way of relating to and working with computers. The authors call this bricolage: "Bricoleurs construct theories by arranging and rearranging, by negotiating and renegotiating with a set of well-known materials" (p. 6). Bricolage is the same process that was later expanded into the notion of tinkering by Resnick & Rosenbaum (2013) as a "valid and valuable style of working, characterized by a playful, exploratory, and iterative style of engaging with a problem or project" (p. 164).

Gender differences in engineering and science process skills were not reported by studies in a study of middle school robotics camp study by Nugent et al. (2010). Varnado (2005) found no gender difference in problem-solving styles (or problem-solving achievement) in a large study of First LEGO League (FLL) participants. [FLL is a traditional, popular, after-school competition focused activity for middle school students.] However, differences in self-efficacy among male and female robotics students have been a strong focus of many studies.

Many studies of traditional robotics activities report lower initial self-efficacy in females (Nourbakhsh et al., 2005; Voyles et al., 2008; Weinberg et al., 2007). Girls can have lower self-efficacy in robotics even if their achievement is the same as boy's achievement (Voyles et al., 2008). Robotics activities do increase female self-efficacy (Melchior et al., 2004; Milto et al., 2002; Nourbakhsh et al., 2005) though it may still measure lower than male self-efficacy even after the activity. Weinberg et al. (2007) found that mentoring can positively impact female self-efficacy gains and overcome lower initial self-efficacy. Girl's self-efficacy in computers precedes loss of interest (Voyles et al., 2008) which shows the importance of self-efficacy for girls in robotics activities (Mead et al., 2012).

In summary, research on gender and robotics:

- suggests that important factors for the lower self-efficacy of females and the achievement differences that have been shown are due to stereotype threat, teacher differences in their treatment of boys and girls, the lack of acceptance of epistemological pluralism, and lack of previous experience,

- suggests that an examination of differences in engineering design processes of elementary age students as STEM gender-specific expectations solidify and how these differences relate to engineering self-efficacy may help inform the issue of STEM related gender differences.

Literature Review Conclusion

The literature review sought to answer the following questions.

- What is known about engineering and robotics particularly as it relates to student learning and development?
- What studies specific to elementary students exist?
- Were there cross-sectional or longitudinal research results that could help elementary teachers?
- How can my work contribute to the knowledge base of robotics based elementary engineering education?

Although robotics has been identified as a promising way to increase STEM interest and also to teach science concepts (Brophy et al., 2008), there is no extant research of student development in the context of a robotics in a sustained, long term elementary program. The studies that do exist show promising results for short term robotics programs in middle and high school (Hynes, 2007; Sullivan, 2008). Many of these studies use design, engineering, or robotics as a way to teach science concepts (Adamchuk et al., 2012; McGrath et al., 2012; Williams et al., 2007). Studies that do not show significant increases from robotics suggest longer term exposures are needed (Wagner, 1999; Williams et al., 2007).

Very few longitudinal or cross sectional studies exist for design or engineering. Roden's (1997, 1999) early study tried to broadly induce cognitive, affective, and social problem solving strategies at two points in early childhood. Fleer (1999) did some early, cross sectional work on characterizing the relationship between design and the artifacts actually produced in a design problem at ages five and eleven. English, Hudson, & Dawes (2013) are doing a longitudinal study of middle school students simple machine based designs. However, they are not looking at how students change over time but are more interested in the complete educational systems of teachers, students, and materials. There are some relevant cross-sectional studies. Crismond (2001) looked only at adults and high school students and the two cross-sectional studies (Fleer; Penner et al., 1997) did not cover the complete elementary spectrum and did not have a primary focus on engineering and robotics. Significant changes in engineering design processes and solutions have been documented for college students from freshman to senior years (Atman et al., 2005; Cardella et al., 2008).

There have been a number of case studies and microgenetic studies focused on engineering or design. However, most do not cover the elementary age spectrum (Crismond, 2001; Fleer, 1999; Leonard & Derry, 2011; Levy & Mioduser, 2010; McRobbie et al., 2001; Outterside, 1993; Roden, 1997, 1999; Roth, 1996; Sullivan, 2011; Wendell & Lee, 2010). Others are focused on design based science rather than engineering (Leonard & Derry; Levy & Mioduser; Penner et al., 1997; Wendell & Lee, 2010). Other case studies are not centered around cognitive development but more on curriculum or analyzing the classroom context (Leonard & Derry; Roth).

Sullivan (2008) does relate difficulties student had with multiple sensors, for example, to developmental issues in causal reasoning. Kazakoff & Bers (2012) related sequencing to the underlying developmental skills of centration and reversibility. However, there is no research that relates elementary engineering more broadly to more general frameworks.

There are many areas of elementary robotics that are unexplored. Examples are interest and motivation of robotics, the workings of social-cultural context, the efficacy of specific programs, and teacher challenges in implementation. The literature review did reveal a few studies have examined pieces of the cognitive puzzle of how development is expressed in design, engineering, and robotics. Other studies have examined engineering design processes thoroughly at different grade levels. However, there is a need for a systemic, developmental characterization and analysis of elementary engineering that will help inform curriculum, instruction, and assessment. This understanding could form the basis of a theoretical framework of robotics or a learning progression (Krajcik, 2011) for robotics based engineering education for K-6 students.

Given that little is known about teaching engineering to elementary students, this study seeks to answer the following questions (all in the context of an open-ended engineering challenge using LEGO robotics):

1) Do grade 2 and grade 6 students' engineering design processes and final products differ? If so, what are the specific differences?
2) Do male and female students' engineering design processes and final products differ? If so, what are the specific differences?

3) If differences are not seen by gender and grade level, what relationships do explain the differing final products and engineering design processes of elementary students?

In order to answer these research questions, it is first necessary to determine the most relevant theoretical frameworks, engineering design process models for a a cross-sectional case study of elementary robotics students in the context of established K-6 elementary robotics curriculum (Heffernan, 2013). The aim is to gain an understanding of students' skills and processes as they undertake open-ended engineering challenges at these two different ages in the context of robotics. The long-term goal is to inform instruction of engineering for elementary aged children.

CHAPTER 3

THEORETICAL FRAMEWORKS

Theoretical frameworks are overall theoretical lenses to view cognitive or other processes related to design. What are the most relevant theoretical frameworks that can inform a developmental cross-sectional, case study of elementary robotics students? In this section, I examine relevant existing frameworks and begin to synthesize a conceptual framework that guided the coding and analysis for this study.

Designerly Play

Designerly play (the elements of design that are found in children's play) has been identified as a fundamental component of childhood (Baynes, 1994; Petroski, 2003). Children "actively seek engagement with their surroundings" and "desire to interact and shape the environment" (Baynes, 1994, p. 12). The learning theories of constructivism (Piaget & Inhelder, 1969) and constructionism (Papert, 1993; Papert & Harel, 1991) provide frameworks to support the teaching of design because: 1) children actively construct their knowledge in design projects (constructivism), 2) they typically do so while building a physical model (constructionism).

Piagetian Constructivism

In a longitudinal or cross-sectional study with a strong focus on cognition, existing cognitive benchmarks are obvious frameworks in which to describe learning in the specific domain of focus, elementary engineering. Piaget's constructivist theory defines four stages of cognitive development: sensorimotor (0 to 2), pre-operational (2 to 7), concrete operational (7 to 11), and formal operational (11 and up) (Piaget & Inhelder, 1969). In a longitudinal or cross-sectional study of K-6 children, students transition from the pre-operational, intuitive thought substage (between grades K and 2) to concrete operational (grades 2 to grade 5) and finally to formal operational (grade 6). Piaget notes that ages are "average and approximate" (Piaget & Inhelder, 1969, p. 3).

The Piagetian developmental characteristics relevant to an elementary robotics study are listed below (Piaget & Inhelder, 1969).

1. Pre-operational, intuitive thought (K to grade 2)
    a. Egocentric – can only see their own point of view,
    b. Early causal reasoning – wanting to and starting to understand the "why" of things,
    c. Children know they have much knowledge but don't know how they acquired it,
    d. Key cognitive characteristics:
        i. Centration – only focusing on one aspect or cause of a situation,
        ii. Irreversibility – children can not mentally reverse a sequence of events,
2. Concrete operational (grade 2 to grade 5)
    a. Start solving problems logically but only with concrete objects,
    b. Inductive reasoning from cases to a general principle,
    c. Trial and error problem solving,
    d. Key cognitive characteristics (for concrete objects):

        i. Seriation – the ability to sort objects by different characteristics,
        ii. Conservation – even if an object’s appearance changes, the quantity remains constant,
        iii. Transitivity for concrete objects – just as in mathematics, if $A < B$ and $B < C$, the $A < C$,
        iv. Reversibility – the ability to mentally reverse a sequence of events or operations, specifically, objects that are modified can be returned to their original state,
        v. Classification – the ability to name sets (and subsets) based on objects’ characteristics,
        vi. Decentering – the ability to take in and reason about multiple aspects of a problem,

3. Formal operational (Grade 6)
    a. Deductive reasoning from a general principle to specific cases,
    b. Logical and systemic problem solving,
    c. Key cognitive characteristics:
        i. Abstract thought – all the operations developed in previous stages can be done mentally without reference to concrete objects,
        ii. Metacognition – the ability to reflect on cognition itself.

Piaget’s groundbreaking work was later modified and improved by Neo-Piagetian researchers.

Neo-Piagetian Constructivism

Neo-Piagetian researchers modified Piagetian theory to address issues that developed. Data showed that there was wide individual variation in the stages and that the cognitive structures Piaget described were not turning out to be as universal as he had claimed (Bidell & Fischer, 1992; Case, 1991; Young, 2011). Research showed that the Piagetian stages are culturally influenced and are, at least to some extent, a product of Western culture and schooling (Rogoff, 2003). This means that the results of this study are a product of their environment of Western educated students experiencing engineering projects every year in the context of their typical American curriculum so that universality across cultures cannot be claimed.

Theorists proposed a variety of modifications to Piaget to address the issues found. Bidell & Fischer (1992), in their skills theory, see cognitive development as more of a web than a linear stage model so that different children take different paths through the web. They also pointed out that active instruction and learning in domain specific areas *is* cognitive development; one cannot just wait for brain development to occur. Bidell & Fischer (1992) also point out the need for developmental sequences in different domains. This latter point reveals the possibility for the identification of a learning progression (Krajcik, 2011) for elementary engineering.

The modification of universal structures to domain specific structures was also delineated by Case (1991) with his notion of Central Cognitive Structures (CCS) and by Demetriou, Gustafsson, Efklides, & Platsidou (1992) with their Specialized Structural Systems. Case's work, in particular, has relevance for elementary engineering research. He defines a progression from stage to stage as children move from sensorimotor, to interrelational, to dimensional, to vectorial with each stage having its own general executive control structures in addition to the domain specific structures. Sensorimotor (1 to 18 months), like Piaget's sensorimotor stage, is centered on direct perceptions and actions such as seeing and grasping. Case conceives of the interrelational stage as being characterized by the addition of representational thought. For example, children can draw a picture or use words to stand for physical objects, feelings, and concepts. In the dimensional stage, general relationships between two things can be established, such as numbers on a number line. Finally, in the vectorial stage, many to many relationships can be established through things like abstract formulas that stand for the relationships. Case (1991) talks about progressing, within each stage, from one operation at a time, to two, and to more than two, and finally integrating the operations. Students, using this framework, would move from direct manipulation only (sensorimotor) to being able to draw their designs (representational) to simple cause and effect (dimensional) to multivariate reasoning (Kuhn, 2007) and systems thinking (Sullivan, 2008) (vectorial). This theory could shed light on the increasing ability of elementary students to plan and to project out the effects of their design decisions, which involves causal reasoning.

Constructionism

Constructionism (Papert, 1993) is the theoretical framework that underlies robotics (Papert, 2000; Papert & Harel, 1991). Constructionism was defined by Papert & Harel (1991) as follows:

> Constructionism--the N word as opposed to the V word--shares constructivism's connotation of learning as "building knowledge structures" irrespective of the circumstances of the learning. It then adds the idea that this happens especially

> felicitously in a context where the learner is consciously engaged in constructing a public entity, whether it's a sand castle on the beach or a theory of the universe. (p. 1)

Constructionism can also be seen as combining designerly play (Baynes, 1994) and constructivism (Piaget & Inhelder, 1969). Robotics embodies constructionism in the following ways.

- The use of programming and computers has a rich history intertwined with constructionism both in terms of the value of debugging as a process (Bers, Flannery, Kazakoff, & Sullivan, 2014; Sullivan, 2008) and the use of computer programming to explore big ideas (Papert, 2000).
- Students construct artifacts as way to explore big ideas; "children … construct powerful ideas through firsthand experience" (Martinez & Stager, 2013, p. 18).
- The use of the engineering design process gives children a balance of scaffolding and open-endedness that provides a "constructionist learning environment" (Bers, 2008, p. 17).
- Robotics, a constructionist learning environment, is a natural way to encourage epistemological pluralism (multiple ways of knowing) (Turkle & Papert, 1991).
- Students document their own designs and processes and share out with a larger community, which provide a vehicle for reflecting on learning, an important tenet of constructionism (Bers, 2008; Papert, 1993; Resnick, 2007).

Problem solving is a key part of robotics and the constructionist approach.

Problem Solving and Design Process Models

Problem solving is defined by Cohen (1971) as:

> Using basic thinking processes to resolve a known or defined difficulty: assemble facts about the difficulty and determine additional information needed; infer or suggest alternate solutions and test them for appropriateness; potentially reduce to simpler levels of explanation and eliminate discrepancies; [and] provide solution checks for generalizable value (p. 5).

Numerous similar, heuristic problem solving strategies have been proposed for ill-structured problems such a open-ended engineering challenges (Varnado, 2005). One example is: "recognizing the problem, defining the problem, selecting a strategy, attempting to solve by acting on a strategy, drawing conclusions and checking results" (Varnado, 2005, p. 18). Varnado (2005) synthesized the literature of technological problem solving strategies as a non-linear process containing the following steps:

1. Identifying and defining the problem,
2. Researching and analyzing relevant information,
3. Generating and implementing solutions to the problem,
4. Evaluating and revising the best possible solution. (p. 20)

The engineering design process is an example of a general problem solving process in the specific context of engineering. Engineering is defined as ": the work of designing and creating large structures (such as roads and bridges) or new products or systems by using scientific methods. ("Engineering - Definition and More from the Free Merriam-Webster Dictionary," n.d.)" Engineering problems are also defined by the inclusion of constraints. For example, safety and a specific manufacturing cost limits are examples of common engineering constraints (Crismond & Adams, 2012).

One way to determine changes over time in children's engineering skills is to characterize their engagement with the various stages defined by engineering design process models at different ages. There are a variety of design process models that can be used or modified for a longitudinal or cross-sectional case study of elementary robotics students that seeks to characterize and compare the engineering design processes of students at different ages in elementary school as they tackle open-ended engineering challenges. In this section, design process models and other relevant models are synthesized. For this study, I am only interested in engineering design process models, that is, specific delineations of the temporal stages of design that subjects use when tackling an engineering design task.

One typical engineering design process model is shown below (see Figure 7) (Portsmore, 2011).

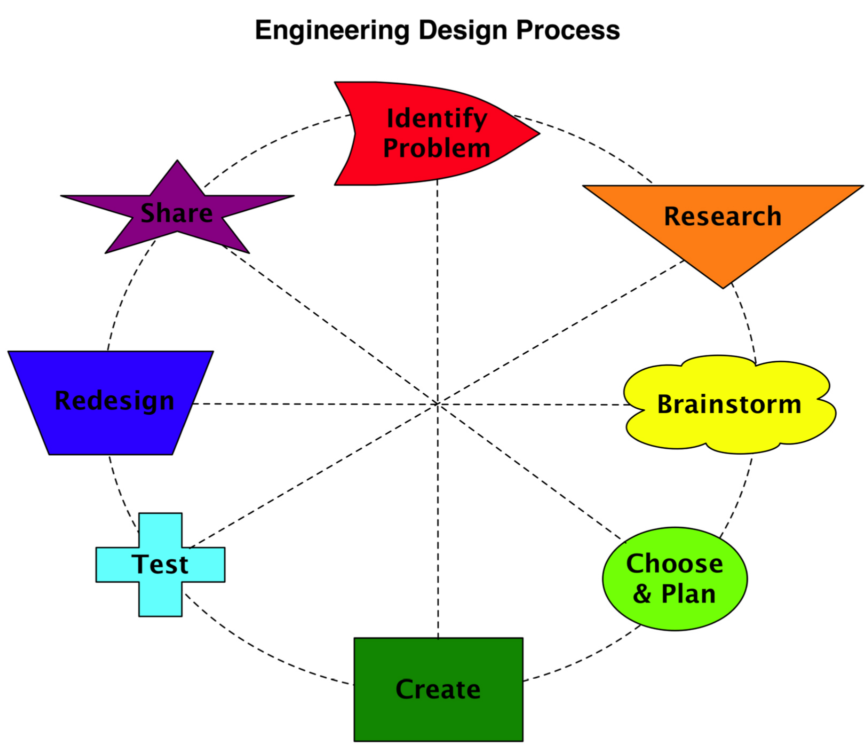


Figure 7. This shows a typical engineering design process model. From Dr. Merredith Portsmore, Tufts Center for Engineering Education and Outreach. Used with permission.

Note the connecting lines across the circle, which indicate that the flow in the process may not be linear around the circle. Note that brainstorming may not applicable in the context of this study since it is a typically a social process and this study uses individual students working alone. This model is an improvement on more linear models such as Mehalik, Doplet, & Schunn (2008). Welch (1999) points out that studies that show linear, rational, deterministic design process models may not actually be followed by designers and even less so by novice designers. Other models such as Resnick (2007) (see Figure 8) and Boehm (Martinez & Stager, 2013) spiral, which indicates that the process can repeat itself with the next iteration of the project. In the Resnick model, some of phases are defined very broadly (such as create and play) which would be hard to discern. Also, there is not a clearly defined evaluation (testing) phase.

Figure 8. This figure shows a spiraling design process model from “All I Really Need to Know (About Creative Thinking) I Learned (by Studying How Children Learn) in Kindergarten” by M. Resnick, M., 2007, *In Proceedings of the 6th ACM SIGCHI conference on Creativity & Cognition* (p. 2). Copyright 2007 Association of Computing Machinery.

EDP models vary according to the domain of interest with Boehm being very formal and applicable to large engineering projects and Resnick geared towards early childhood projects. Resnick’s model is also more general, that is, it applies to learning in general as well as the design process. In other cases, the model is essentially the same but some of the steps have different names. This can be seen in the Learning By Design Cycle (Kolodner et al., 2003; Puntambekar & Kolodner, 2005). Because the educational goal is learning science using design, this model, like that of Apedoe, Reynolds, Ellefson,

& Schunn (2008) (see Figure 9) and Fortus et al. (2005) incorporates science inquiry into the model. Since my primary purpose is teaching and understanding engineering design in children, design based science models may have extraneous aspects in terms of this study.

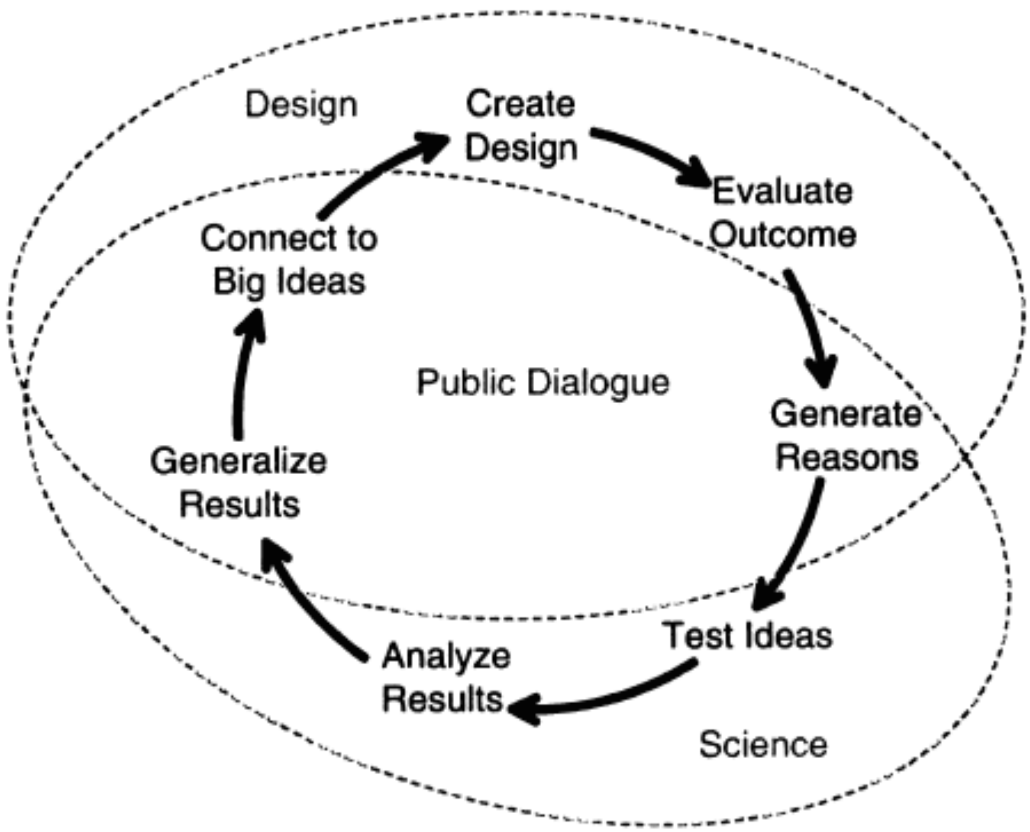


Figure 9. This figure shows a design process model with the inclusion of science processes and skills from "Bringing Engineering Design Into High School Science Classrooms: The Heating/cooling Unit" by X.S. Apedoe, B. Reynolds, M.R. Ellefson, & C.D. Schunn, 2008), *Journal of Science Education and Technology*, *17*(5), p. 458. Copyright 2008 Springer.

The Next Generation Science Standards (NGSS), developed in the United States in partnership with twenty six lead states and currently being adopted and implemented, integrates both engineering and scientific practices as both content standards and practices ("Next Generation Science Standards," 2012). Students are expected to be able to follow the enginering process as well as learn specific content on the engineering design process itself. The NGSS engineering design philosophy is found in three places in the final documents. First, NGSS defines a three step engineering process that increases in sophistication as students progress ("Next Generation Science Standards," 2012). Figure 10, Figure 11, and Figure 12 show that the models increase in sophistication.

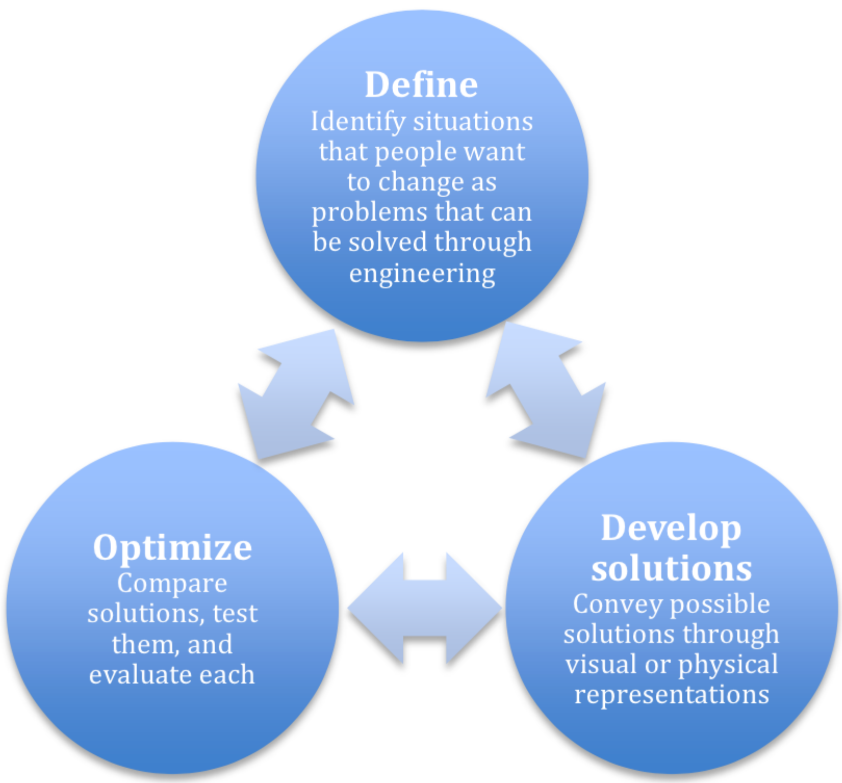


Figure 10. NGSS K-2 Engineering Design Model from Appendix I - Engineering Design in NGSS - FINAL_V2.pdf, 2013, retrieved 2015-04-06 06:24:30.

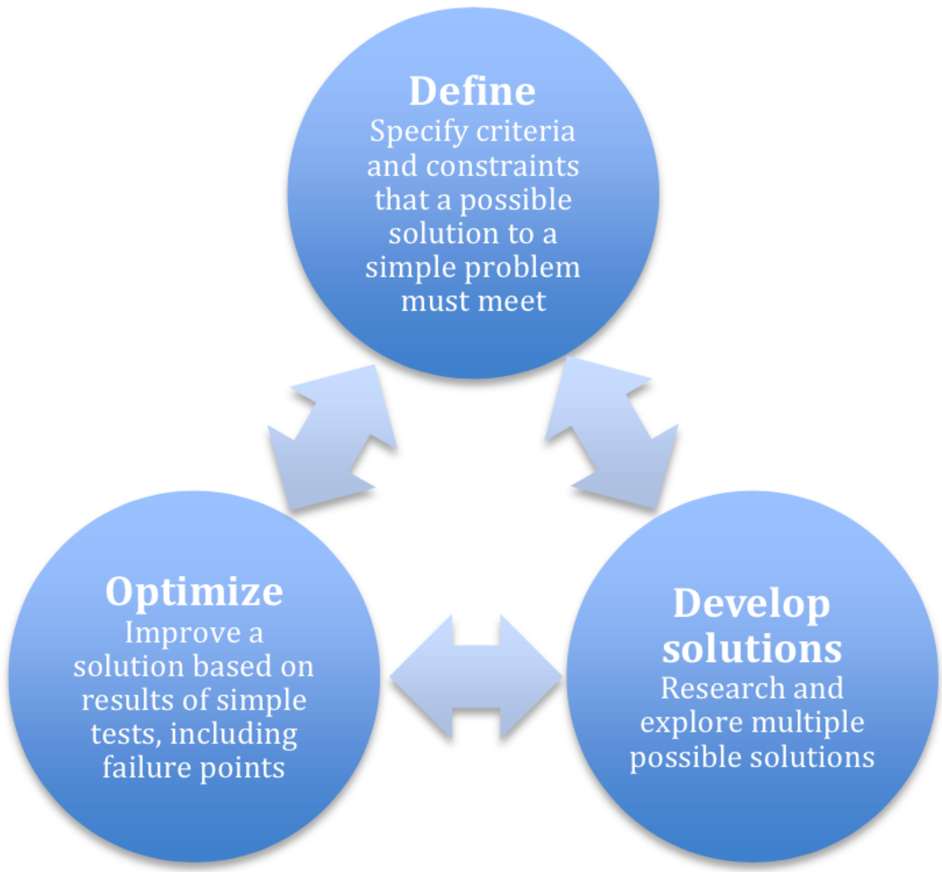


Figure 11. NGSS Grade 3-5 Engineering Design Process Model from Appendix I - Engineering Design in NGSS - FINAL_V2.pdf, 2013, retrieved 2015-04-06 06:24:30.

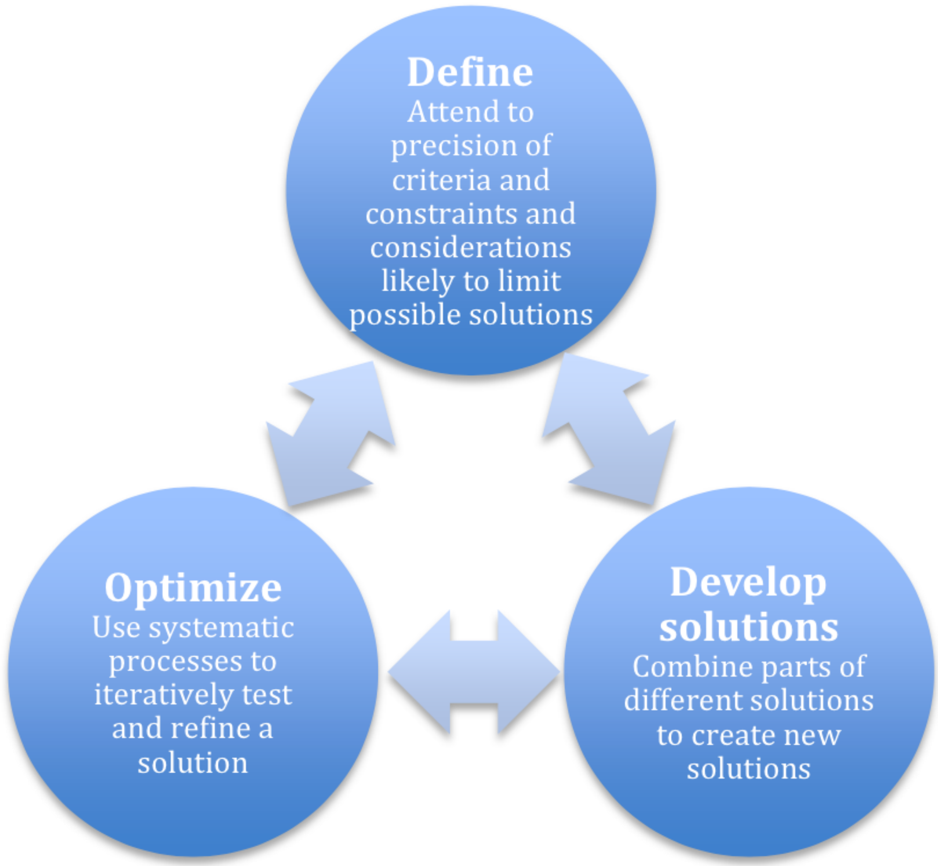


Figure 12. NGSS Grades 6-8 Engineering design process model from Appendix I - Engineering Design in NGSS - FINAL_V2.pdf, 2013, retrieved 2015-04-06 06:24:30.

The common elements of define, develop solutions, and optimize appear at each grade level. Problem definition adds an increasing focus on criterion and constraints over time. Solution development increases in sophistication as students get older, adding multiple solutions, and then combining different possible solutions. The optimization of solutions increases from simple testing to test and improve to systemic testing. The inclusion of systemic testing as well as the increased ability to keep in mind multiple solutions is consistent with Piagetian developmental milestones (Piaget & Inhelder, 1969). As in other models with few steps, the multiple phases of more complex models are combined. For research purposes, however, a more fine-grained model is needed to better describe the engineering design processes of elementary students.

NGSS also defines eight scientific and engineering practices that can also be seen as an engineering design process model ("Next Generation Science Standards," 2012). The engineering practices are shown below.

- Defining problems (for engineering)
- Developing and using models
- Planning and carrying out investigations
- Analyzing and interpreting data
- Using mathematics and computational thinking
- Designing solutions (for engineering)
- Engaging in argument from evidence
- Obtaining, evaluating, and communicating information. (p. 1)

Note that the definition of developing and using models above specifically includes prototypes, which are built in the robotics curriculum and engineering task used in this study. However, in our case of LEGO robotics based open-ended challenges, this consists of the major iterative task of building and programming of the prototype and needs to be examined in more fine-grained detail. These practices contain many elements of a traditional engineering design process model.   Example are defining problems, designing solutions, developing and using models (prototypes). However, some of these practices, such as analyzing and interpreting data, are not typically seen in elementary LEGO robotics tasks.

Finally, NGSS contains content standards for engineering design at each grade band. For example, the grade 3-5 engineering design standards are shown below ("Next Generation Science Standards," 2012).

> 3-5-ETS1-1. Define a simple design problem reflecting a need or a want that includes specified criteria for success and constraints on materials, time, or cost.
>
> 3-5-ETS1-2. Generate and compare multiple possible solutions to a problem based on how well each is likely to meet the criteria and constraints of the problem.
>
> 3-5-ETS1-3. Plan and carry out fair tests in which variables are controlled and failure points are considered to identify aspects of a model or prototype that can be improved.

Again, the curriculum and task (described in Chapter 4 - Methodology) used in this study are consistent with the NGSS engineering design standards ("Next Generation Science Standards," 2012).

Models also vary with the number of steps and complexity. Martinez & Stager (2013) have a simple three-step model they call TMI: Think, Make, Improve. The steps delineated in other models are subsumed into one of the three steps of the TMI model. For research purposes, however, a more fine-grained look at the engineering processes is needed. Bers, Flannery, Kazakoff, & Sullivan (2014) use another child friendly variation (see Figure 13) in robotics studies of kindergarten students. This model reflects the engineering design process of elementary students. However, the difference between imagine and plan would be difficult to detect.

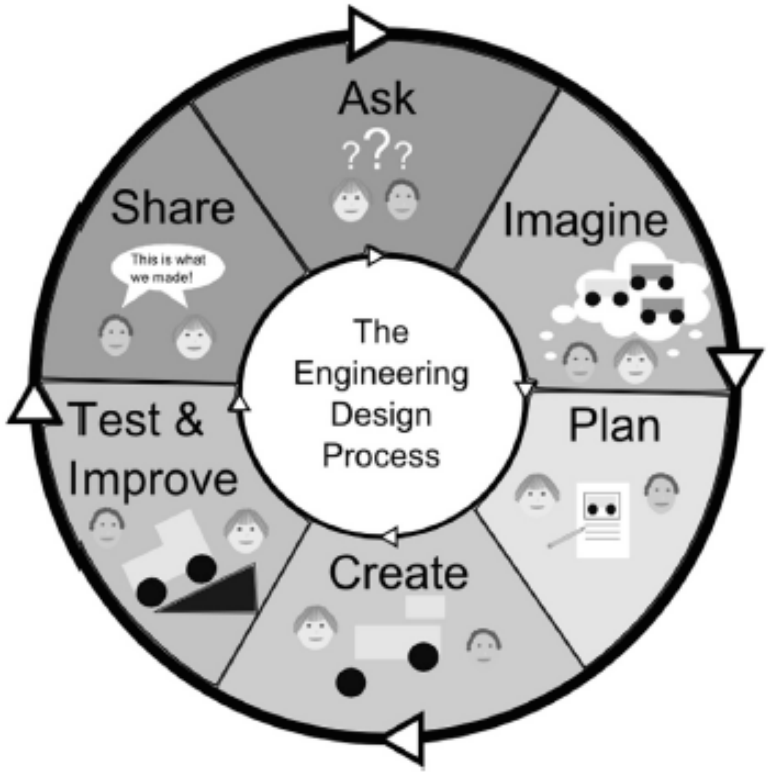


Figure 13. This figure shows a child friendly engineering design process model from "Computational Thinking and Tinkering: Exploration of an Early Childhood Robotics Curriculum" by M. Bers, L. Flannery, E. Kazakoff, & A. Sullivan, 2014, Computers & Education, 72, p. 155. Copyright 2014 Elsevier Ltd.

Crismond & Adams (2012) reviewed existing design process models and attempted to synthesize extant models into a parsimonious and widely applicable model. They do not explicitly label these strategies a design process model because they want them to fit into extant design process models with different numbers of steps (Crismond, personal communication, March 16, 2014). They define these nine parsimonious design strategies as part of their larger Informed Design Teaching and Learning Matrix.

1. Understand the Challenge
2. Build Knowledge
3. Generate Ideas
4. Represent Ideas

5. Weigh Options & Make Decisions
6. Conduct Experiments
7. Troubleshoot
8. Revise/Iterate
9. Reflect on Process

For each strategy row, the authors created a rubric consisting of columns for novice and informed designers. They also created columns of learning goals and teaching strategies. For example, for the design strategy "Understand the Challenge", novice designers "Treat design task as a well-defined, straightforward problem that they prematurely attempt to solve" while informed designers "Delay making design decisions in order to explore, comprehend and frame the problem better" (Crismond & Adams, 2012, p. 748). At the elementary level, some of the strategies would be hard to discern and could be combined. For example, generate ideas, represent ideas, and weigh options could be all consider planning.

Different researchers have created EDP models that best reflect their theories, age group, area of interest (for example, application of science), and materials. In a clinical interview setting (Ginsburg, 1997) such as the one planned for the this study, a design process model based on observable behaviors (visually and with a think-aloud protocol (Ericsson & Simon, 1993)) proved the most useful for measuring how engineering processes change over time in the pilot study. See Figure 14 for a diagram of the engineering design process model I created to use in this study. This model proved comprehensive and parsimonious for my pilot study. The model is strongly based on those of Bers et al. (2014); Crismond & Adams (2012); and Portsmore (2011)

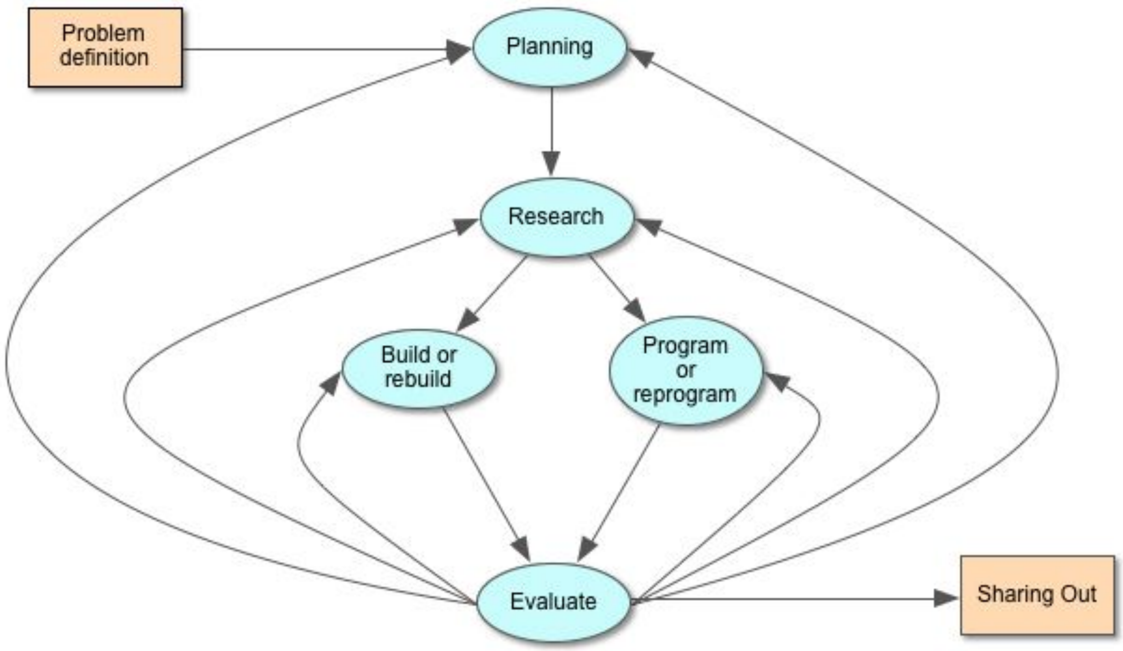


Figure 14. Engineering design process model for study. Note that problem definition and sharing out are parts of the model but were not part of the task so they may not be coded.

The specific phases in my EDP models are: problem definition, planning, researching, building, rebuilding, programming, reprogramming, evaluating, and sharing out. Each phase is defined as follows:

PLAN - subject was planning some aspect of their design, typically verbally.

RESEARCH - researching a problem or possible solution. Looking for parts can be considering research if it is affecting major design decisions before building starts. Otherwise, it is considered part of building.

BUILD-NORMAL - normal building, which includes looking for parts unless the looking for parts was part of researching the feasibility of a potential design.

BUILD-REBUILD - rebuilding (fixing) something that was built previously. This includes building it in a different way as well as reattaching a subsystem that fell off.

PROGRAM-NORMAL - programming the robot.

PROGRAM-REPROGRAM - fixing a previous program.

EVALUATE-PHYSICAL - evaluate by testing physically.

EVALUATE-VERBAL - evaluate without any physical test but by talking.

EVALUATE-VISUAL - evaluate by visual inspection without touching or talking.

EVALUATE-SYSTEM - evaluate the whole system including the program by running the program, which typically moves the robot in some way.

The distinction between building and rebuilding and between programming and reprogramming is germane to this study because the study seeks to identify the difficult parts of each session. Evaluation, in the context of engineering, refers to the determination of current state of a design in relation to the overall or intermediate goals of the prototype or final engineering solution (Cross, 2008). Different researchers use different terminology for this phase of the engineering design process. Examples are: testing, evaluation, and troubleshooting.

Note that problem definition and sharing out are parts of the model but were not part of the task so they are not expected be coded. In this study, the researcher defines the problem for the student. Furthermore, although refinement of the problem definition typically reoccurs throughout the design process (Atman et al., 2008), for the simple task and constraints used in this study, this was not observed in the pilot study. Students continually share out as part of the talk-aloud protocol and so sharing out is not a naturally occurring part of the EDP in this context.

Framework for Elementary Engineering Developmental Strengths and Challenges

The engineering design process model described previously (see Figure 14) above defines the codes that were used to characterize and compare the engineering design processes of the second and sixth graders. These codes were derived deductively using theoretical frameworks and verified in my pilot study. (Note that additional sub-codes were also developed and can be found in Appendix A - Code Book. There is no existing, coherent framework to describe the developmental strengths and challenges of elementary engineering students. Therefore a coding scheme and tentative conceptual framework was developed using a combination (Barron & Engle, 2007) of deduction (from what existing frameworks suggested) and induction using techniques from grounded theory and developed during the pilot study (Charmaz, 2014; Glaser & Strauss, 2009).

Figure 15 shows the initial conceptual framework that will be used to code the video captured in the study. Basically, the framework defines factors that most strongly influence open-ended engineering tasks at the elementary level. Ellipses in yellow indicate codes and categories primarily derived from induction. However, possible theoretical factors not revealed in the pilot study were added to the coding dictionary. An example of this is magical thinking in the causal reasoning category. Although not seen in the pilot study, it is believed to be a important stage in causal reasoning (Fuson, 1976). The blue engineering design ellipse was primarily deductively derived but verified experimentally in the pilot study.

The categories of codes are:

- Engineering Design Process Skills - students' utilization of the engineering design process. Examples: planning, researching, building, and evaluating (their design).
- Problem solving - secondary aspects of problem solving as predicted by theory or as seen in the pilot study. Examples: the application of mathematics and science to solve an engineering problem and the use of systemic testing.
- Causal Reasoning - causal reasoning skills seen. Examples: magical thinking, projection (prediction), and control of variables strategy.
- Designerly Play - elements of fantasy play seen which is predicted to change from simple storylines (Fleer, 1999) or talking to the robot to more mature manifestations such as playful talk (Sullivan & Wilson, 2015) as students age.

The methodology section will further define the details of the coding and analysis process used to create this framework.

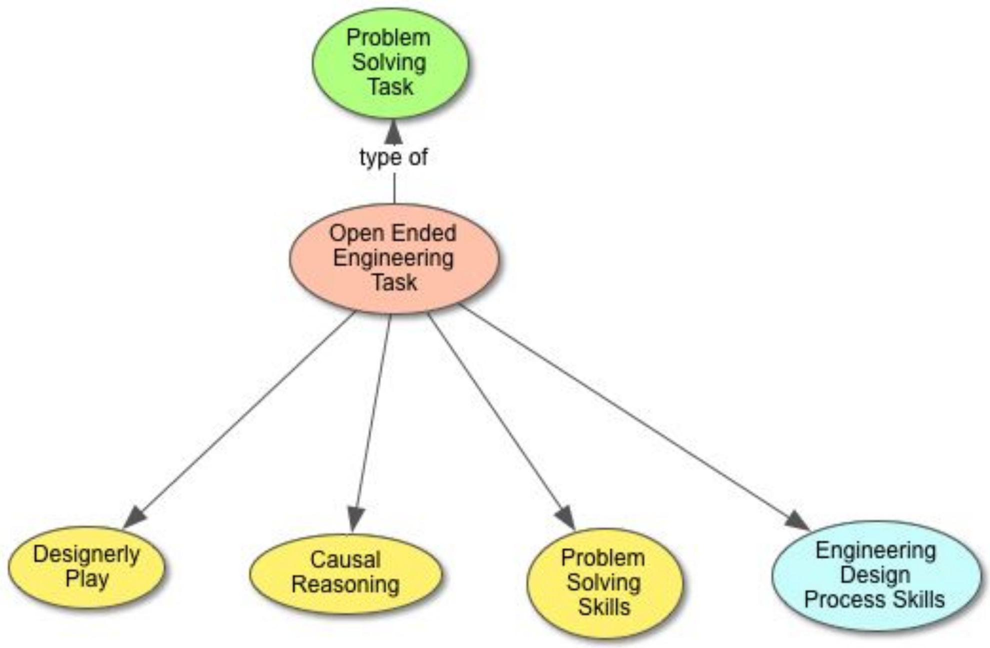


Figure 15. Proposed, theoretical framework of key factors in elementary engineering open-ended challenges initially used for study. Ellipses in yellow were primarily derived from induction. The blue engineering design ellipse was primarily deductively derived.

Presumably, these factors have developmental, previous experience related, social-cultural, and ability related components. Neo-Piagetian theory suggests that development and experience are intimately related and not separate (Bidell & Fischer, 1992). Therefore, it is not possible to directly trace cognitive changes seen in engineering design processes solely to development. However, a secondary aim of this study is to investigate how developmental milestones might play important roles in age related differences in elementary engineering. For example, in my pilot study, the second grade subject showed a marked tendency to persist in non-optimal design decisions, which can explained by Piagetian notions of centration (only being able to focus on one aspect of a problem at a time), irreversibility, and egocentrism.

Many studies focus on composite cognition skills. For example, sequencing (Kazakoff & Bers, 2012) involves centration and reversibility, which the authors specifically call out. I also infer that seriation is an important component to sequencing. Most researchers do not specifically trace composite cognitive skills to their Piagetian or neo-Piagetian building blocks. Furthermore, the developmental skills found by Piaget may omit important cognitive, affective, and physical skills important to elementary engineering. For example, the application of math and science knowledge may prove important.

Piaget's constructivism showed that milestones could be found for logical and mathematics tasks and that children create their own knowledge (rather than being empty vessels that receive knowledge directly from an adults). Constructivism is key to the development of constructionism, of which robotics is often cited as a prime example (Bers, 2008; Eguchi, 2012). The neo-Piagetians (and others) determined that the milestones are not as universal and uniform as Piaget claimed but are more domain, culture, and child specific (Case, 1991; Rogoff, 2003). For example, there does not appear to be one age when children "get" conservation (Case). Different conservation tasks are mastered at different ages. However, it does appear that within any given domain, there are common, domain specific milestones that can be determined. Reaching these is also a function of a general cognitive level Case calls central conceptual structures (Case, 1992). The neo-Piagetians also pointed out the development is tied to learning experience and is not separate so domain specific milestone attainment is also a function of experience.

What does this mean for this study of elementary engineering and development? This study will look for milestones and key factors in the engineering design processes of these students by looking at the two age samples of typical students. These may or may not map directly to Piagetian (or neo-Piagetian) milestones. The mapping of engineering to cognitive milestones is an interesting area for future research but is not the primary purpose of this study. I hypothesize that the engineering design process, problem-solving, and causal reasoning differences that will be found have "behind" them a complex mix of the logical-mathematics Piagetian and neo-Piagetian defined skills, engineering specific skills, and composite skills, and also executive function skills such as cognitive flexibility.

This study will characterize and compare the engineering design processes of typical grade 2 and grade 6 students in the context of a long-term, sustained elementary engineering curriculum. In addition to the examination of engineering design process, related causal reasoning and problem solving skills will also be analyzed to see if and how they change by age and gender. Based on the significant differences found in the pilot study and the examination of developmental frameworks, I hypothesize that significant changes in grade 6 students may be seen in:

- Increased planning and research,
- More use of drawing as a means of planning,
- Increased ability to "start from scratch" and rework problematic designs,
- Increased use of mental prediction to project out the effects of design decisions,
- Increased use of inference to speed troubleshooting (as opposed to more concrete and trial and error approaches of younger students),
- More systemic testing and systems thinking.

Differences based on gender are harder to predict. However, I conjecture that, despite the participation in yearly engineering projects, some decrease in self-efficacy due to social-cultural pressures may be occurring even in elementary school. Therefore, differences between boys and girls in their engineering design processes should increase from grade 2 to grade 6.

Summary

In summary, the extant research on design, engineering design, causal reasoning, and robotics comes out of constructivist, and constructionist frameworks. A constructionist/constructivist framework best informs my own research questions on the cognitive aspects of elementary engineering in the context of the EEC curriculum. The goal of this study is to use the constructionist/constructivist theoretical framework combined with an inductively derived factor framework to gain an understanding of students' processes as they undertake open-ended engineering challenges at two different ages. The long-term goal of this line of research is to optimize the teaching of elementary engineering taking student development and engineering experience into account. The next chapter describes the techniques that will be used to answer the research questions.

CHAPTER 4

METHODOLOGY

Study Design

This section describes the methodology used to answer the following research questions which all take place in the context of an open-ended engineering challenge using LEGO robotics:

1) Do grade 2 and grade 6 students' engineering design processes and final products differ? If so, what are the specific differences?
2) Do male and female students' engineering design processes and final products differ? If so, what are the specific differences?
3) If differences are not seen by gender and grade level, what relationships do explain the differing final products and engineering design processes of elementary students?

To meet the goal of understanding K-6 elementary engineering skills and process development, I conducted a study that had the following characteristics:

- Studied students changes over time with either a longitudinal or cross-sectional study,
- Unpacked student learning in detail with a case-study study design,
- Focused on K-6 elementary students,
- Focused on student cognition,
- Analyzed the engineering design processes of students at different ages and by gender.

In the pilot study I completed as part of my comprehensive exams, I conducted a cross-sectional, cross-case, qualitative case study that examined two students (one at grades 2 and one at grade 6) as they implemented the same open-ended engineering challenge with age appropriate robotics and craft materials. The materials were the ones that they have used in the classroom robotics curriculum (Heffernan, 2013) and changed according to the grade level. A cross-sectional design was used so the study could be completed within the dissertation timeframe. (A longitudinal design would take four to five years to complete.) Students were invited to describe and capture their initial ideas and plans through talking, writing, and/or drawing. The pilot study determined most relevant methodologies that will be used for this larger cross-sectional, case study of elementary robotics students that seeks to characterize and compare the engineering design processes of students at different ages in elementary school as they tackle open-ended engineering challenges.

The pilot study verified an engineering design process model (see Figure 14) that was appropriate for the elementary age range and LEGO robotics open-ended engineering task. The pilot study and literature review suggested that significant age related differences also exist in student problem solving and causal reasoning for open-ended engineering challenges. A more systemic approach (including some initial codes and categories) for characterizing these differences also emerged from the pilot study (see Figure 15 and Appendix A - Code Book.

The pilot study determined the following:

- The task,
- The videotaping and interview process,
- The transcription process,

- A coding scheme for the video,
- An engineering design process data analysis process and outputs,

The methodologies developed in the pilot study and additional methodologies for this study are described in this chapter. First, the context of this study is described.

Curriculum, Instruction, and Materials

Students were presented LEGO robotics materials both appropriate to their age and what they had used in class that year as well as craft materials: writing utensils, paper, tape, wooden blocks, and post-it notes.   The second grade students used the Lego Education WeDo Construction Set 9580 and LEGO Education WeDo Resource Set 9585.

Figure 16. LEGO WeDo Base Set used by grade 2 students.

Figure 17. LEGO WeDo Resource Kit used by grade 2 students.

Sixth grade students also used the LEGO robotics materials that they use in class and that are appropriate to their grade level: the LEGO Education NXT Base Set and the LEGO Education Resource Set. The resources sets at both grade levels add many additional elements that greatly increase the design possibilities for each grade level.

Figure 18. LEGO Education NXT Base Set used by sixth grade students.

Figure 19. LEGO Education NXT Resource Set used by sixth grade students.

Both kits are very similar in that they contain a controller, sensors, motor(s), gears, pulleys, wheels, axles, connector pegs, bricks, beams, and plates. They differ in the number of pieces. NXT programming is more complex but based on the same block based design. The use of different materials for each grade level had a slight risk of influencing the design processes. However, during the pilot study and in classroom practice, the differences in age, cognitive development, and building style seem to be the dominant factors rather than the particular materials.

Students in this study are taught using the The Elementary Engineering Curriculum (EEC) (Heffernan, 2013), which uses a mediated learning approach (Suomala

& Alajaaski, 2002) combining teacher instruction, structured activities, and open ended engineering challenges.

The EEC was designed with the following goals.

- Engage students.
- Provide a progression of programming skills.
- Provide a progression of building skills.
- Provide a progression of underlying science concepts.
- Spiral back to reinforce programming, building, and science concepts.
- Integrate technology, science, math and English/Language Arts.
- Be teachable by classroom teachers.
- Teach cooperative learning skills.
- Mix teacher directed and student centered (open ended challenges) projects. The teacher directed activities provide the base knowledge the children build upon for the open-ended challenges.
- Meet state and national standards.
- Start in kindergarten and continue to grade 6. Students experience one or two units a year, each consisting of six to eight class sessions.

Students in kindergarten program Terrapin Logo BeeBots to:

- trace letters,
- count, add, and subtract on a large, laminated number line,
- help their BeeBot get from one point to another going around obstacles.

No building is required for BeeBots so the focus is on programing and the underlying cognitive skill of sequencing (Kazakoff & Bers, 2012).

Figure 20. Terrapin Logo BeeBot.

Grade 1 to grade 4 students use the LEGO Education WeDo kit. Students typically start each grade with lessons based on the LEGO supplied curriculum and building instructions. For example, grade 4 students make soccer players (kickers, goalies, and fan) and take data with a mathematics-focused unit. They then make and "sell" their own burglar alarm with an open-ended engineering challenge.

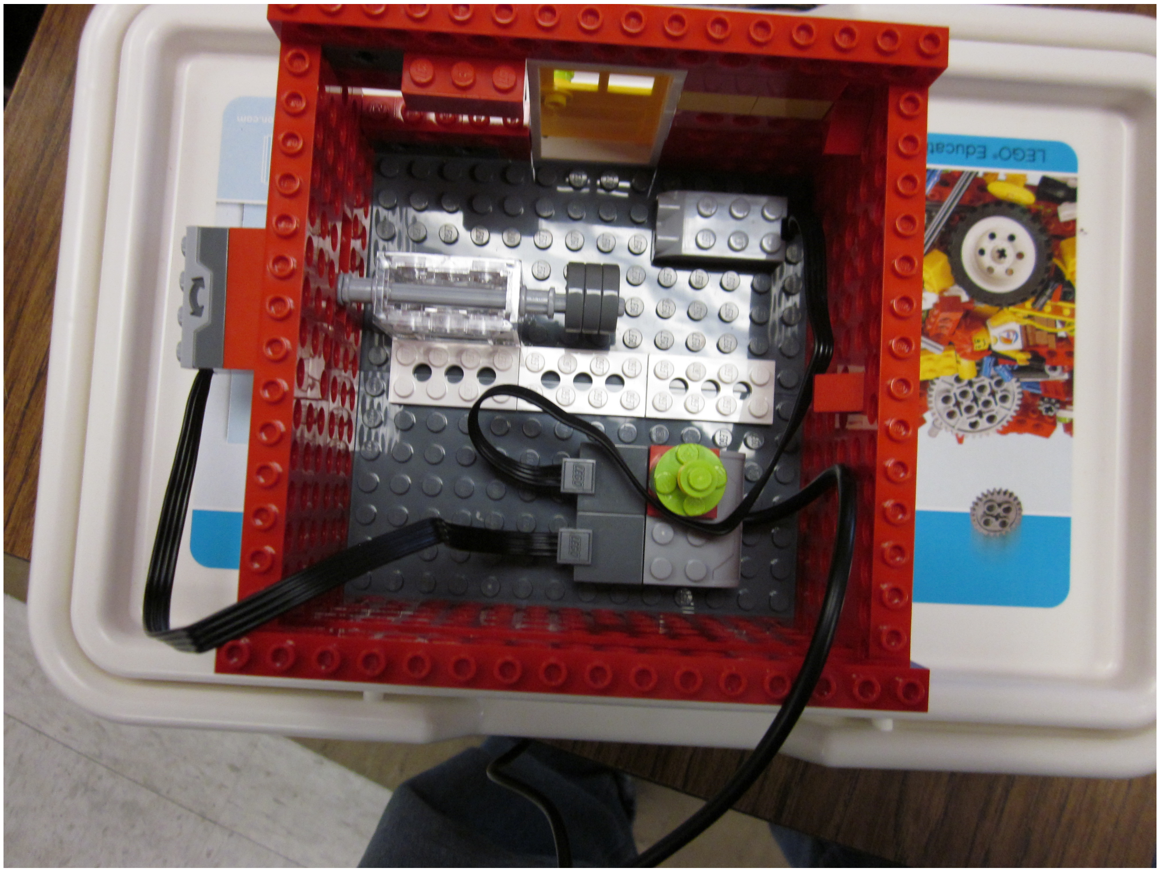


Figure 21. Example of a grade 4 WeDo based burglar alarm.

Grade 5 students, in a spiraling of the kindergarten curriculum, build and program an LEGO Education Mindstorms NXT robot to trace different geometric shapes on the floor. Grade 6 students, again with a spiraling of their previous experience with gears, design and build a dragster to go as fast as possible using gearing up.

Note that although students work in dyads in class to develop collaboration and communication skills (The Partnership for 21st Century Skills, 2002), this study focuses on individual cognition and building style so the students worked alone.

Study Setting and Participants

The school is a small, rural elementary school (PK-6) located in Western Massachusetts with 158 students. The school is 94.9% white. 19% of students have identified disabilities and 1.9% are English language learners. 25% are classified as low income. ("MA DESE School Profiles," n.d.). This study examined the open ended engineering processes of twelve students, six at grade 2 and six at grade 6. Three boys and three girls were chosen at each grade level. Gender was assigned by how the students self-identified and the gender they were assigned by parents and teachers, which in this sample was the same. Students were also chosen by who would do well with the think-aloud protocol, that is, they are able to verbalize their actions to the researcher. Each student at each grade level is a typically developing STEM student. This was determined by the classroom teacher and technology teacher (the researcher) looking at the following factors:

1) MCAS (Massachusetts Comprehensive Assessment System) grades for science/engineering/technology and mathematics for sixth grade students,
2) Report card grades for science and mathematics for second and sixth grade students,
3) Student participation in STEM enrichment programs,
4) Observation of students in the regular robotics curriculum.

All second and sixth grade students participated in the research have been at the school since kindergarten so they have participated in the Elementary Engineering Curriculum for three and seven years respectively.

Data Collection and Analysis Timing

Data collection in the form of videotaping took place in November and December of 2015. One subject was rejected due to her difficulty talking aloud as she worked. A suitable replacement was found. One subject was redone because he did not use any LEGO pieces initially. However, he basically built the same ride, a roller coaster, with LEGO pieces. The second video session was used. One subject was redone because the camera was not started initially. Simultaneously filming and executing the talk-aloud and clinical interview was challenging at times. The video camera had some issues with autofocusing from the particular angle and materials setup. However, all video was usable.

The audio recorder files were sent out immediately for transcription. Segmenting took place in February to March of 2016 and coding took place from March to June of 2016. Data analysis took place in June and July of 2016. However, it should be noted that data was also partially processed as it came in so that preliminary analysis was ongoing.

Raw Data Collection

Students were videotaped to capture their discourse and building/programming moves. Through a think-aloud protocol (Ericsson & Simon, 1993) and semi-structured clinical interview (Brenner, 2006; Ginsburg, 1997) their verbal discourse was captured. Subjects described their thoughts and actions as they performed the open-ended engineering task also using the same think-aloud protocol. Subjects were gently reminded to think-aloud if they lapsed into silence. The think-aloud protocol was used in the context of a clinical interview process to further probe their engineering design processes.

> Ginsburg (1997) defines the clinical interview process this way: the clinical examiner begins with some common questions but in reaction to what the child says, modified the original queries, asks follow-up questions, challenges the student's response, and asks how the student solved various problems and what was meant by a particular statement or response. (p. 2)

A similar process was used in this study. However, the goal was to neutrally ascertain students' thinking and processes so student responses were not challenged during the actual building. The discourse, in combination with the videotape of the building and programming moves, comprised the main data for this study. The use of "careful observation of the child's work with 'concrete' intellectual objects" (Ginsburg, 1997, p. ix) was critical to later analysis of the building of the engineering prototypes.

Before students built their amusement park ride for the main part of the research, they did a warm-up task. The purpose of the warm-up task was two fold. The study aimed to compare the engineering processes of *typical* second and sixth grade students. The task provided a baseline of student performance on open-ended engineering tasks. The task was an additional way to verify that students are typical performers. For example, if a second grader shows advanced performance on the main task, the warm-up was checked to verify that this student is not a typical second grader. The task also provided a means to teach and practice the talk-aloud protocol before the main task begins (Ericsson & Simon, 1993).

In the task, students constructed a flat and sturdy roof to an existing set of walls using a set of provided LEGO beams and plates. The provided beams and plates do not span the walls so students must use different techniques to make the roof. They might create composite pieces or add interior walls to solve the problem. After the warm up tasks was completed, students did the main amusement park ride task.

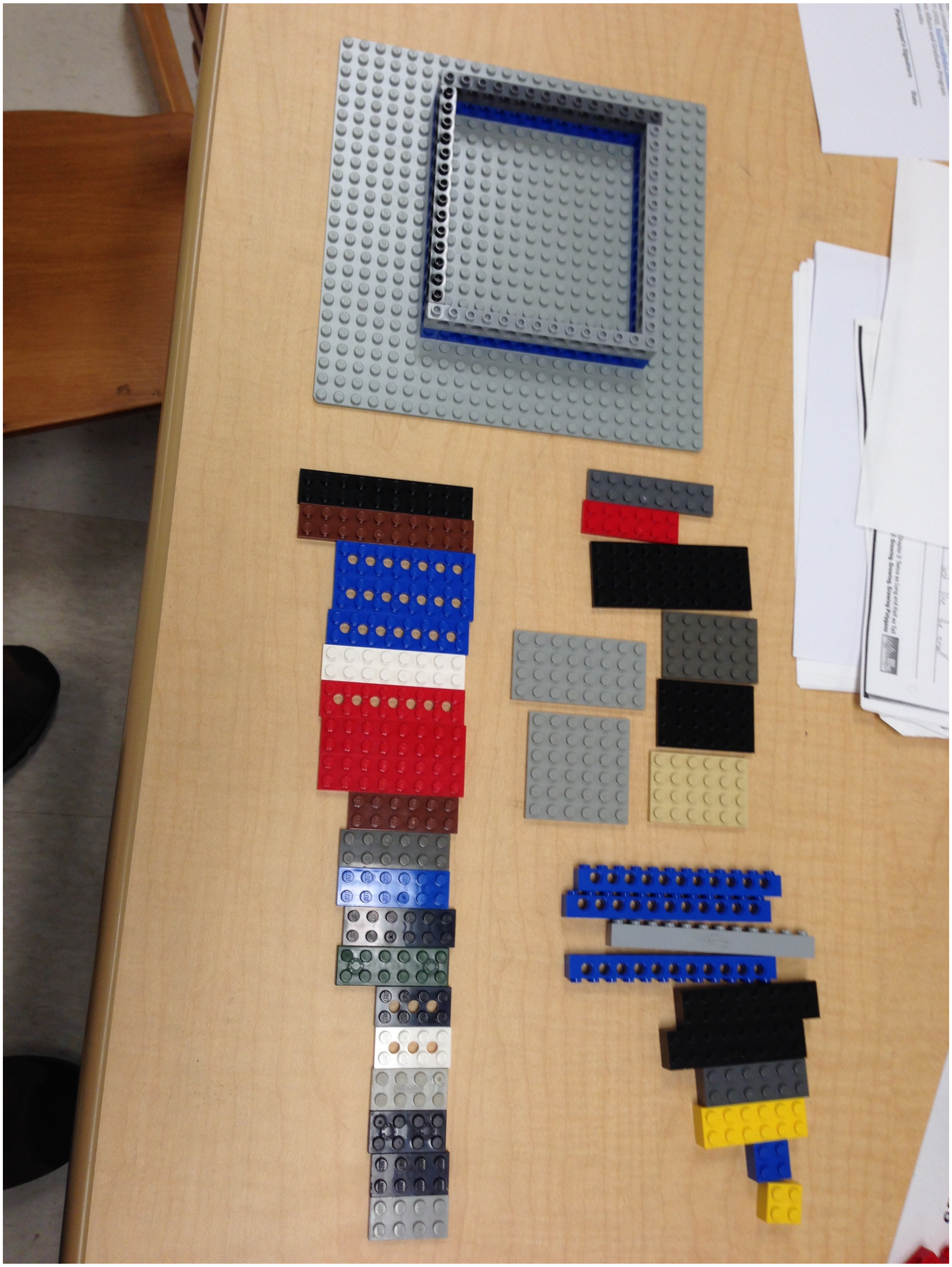


Figure 22. Warm up task setup and materials.

Students were rated on their warm up task according to a rubric. A rubric was created using video from two second graders and two sixth graders. The rubric was further refined using the eight main subjects. See Appendix D - Warm Up Task Rubric for the actual rubric.

For both the warm and main tasks, the subjects were videotaped from the side. The researcher took field notes during the sessions. The researcher also watched the video and took notes on each session (Erickson, 2006) before the transcripts are examined to get an overall impression of the sessions before coding in detail.

For the main task, four questions were asked using a clinical interview methodology (Ginsburg, 1997) after the build is completed to see if additional reflection on the ask might yield more information. Two questions ask the student what they found easy and difficult about the task. Two age-appropriate questions ascertained the students' self-efficacy for the completed task. See Appendix B - Research Prompt for the post interview questions.

Other data that helped characterize the designs and triangulated the video data was also captured: elapsed time of design activity, design artifacts, photos of the design in progress and the completed design, and the computer program the student developed.

This section has described the raw data that was captured and the context of that data. The next section describes how the raw data was developed into data that could be analyzed.

Derived Data

The raw data was transformed into derived data that could be analyzed. The data can be classified into four different types: finished model design data, engineering design process (EDP) data, secondary EDP data, and summary rubric data.

Finished model design data. The first type of data is data from the finished ride models and programs. Each finished prototype (model) was analyzed in terms of its design attributes such as number of parts, types of parts used, and overall quality (using a rubric, see Appendix E - Finished Design Quality Rubric). The capture and analysis of finished artifacts has been done previously in studies of this type (Portsmore, 2009; Portsmore & Brizuela, 2011; Stiles & Stern, 2001).

The following data was captured or derived from the finished rides and programs. The first group of finished model design data was derived from the warm-up task: time to complete, time rating, functionality rating, task process rating, task overall rating. The ratings were determined using Appendix D - Warm Up Task Rubric. The second group of finished model design data was from the main task of designing and building a model amusement park ride. See Appendix E - Finished Model Design Quality Rubric for the criterion used to determine the ORIGINALITY, FUNCTIONALITY, and PROCESS ratings.

NUMBER-PARTS - number of parts used in final prototype.

- NUMBER-STEPS - number of steps/blocks in final program.
- ORIGINALITY - rating of whether design did (or did not) shown originality (4 highest to 1 lowest). This criterion based rating captures how much the student did (or did not) use elements of designerly (creative) play (Baynes, 1994) in their model.

- FUNCTIONALITY - rating of how well the ride meets the design criteria. This criterion based rating captures how well the student did (or did not) meet the engineering requirements and criterion of the design (Brophy et al., 2008; Crismond, 2001; McCarthy, 2012).
- PROCESS - rating of the subject's engineering design process specifically with respect to causal reasoning and planning (4 highest to 1 lowest). This criterion based rating gave a basic evaluation of the student's EDP using some of the aspects discussed in Chapters 2 and 3 such as cognitive flexibility, causal reasoning, the application of mathematics and science. In some of the visualizations, this is termed Preliminary EDP Rating since EDP was also later analyzed with the EDP timelines and the Summary Rubric (see below).
- RATING - overall rating of finished ride quality; mean of above three aspects - originality, functionality, and process (4 highest to 1 lowest). Note that a four point scale was selected because it distinguishes sufficiently and uniquely between different levels of performance without having so many levels that would have made rating difficult (Arter & McTighe, 2001).
- STABLE - final design is stable (1/0)
- SYMMETRICAL - final design is symmetrical (1/0)
- SCALE - final design is to scale (1/0)
- USE-COMPUTER - subject used the computer to animate the prototype. (1/0)
- USE-CRAFTS - the subject used craft materials (includes blocks) in the prototype. (1/0)

- USE-DIRECT-COUPLING - the ride uses direct coupling of motor to axle to move. (1/0)
- USE-GEARS - the ride uses gears to move. (1/0)
- USE-MOTOR - the rides uses a motor. (1/0)
- USE-PULLEYS - the ride uses pulleys between to move. (1/0)
- USE-SENSOR - the ride uses a sensor. (1/0)
- USE-PLANNING - the student produced planning artifacts on paper before building. Post-make drawings are not counted. (1/0)
- TIME - elapsed time of build. Not evaluated in any way but captured as a possible item of interest.

While the design data captured important characteristics of each final product, data needed to be derived that captured the engineering design process (EDP) of students.

EDP data. The second type of data is called the engineering design process or EDP data. A model for the different phases of engineering design process of elementary students doing this open-ended, LEGO robotics, engineering task was shown in Figure 14. It is briefly summarized here.

PLAN - subject was planning some aspect of their design, typically verbally. Planning was also observed through drawing.

RESEARCH - researching a problem or possible solution. In this context, research was usually seen as either a side build or moving a part into position to try out an idea in advance.

BUILD - building or rebuilding. Typically, building is looking for parts or connecting parts.

PROGRAM - Programming or reprogramming the robot using a computer.

EVALUATE - evaluate by testing physically, evaluating verbally, evaluating visually, or testing the whole system by running the program.

Although not analyzed specifically in this study, the BUILD, PROGRAM, and EVALUATE codes were actually coded as a code and sub-code combination. For example, BUILD was coded as either BUILD-NORMAL or BUILD-REBUILD. PROGRAM was coded in the same way. EVALUATE has four sub-codes: EVALUATE-PHYSICAL, EVALUATE-VISUAL, EVALUATE-SYSTEM, and EVALUATE-VERBAL.

There were two EDP codes that were not planned but were added. SHARE-OUT and PROBLEM-SCOPING. Problem scoping is defined by (Atman et al., 2008) "as the stage of the design process during which designers explore the relevant issues and set the boundaries of the problem they will continue to solve" (p. 235). The problem, although open-ended, was very well defined so there were a very small number of problem scoping instances observed. These instances were coded but not analyzed since they were so few in number (nine short instances in six subjects). It was anticipated that the SHARE-OUT of the project would occur in the post-make interview and would not be coded. However, a few students did significant, unprompted sharing out in the form of post-make drawing so these instances were coded and analyzed. Other codes can help describe important, but secondary aspects of the students' engineering design process.

EDP secondary data. The third type of derived data is called the secondary EDP data. The theoretical frameworks, literature review, and pilot study predicted a large number of secondary codes. However, many were not observed. A smaller number of secondary codes that occurred frequently were coded. These were PROJECTION (prediction), INFERENCE, CREATIVE-PLAY, PERSISTENCE, SCALE, SYMMETRY, STABILITY, CONNECTOR-META, PLAN-AHEAD, MATH, and SCIENCE. Most of these also were coded with a value: positive effect (+), neutral effect (=), and negative effect (-). The extant secondary codes were extracted and examined as part of the summary rubric data.

Summary rubric data. The fourth and final type of developed data is the summary rubric data. This important rubric (see Table 1) was developed during the data analysis phase of the research to reflect the important aspects of the EDP process and the model build that were emerging after it became clear that neither grade level, gender, nor the EDP timelines were determining the finished model ride quality. What did explain the clear differences in finished model rides and EDP process? It became clear that a group of different factors was involved and that an instrument to measure these factors was needed. This instrument was the summary rubric.

The summary rubric was developed by looking at a list of potential independent variables (factors) that might explain the differences in EDP timelines and finished model quality (part of the finished model design data). A list of potentially significant independent factors was produced and used as a way to look for correlations in EDP patterns, ride quality, and these variables. The possible factor list was constructed by considering important and repeated observations of phenomenon when viewing the video and considering the final model rides. Most of these were already theorized and were already described in the code book: causal reasoning, application of mathematics and science, EDP knowledge, use of design principles (of scale, symmetry, and stability), planning, LEGO structural knowledge, and cognitive flexibility.   Some were potentially important differences in the final model rides that might explain the differences in EDP processes: the use of a motor (or not) and the use of computer (or not).   Finally, build complexity emerged as important factor that had not been coded explicitly but had a basis in the theoretical framework, previous research, and my experience as a robotics teacher.

In the context of open-ended design problems such as the amusement part ride task studied here, students choose what they want to build, which defined the ride complexity. According to Funke (1991) and Jonassen (2000), the most relevant aspects of problem (or build) complexity are the structuredness of the problem, the number of issues, functions, or variables in the problem, and the degree of connectivity between the variables. The ride challenge and robotics in general, depending on what the student chooses to build, can be high complexity since they are ill structured, have a high number of variables, functions, and issues, and can have connectivity between the variables. Furthermore, systems understanding is needed to fully understand a complex systems such as LEGO robotics (Sullivan, 2008). The build complexity rating was based on these factors in the particular context of this challenge. The possible factor list was narrowed in a summary rubric (see Table 1 - Summary Rubric) to seven factors by a process described in the next section. In this case, a three point rating scale was used. There was not sufficient variation especially in the EDP timelines themselves to distinguish between four different ratings (Arter & McTighe, 2001).

		Low	Medium	High
Structural Knowledge		Student does not show knowledge of LEGO connector parts and connection techniques. Student is unable to learn new parts and techniques when needed. No knowledge or use of programming.	Student has some knowledge of LEGO connector parts and connection techniques. Student sometimes learns new parts and techniques when needed. Some knowledge or use of programming.	Student has extensive knowledge of LEGO connector parts and connection techniques. Student consistently learns new parts and techniques as needed. Extensive knowledge or use of programming.
Engineering Process Skills	**Subskills**			
	Math/ Science	Student does not apply math or science to a problem.	Student sometimes applies math or science to successfully solve a problem.	Student frequently applies math or science to successfully solve a problem.
	Design Principles	Student does not mention or use scale, symmetry, or stability in their build.	Student sometimes mentions or uses one of scale, symmetry, or stability in their build.	Student frequently mentions and uses two or more of scale, symmetry, and stability in their build.
	Other Process	Student does not use other techniques and strategies such as control of variables, troubleshooting tactics, systemic testing, and engineering	Student sometimes uses other techniques and strategies such as control of variables, troubleshooting tactics, systemic testing, and engineering	Student frequently uses other techniques and strategies such as control of variables, troubleshooting tactics, systemic testing, and engineering

		design process knowledge.	design process knowledge.	design process knowledge.
Executive Function Skills	Casual Reasoning	Student usually makes incorrect predictions and inferences.	Student sometimes makes correct predictions and inferences.	Student makes frequent and correct predictions and inferences.
	Plan-Ahead	Student is a serial builder using trial and error who seldom plans ahead.	Student shows evidence of near term planning ahead. Student uses a clear mix of trial and error and planning. Try and classify as serial builder or planner but put in this category if there is a clear mix of serial and plan-ahead building styles.	Student shows evidence of planning the complete ride (as a system) ahead of time. Student consistently shows evidence of planning their next step.
	Cognitive Flexibility	Student shows evidence of cognitive inflexibility (non-optimal persistence). Student seldom rethinks strategies even when there are persistent failures.	Student shows some evidence of cognitive flexibility. Student sometimes rethinks strategies when there are persistent failures.	Student shows cognitive flexibility. Student frequently and creatively rethinks strategies when there are failures.
Build Complexity		The ride is not animated (no computer, no motor). There are no decorative elements or mini-figures. There are a small number of parts put	The ride is animated with one motor and computer. There is some decorative elements or mini-figure use. The ride uses a simple program. There are a	The build in animated with a computer, motor, and uses gears. There are many decorative elements or mini-figures. The ride has multiple motors or has a sensor.

		together simply.	moderate number of parts and subsystems.	The ride uses a complex program. There are a large number of parts and subsystems.

Table 1. Summary Rubric.

Now that the derived data has been defined, the methodology used to actually create the derived data will be described.

Derived Data Process

The next section describes the process that transformed the raw data into derived data that was further analyzed.

Finished model design data. Before each model was taken apart for the next student, the number of LEGO parts was counted. Photographs were taken from a number of different angles of both the intermediate building and the finished product. A photograph was also taken of the robotics computer program the student may have created by simply taking a photograph of the screen. All the different aspects of the build (such as number of parts, motor used, etc.) were recorded in a Microsoft Excel spreadsheet. Finally, the warm-up task and ride models were evaluated using their respective rubrics.

EDP data - transcription, time stamp, and segmentation process. The video sessions were transcribed by a transcription service. [Eight and a half hours of separate audio recorder files totaling were extracted and submitted to the transcription service]. The transcriptions were not literal so that “ums”, extra “likes”, and other non-essentials words were not transcribed. When the researcher and subject spoke at the same time, a reasonable facsimile was produced. Because the video was watched many times to capture the building moves of each student, the use of a transcription service was not a problem in terms of the researcher not being intimately familiar with each session. An initial pass consisted on watching the video of each session and taking field notes (Erickson, 2006).

Next, the transcripts were time stamped and the verbal output segmented. The purpose of segmenting is to, "to break the verbal text into units (or segments) that can be coded with a pre-defined coding scheme" (Atman & Bursic, 1998, p. 332). Verbal output was generally easy to segment because it consisted of short question and answer snippets.

In this study, there are two different "tracks" of data. The first is the verbal output of the subject that is obtained via the talk-aloud protocol (Atman & Bursic, 1998; Ericsson & Simon, 1993). Other studies of this type only look at the verbal output of subjects who work in teams (Atman & Bursic, 1998; McFarland & Bailey, 2015). Because this study is interested in comparing individuals and because the physical building is so important to LEGO robotics, the physical building and programming activity of each subject were transcribed by the researcher with some assistance by another graduate student. By examining the building moves of a number of subjects, a unique physical move segmenting scheme was created and continually refined. [fix]

Physical move segmenting rationale. Another pass consisted of segmenting the physical move activity into units that could subsequently be coded. Segmenting occurs at at a lower level than the coding and requires minimal interpretation, unlike coding. Because this study looks at transitions between EDP phases, a single segment may contain multiple contiguous physical activity segments of the same type. Physical activity descriptors were defined to have a similar level of atomicity. They were confined to the subjects' use of their hands. There was not sufficient and consistent data of the subjects' gaze to include that information. Note that connecting parts included a direct acquisition of a LEGO part without searching through parts. The lower level physical activity descriptors ultimately allowed interpretive coding of EDP phase transitions in combination with verbal output segments. EDP phase transitions always occurred at segment boundaries.

Segmenting rules. Verbal activity was segmented by the snippet or interaction. In other words, talk was segmented when there is a change of speaker. For longer subject text in a transcription, talk was broken into additional segments by long pauses (more than 2 seconds) or clear changes of topic at (Atman & Bursic, 1998; McFarland & Bailey, 2015). Verbal segments were also split into multiple segments during the coding process if there was an EDP transition detected in the middle of an existing segment.

Physical activity was transcribed by activity descriptors (shown in *italics* below). When the physical activity changed, a new timestamp and descriptor was inserted. Descriptors were put in {} to differentiate them from codes, which were enclosed in square brackets. Multiple contiguous instances of the same physical activity did not need to be segmented because EDP transitions occured only when physical segment type changed. Activities needed to last at least one second to be segmented.

- *no_activity* - no activity with hands for more than 1 seconds. This was also used if subject is absently moving or holding model or parts with no apparent purpose.

- *pointing* - pointing at a part, model, or drawing with hands, pencil, or other object. Pointing can be *gesturing* if it is used to demonstrate movement or the intended actions of a model rather than simple pointing.
- *gesturing* - acting out or demonstrating something with hands or other object without model. If gesturing involves the model, use *moving*. If gesturing is not about the model or parts, use *no_activity.*
- *searching* for parts - note that subject could be holding model while searching, searching is main activity. If less than 1 second and the subject subsequently connects parts, use *connecting.*
- *measuring* parts - includes counting holes and comparing one part to another. In some cases, when subjects move parts close to another part to check the size, this is considered measuring. Includes counting or measuring with their drawing.
- *crafting* - making something. Could be using scissors to cut something, typically string or paper, taping, folding papers, etc.
- *connecting* parts - includes getting parts quickly without searching, includes reconnecting parts that have fallen off. Includes rare cases where part is not actually connected, for example, getting and putting down a base plate. Includes disconnecting parts.
- *moving* model or parts - includes picking up model if it fell over, includes manipulating model or parts of model in some way to evaluate it or demonstrate it, includes touching model. If absently moving or holding model or parts, use *no_activity.*
- *programming* -using the computer to add or modify a program.

- *downloading* program - including connecting USB cable, NXT only; WeDo programs are not downloaded but count connecting cable as *downloading*.
- *starting* robot - includes finding correct program.
- *stopping* robot - stopping the computer program.
- *drawing* - drawing a plan for or drawing a post-build artifact of a model.

Transcribing (segmenting) of physical activity and talk is independent. If change of physical activity occurs at the same time as a verbal segment, physical activity descriptors were inserted after the timestamp. Otherwise, physical activity timestamps and descriptors were put after verbal segments if they overlapped (but not exactly). Time stamps were recorded for all parts of the transcript that were later coded. The problem introduction prompt and the post-interview were not time-stamped, segmented, or coded. A fully time-stamped and segmented extract of a transcript is shown below.

[00:07:14] {connecting} Girl 05: I think this is going to be the last layer, and then I'm going to put the base through the middle.

[00:07:18] {searching}

[00:07:19] {connecting}

[00:07:23] {moving}

[00:07:24] Girl 05: Wait a second. (Lifts structure)

Researcher: What did you notice?

[00:07:29] Girl 05: It's uneven.

Field notes were taken during each pass of initial viewing, time-stamping, verbal segmenting, and physical move transcription/segmenting.

EDP Code Development

For guidance in analyzing students' engineering design process and skills change by age, the literature review revealed an EDP analysis technique (Atman et al., 2007; Crismond, 2001; Welch, 1999) that was modified to characterize the design processes of elementary students. A deductive approach (Barron & Engle, 2007) defined an initial set of codes and sub-codes was used that describe the engineering design process for the pilot study. This was shown in the pilot study to accurately capture the engineering design process of each student. It was also used for this study.

As an example, one main EDP code is BUILD. BUILD has two possible sub-codes: BUILD-NORMAL and BUILD-REBUILD. The schema of EDP codes and sub-codes was created so that the primary EDP could be examined as well as a more refined look that included subcodes of many EDP phases.

The pilot study used an inductive analysis (Welch, 1999) to produce additional, secondary codes that might shed light on the processes related to not directly captured by the EDP codes. For example, a number of codes were developed that identify and describe causal reasoning activity. The literature review examined studies that identify possible skills (and hence possible codes) that may impact students ability to realize their design ideas such as sequencing (Kazakoff & Bers, 2012), planning (Portsmore, 2011), causal reasoning (Sullivan, 2008), and systems thinking (Sullivan). Therefore, the initial coding scheme is a combination of inductive codes produced in the pilot and deductive codes found in the literature review. The codes were refined iteratively (Glaser & Strauss, 2009) during the pilot study. For this study, the pilot study codes were analyzed using axial coding, which defines categories for each code and the relationship between the categories (Charmaz, 2014; Glaser & Strauss, 2009). See Appendix A - Code Book for the categories and codes developed and their definitions. Not all codes were detected and one additional secondary code was added (PLAN-AHEAD) during the study.

EDP Coding

Transitions between EDP phases were determined by both the student's physical building moves and their verbal output. For example, if the student stops building with the LEGO parts and moves their design to see it works, it is clear that a transition from building to evaluation has occurred.

As coding commenced, it became clear that there could be multiple interpretations of the phases (for example, building and research) in some cases. If a student did a side build to see if an idea was plausible, that was coded as research. The context had to be examined. In this case, what you see in one moment looked like building but was really research when the clip was examined in a broader context. That is, it was sometimes necessary to consider more video around the smaller clip. The key was to be consistent across subjects.

Also, it became clear very early on that the study would have to account for the frequent occurrence of overlapping and different verbal and physical EDP phases. For example, a student could be building while, at the same time, talking about their plan for what comes next. In the example below, Girl 5 plans as she is rebuilding and then evaluates when she is building.

[00:34:14] {connecting} [BUILD-REBUILD] (Tweaks connections.)

Researcher: Trying to figure out something with the people?

[00:34:16] {moving} [2:PLAN] Girl 05: Yes, something with the people. How I'm going to get them upright for the whole ride, and if I can't figure that out.

[00:34:26] [2:END]

[00:34:28] {connecting} [BUILD-NORMAL]

Researcher: Oh yeah. Just like a real Ferris wheel.

[00:34:29] [2:EVALUATE-VERBAL] Girl 05: Yeah. The good thing about this it's not really a real Ferris wheel. It's a discombobulated Ferris wheel.

[00:34:42] [2:END]

There were a few possible solutions to handling the overlapping verbal and physical phases. The first would be to choose the dominant phase and ignore the secondary phases or give priority to the physical or verbal track. However, important information would have been lost and it is not clear that one is more important than the other. The second way would be to create new codes that were composites of each extant combination of codes (McFarland & Bailey, 2015). This solution was rejected because of the large number of possible combination and the desire to clearly represent what actually occurred graphically. The solution chosen represents each phase independently and exactly captures the overlapping phases. For example, let's say we have the following data.

A	B	C	D	E
Start	Duration	Code	End	
0:00:00	0:00:05	1	0:00:05	
0:00:05	0:00:30	2	0:00:35	
0:00:35	0:00:24	1	0:00:59	
0:00:59	0:00:04	3	0:01:03	
0:01:03	0:00:17	4	0:01:20	
0:01:20	0:00:50	5	0:02:10	
0:02:10	0:00:02	3	0:02:12	
0:02:12	0:01:33	4	0:03:45	Overlap
0:02:30	0:00:10	1	0:02:40	Overlap
0:03:45	0:00:10	5	0:03:55	
0:03:55				

Figure 23. Sample Excel EDP data.

First, a scatter chart was created in Microsoft Excel.

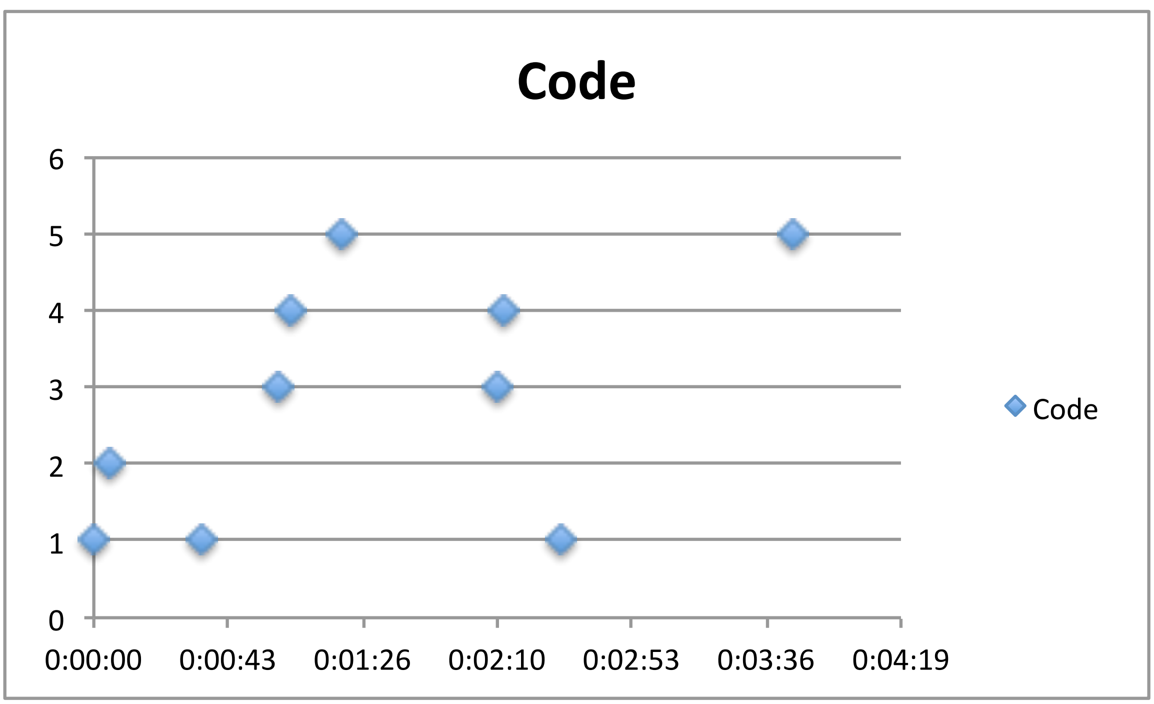


Figure 24. Sample EDP scatter chart.

The final step was to use custom error X-axis bars that point to the duration of each phase occurrence to show the duration of the phase.

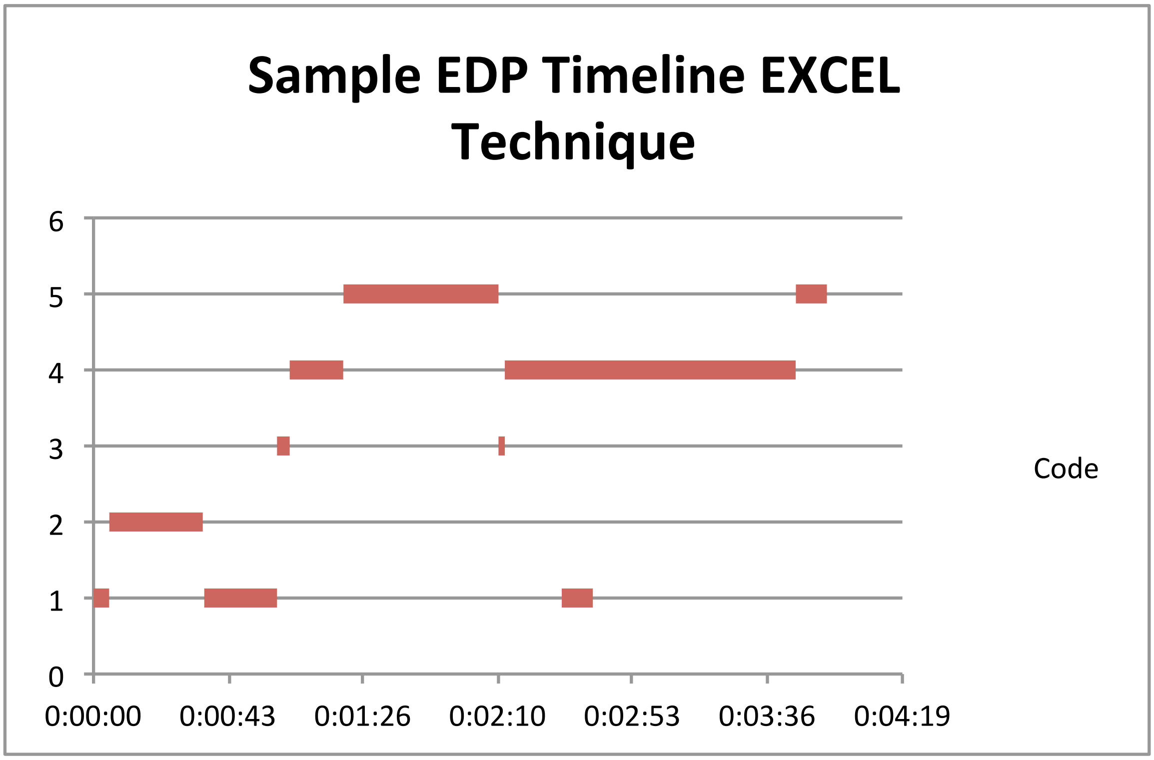


Figure 25. Sample EDP timeline.

Multiple coding passes were made to ensure consistent and complete application of codes. A second coder was used to refine the coding dictionary. Over 80% (83.3%) intercoder reliability was achieved using Krippendorff's alpha (Freelon, 2010; Krippendorff, 2007) on 20% of the video. 3% of the video was coded together. Then 7% was coded independently with the two coders meeting after to resolve differences and refine the code definitions. Next, 10% was coded independently and used to calculate the intercoder reliability. The 80% threshold was the same or better than similar studies with college level engineering students (Atman et al., 2005). Systemic errors were counted once. Given that coders were coding potentially separate verbal and physical tracks, the reliability achieved was considered high. Once the reliability was calculated, the author coded the remaining 80% of the transcripts. A total of 312 pages of coded transcripts were produced.

As the transcription and coding processes progressed, a research journal was created (Galman, 2007) to track important process ideas and emergent themes.

See below for an extract of the sixth grade transcript. The EDP codes were placed directly after the timestamps and the secondary EDP-related codes were placed at the end of each segment for clarity. The building moves, as well as the discourse, were transcribed and inserted using curly brackets immediately after the timestamps. Brief notes, if any, were places in parenthesis. Longer notes were placed in the research journal.

[00:17:01] [BUILD-REBUILD] {connecting}

[00:17:03] [2:EVALUATE-VERBAL] Boy 05: I put this on backwards. [INFERENCE+]

[00:17:04] {moving} [EVALUATE-PHYSICAL]

[00:17:05] [2:END]

[00:17:07] [BUILD-REBUILD]

[00:17:14] {moving}

[00:17:15] {connecting}

Researcher: I notice you're keeping your design so that it's usually the same thing on the other side, all the time.

[00:17:32] {gesturing} [EVALUATE-VERBAL] Boy 05: Yeah, so it's not off balance. If it's off balance, it has more likely to tip over. [PROJECTION+] [IMPORTANT][SYMMETRY+]

[00:17:34] {connecting} [BUILD-REBUILD]

[00:17:40] [EVALUATE-PHYSICAL] {moving}

[00:17:45] [BUILD-NORMAL] {connecting}

The relationship between segments and codes is interesting and a somewhat complex one. Certain segments typically indicate a possible EDP phase transition. Here are some examples.

- {moving} - typically indicates EVALUATE or RESEARCH
- {connecting} and {searching} - usually indicates BUILD
- {no_activity} - indicates WAIT or PLAN
- {gesturing} - usually indicates PLAN

See Figure 26 for an illustration of the relationships between segments and codes.

Segmenting and Coding Example

Main Code	[BUILD]		[BUILD]	[PLAN]	[RESEARCH]	
Overlapping Code (verbal, if any)			[2:PLAN]			
Verbal Segment	"I am adding a block to make the tower more stable."		"I am going to add a mini-figure later.	"I will also make a seatbelt."	"I am trying it over here."	"YES!"
Physical Segment	{search}	{connect}	{connect}	{no_activity}	{connect}	{move}

Figure 26. Segmenting and coding example.

The first BUILD code contains two physical segments that both indicate building as well as a verbal segment that, in this case, also indicates the same EDP phase. However, the second BUILD code shows a simultaneous and different verbal code of PLAN while the subject is connecting parts. Note that the overlapping code starts with “2:” to help with the later computer program extraction of the codes. The subject then stops connecting and is only planning. The last part of the example shows a RESEARCH EDP phase that consists of connecting pieces and moving pieces. The RESEARCH code counts the evaluation of a side build as part of research. This final part also has an example of the verbal track overlaps and extending beyond the physical track. The code extraction and visualization process (described later) handles all these cases accurately. Before that is discussed, however, the methodology used for secondary codes is briefly described.

Secondary EDP Coding

Note in the transcript above that secondary EDP codes were placed at the end of segments. Most secondary codes have a value of +, =, or - indicating a positive, neutral, or negative effect. Three subjects were fully coded with secondary EDP codes.

Code Checking, Extraction, and Importing Into EXCEL

Two "little programs" were developed (based on the pilot study program) in the Python programming language (Summerfield, 2010) to extract the timestamps and codes from the transcripts. The two programs are a code scanner and a code extractor. See Appendix F - Code Scanner Program and Appendix G - Code Extraction Progrm for the actual Python code. The code scanner checks for valid codes and common errors. The extractor program creates four output files for each transcript:

Main Codes - timestamps and main EDP codes,

Sub-codes - timestamps and EDP codes and EDP sub-codes,

EDP Related Codes - timestamps and EDP-related problem solving and causal reasoning codes.

Error log - file of any errors encountered. These are also shown on the screen.

Here is an example of some of the error detection output of the code extractor program.

timeStamp Error in line [00:13:32] {moving} [RESEARCH] [2:PLAN] Girl 06: If I can put this together-

Unexpected S Phase expecting store in line [00:13:33] [2:END]

timeStamp Error in line [00:13:34] [WAIT] Researcher: Let me press this for you. [HELP]

timeStamp Error in line [00:13:50] [2:PLAN] Girl 06: And then so I could do it a little lower, so it wouldn't fall.

Unexpected S Phase expecting store in line [00:13:54] {connecting} [2:END] [BUILD-REBUILD]

When coding errors were detected in either program, they were corrected and rechecked. The improved error detection in this study improved the validity of the data and the reliability of the results.

The main code files were then imported into Microsoft Excel. See below for a sample extract of the main codes Excel file.

Time	Elapsed	Code	Code
0:01:48	0:00:41	PLAN	6
0:02:29	0:00:08	BUILD	4
0:02:37	0:00:59	PLAN	6
0:03:36	0:00:20	BUILD	4
0:03:56	0:00:11	PLAN	6
0:04:07	0:01:07	BUILD	4
0:05:14	0:00:11	PLAN	6

The phase code number is needed for later analysis using Excel, specifically to produce the EDP timelines. Elapsed times for each phase for the main and sub EDP codes were calculated in Excel. Once the EDP data was imported into Microsoft Excel, visualizations were produced that could be analyzed.

Visualization Production

Once the data was imported into Microsoft Excel, a number of different types of visualizations were produced: finished model design data graphs, EDP timelines, and EDP count, frequency, and duration graphs.

Finished model design data graphs. Graphs were produced using Microsoft Excel that show the data about the finished model such as number of parts, parts used (motor or no motor), originality rating, functionality rating, EDP rating, and other attributes of the finished amusement park ride models by gender and by grade level. Because no significant differences were found by gender or grade level but significant differences did seem to be occurring, additional graphs were produced by LEGO experience and EDP rating, which were added as new, possibly significant, independent variables.   LEGO experience was rated using a questionnaire that was filled out by second grade parents and sixth grade students. See Appendix H - LEGO Experience Questionnaire for the questionnaire and rating scheme. The finished model design data showed attributes of finished design. However, a big part of this research was to understand the difference engineering design process of elementary students.

EDP timeline graphs. Using the EDP data in Microsoft Excel, individual graphs were produced that show the engineering design process phase by the elapsed time. Sample data and the corresponding sample EDP timeline are shown in Figure 23 and Figure 25 respectively.

EDP count, frequency, duration graphs, and other data. Additionally, individual graphs for each subject were produced that show the count of each EDP phase, the time spent in each EDP phase, and the average duration (in seconds) of each EDP phase. See the Results Chapter for examples.

While it was initially planned to produce additional visualizations of aggregated EDP and secondary EDP data by the two initial, independent variables of grade level and gender, these were not done because significant differences were not being seen. A summary rubric was created that rated the factors that did seem to the driving the differences seen in EDP timelines and final model quality. These factors are the build complexity, the LEGO structural knowledge possessed by the student, three specific executive function skills, and three specific domain specific EDP skills. [The process of creating and using the summary rubrics is explained in more detail in the next section.] Figure 27 shows the overall relationship between the different data produced and analyzed in this study. Moving up in diagram indicates the timing of the data production process and also the increased level of abstraction from the actual sessions.

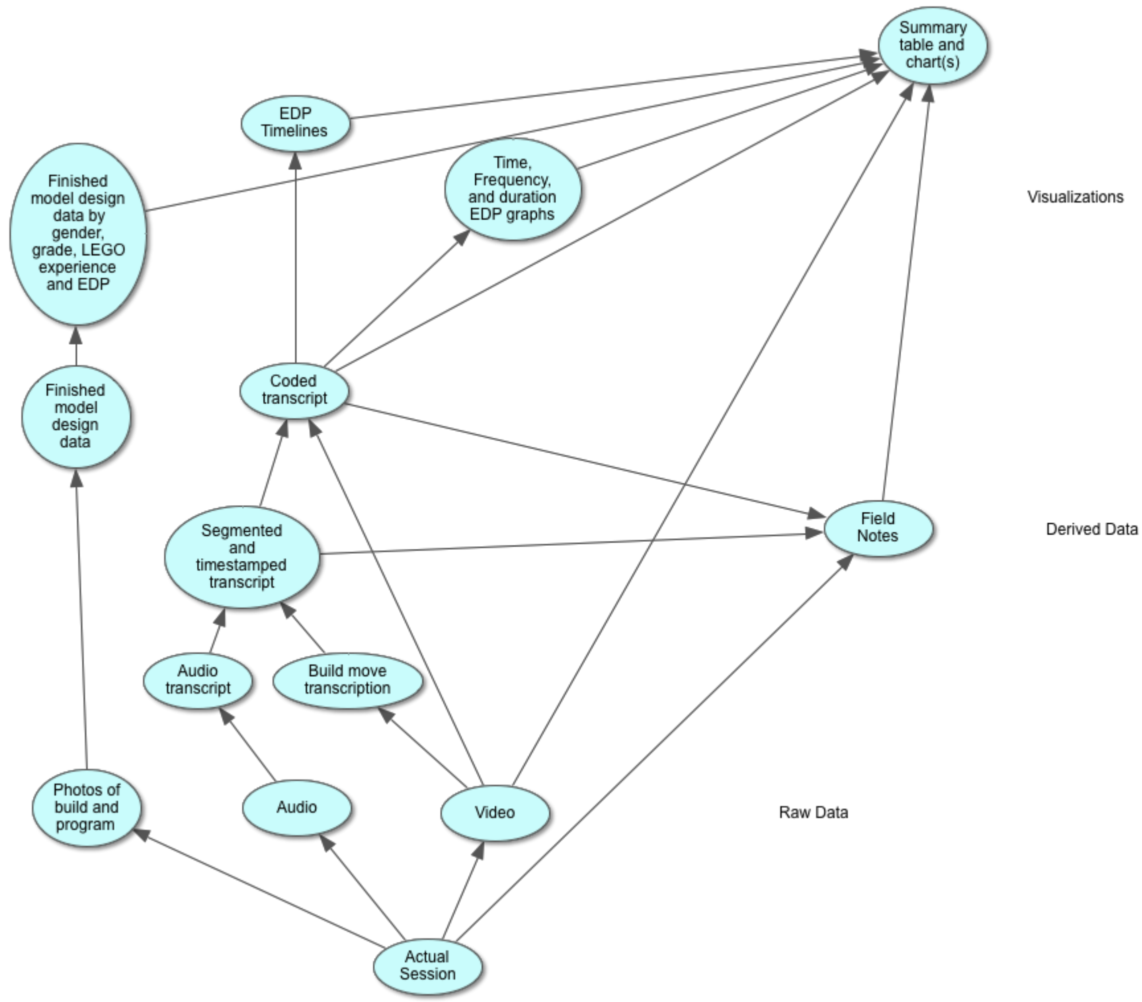


Figure 27. Overall study data taxonomy.

Now that that data and derived data process has been fully defined, a short description of the analysis process used is given.

Data Analysis Process

First, the finished model data graphs were examined for significant differences by gender, grade level, LEGO experience, and EDP rating. The next and more complex step looked at the frequency and distribution of events in the EDP timelines of the twelve students. This methodology is called inductive contrastive analysis (Goldman, Erickson, Lemke, & Derry, 2007). Basically, patterns were searched for in the EDP timelines of students. A similar approach has been using by others in studies of the design process of undergraduate students (Atman et al., 2007, 2005; Atman & Bursic, 1998) and in novice/expert engineering studies (Crismond, 2001). As an example, Atman et al. (2007) found what they considered an ideal EDP timeline shape by looking at EDP timelines of expert practitioners and the undergraduate engineering students in the study.

The next step was to again look for patterns in the EDP count, frequency, and duration graph of the students by a number of various factors. Since the original independent variables of gender and grade level were not showing significant differences, both the EDP timeline and EDP count, frequency, and duration graphs were labeled with a variety of potential independent variables (also called factors and described in previous section above) and sorted by each variable in turn to see if patterns emerged. One example of the twelve visualizations created for this purpose is shown below.

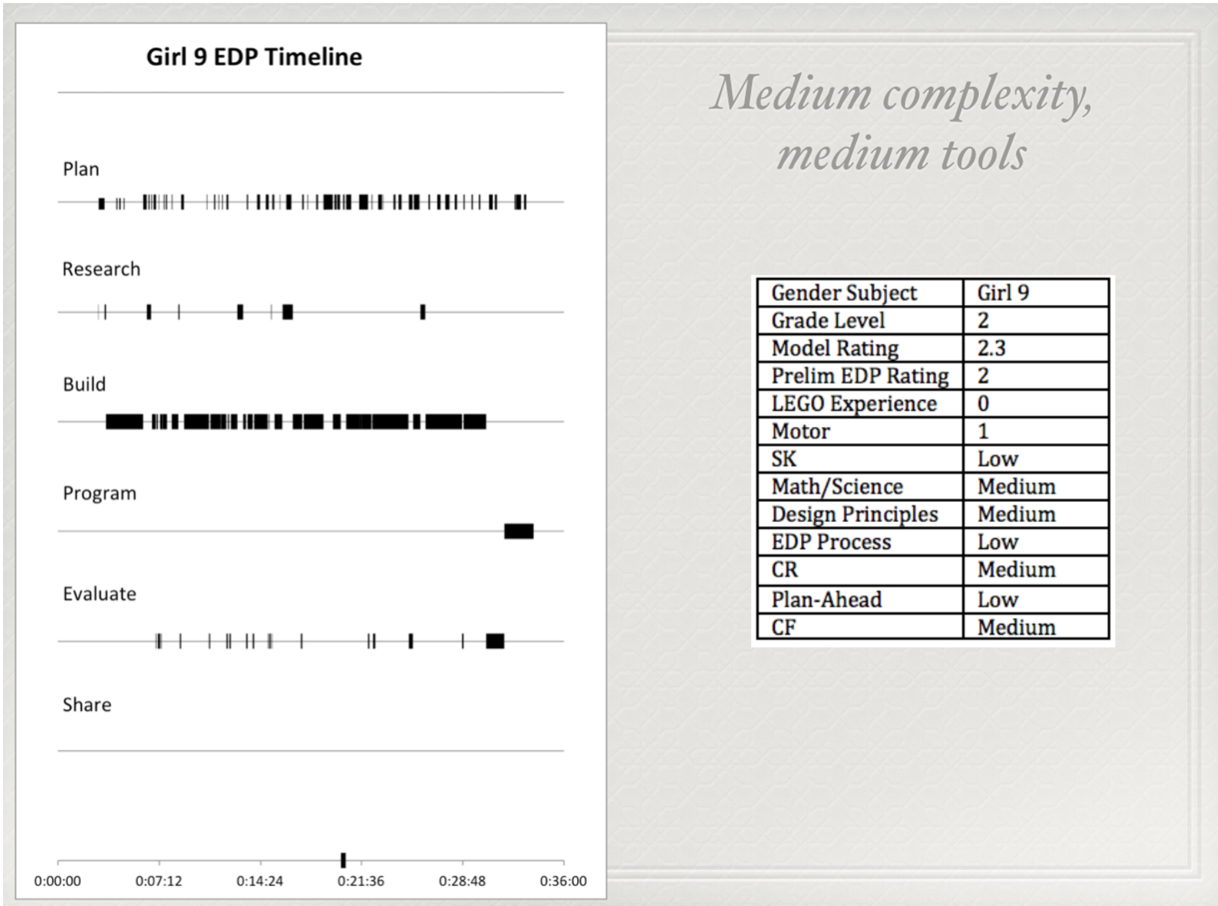


Figure 28. EDP timeline summary.

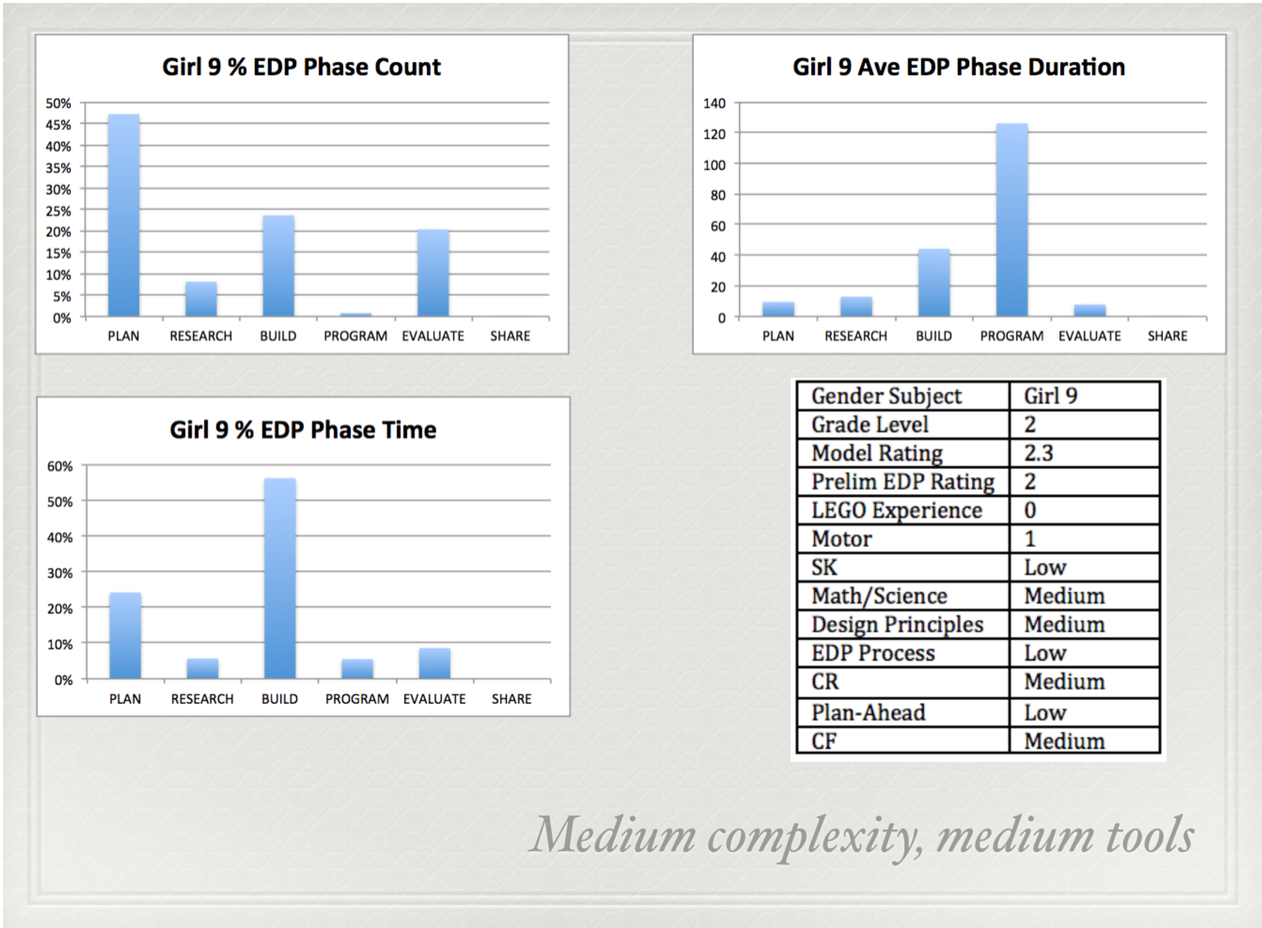


Figure 29. EDP count, frequency, and duration summary.

When a pattern did emerge, a summary rubric (see Table 1 - Summary Rubric) was used that measured the seven most relevant factors for each design and design process and appropriate visualizations were created that show some of the relationships between the seven factors. The Results and Discussion chapter will describe the relationships that were found.

CHAPTER 5

RESULTS

Warm Up Task Results

Recall that the warm up task served two purposes: to help students understand and execute the talk-aloud protocol and to serve as a check on the students' skills, process, and knowledge when compared to the main task. For the latter, there was a close correlation between the tasks.

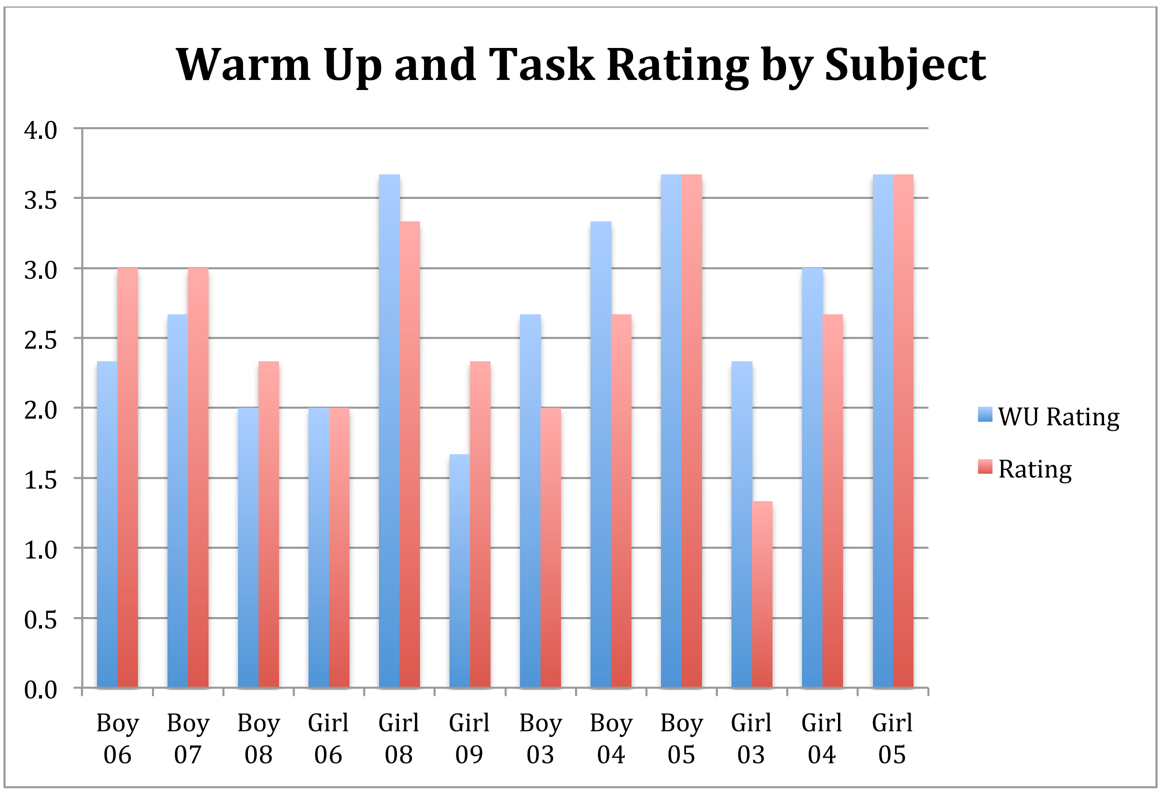


Figure 30. Warm and main task ratings.

Girl 3 was the exception. However, as we shall see, she had good EDP skills but lacked structural knowledge and general executive functions process skills that caused problems building the complex amusement park ride build she chose but did not cause problems in the much simpler warm up task. In general, many students used a combined set of materials where no single piece spanned the walls with the parts given. Many students build somewhat haphazardly using trial and error and ignored the flatness constraint.

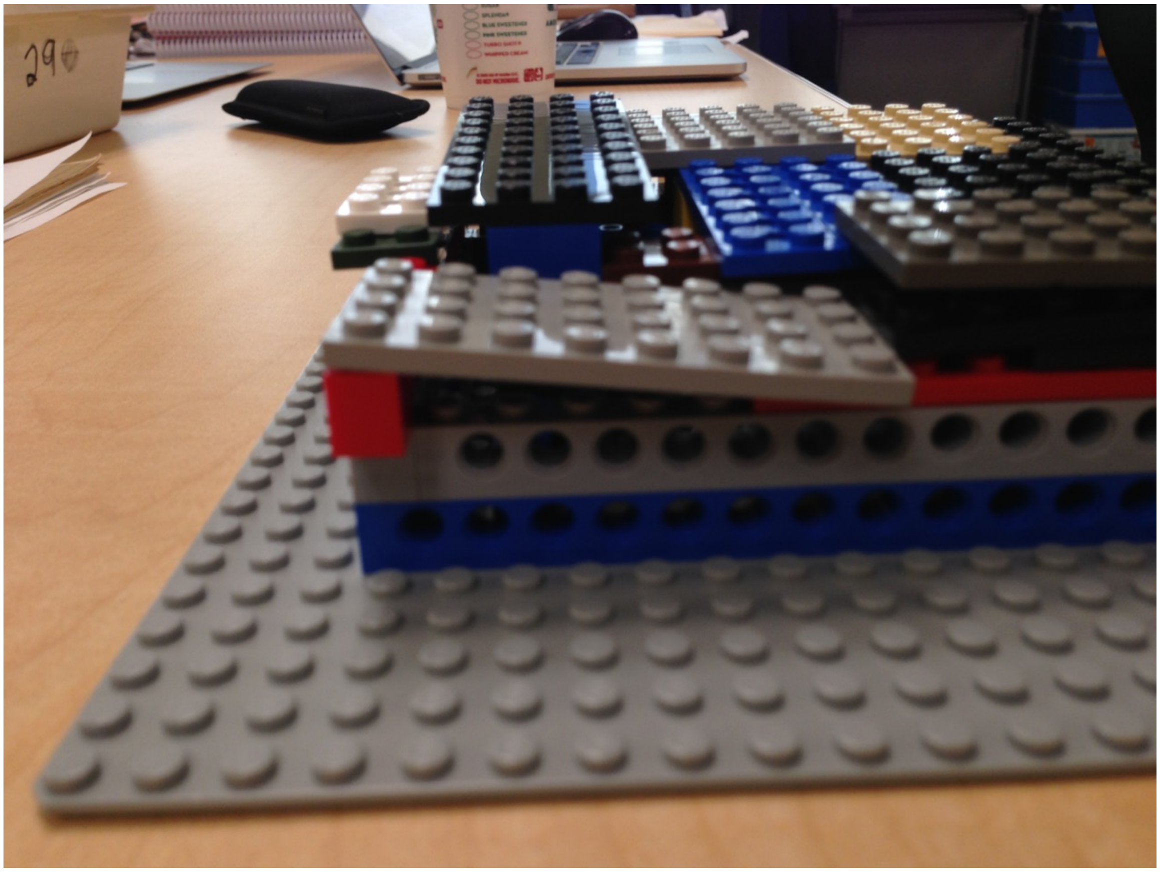


Figure 31. Girl 9 warm up task roof, which did not attend to the flatness constraint.

The more advanced designs used intermediate walls.

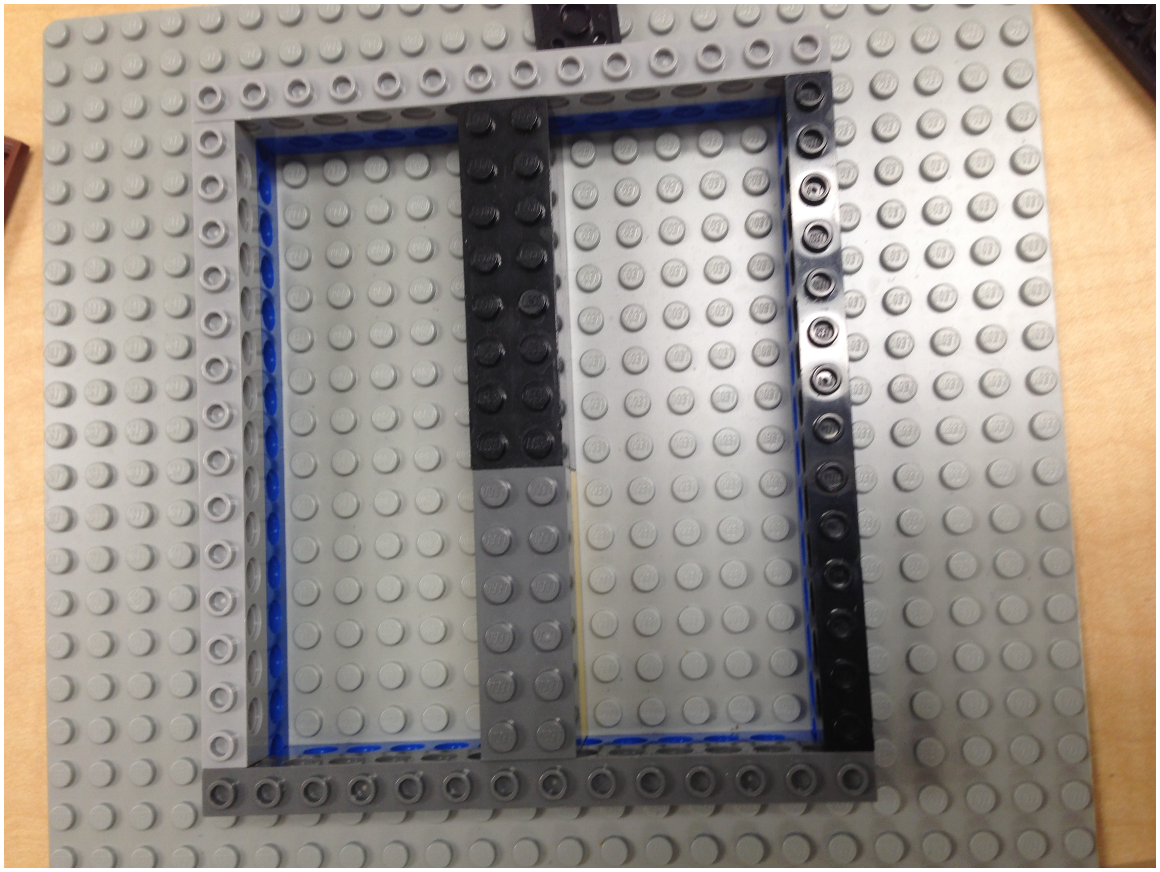


Figure 32. Girl 8 solution with intermediate wall design.

Girl 5 even built a removable roof.

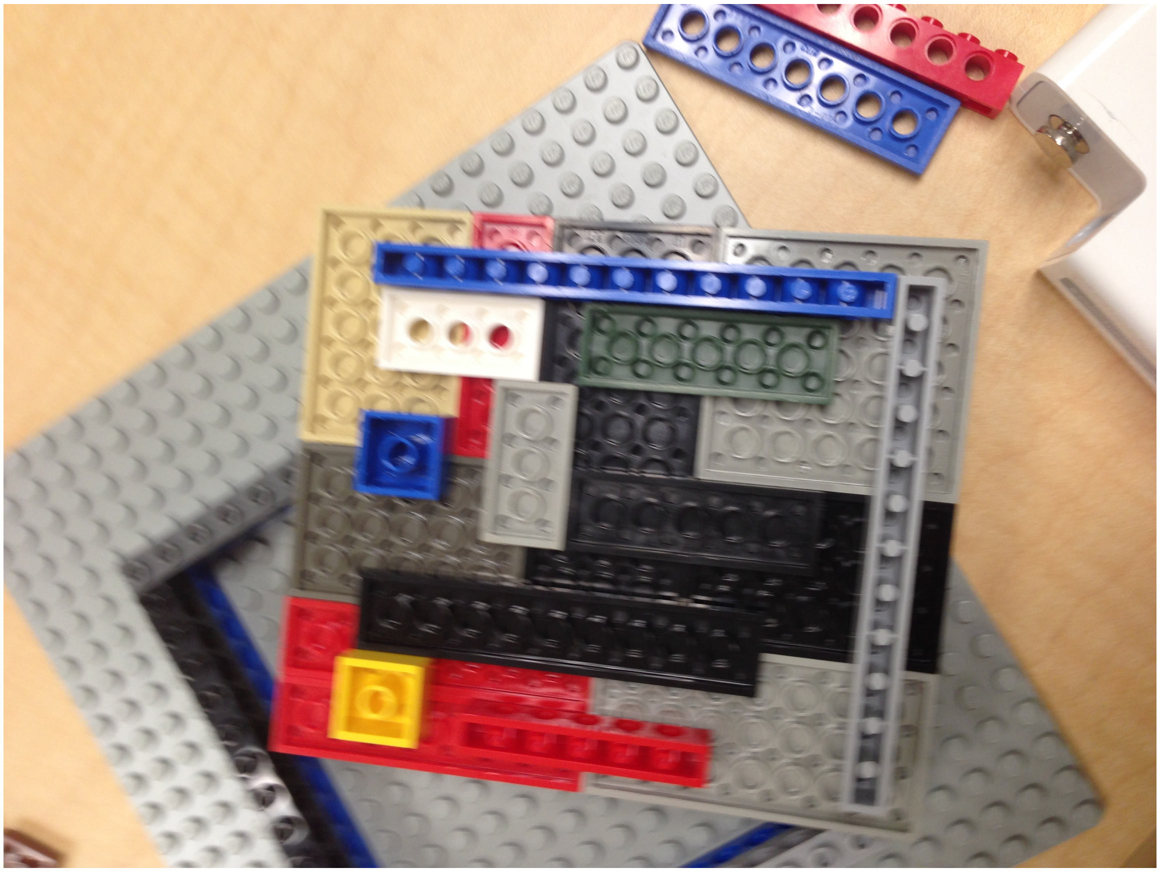


Figure 33. Girl 5 removable roof. Note that it was flat on the top side.

Some designs met the constraints better than others and also attended to design principles such as symmetry, stability, and scale. Instances of scale were seen when students built up walls first in order to leave room for mini-figures. At least two second graders clearly expressed that that was why they built up the walls first (which later limited the available parts). This is related to the creative play (designerly play) aspect of the mini-figures, which was seen more in second graders. Now that the warm up task results have been briefly described, the main task results will be shown next.

Finished Model Design Data Results

This section describes the finished model design data results of each student's warm and main task. With the exception of a rating of each student's EDP, originality, and model functionality, this data consists of various attributes of each model and more ratings based on a warm up rubric and ride rubric (see Appendix D - Warm Up Task Rubric and Appendix E - Finished Model Design Quality Rubric).

This data was first examined by gender and grade level.

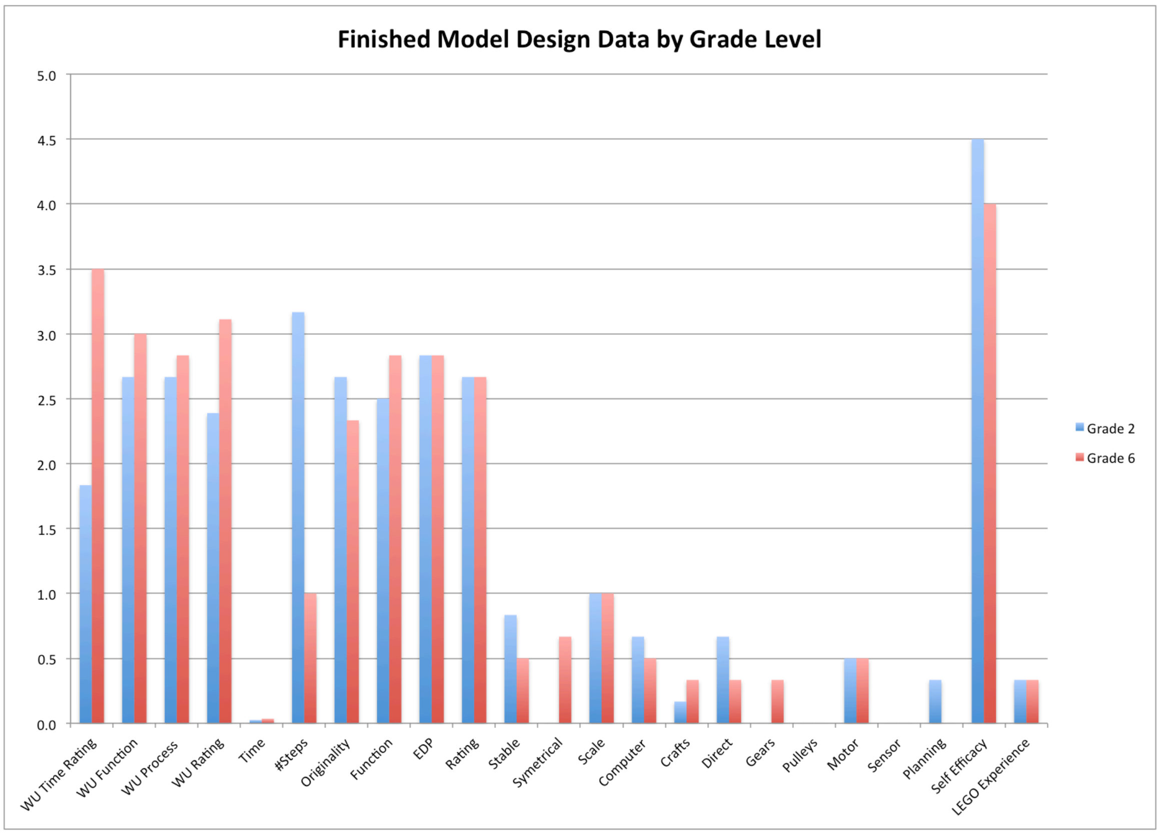


Figure 34. Finished model design data by grade level.

There are 2 different scales used in this diagram. Self-efficacy is a 1 to 5 point scale. The various rubric-based ratings (WU Time Rating, WU Functionality, WU Process, and WU Rating, Creativity, Function, Process, and Rating) are on a 1 to 4 point scale. WU refers to warm up task and the other ratings are for the main task; the Creativity, Function, Process, and Rating refer to the main task. WU rating and Rating are the mean of the three aspects of each rating. Stable, Symmetrical, Scale, Computer, Crafts, Direct (coupling), Gears, Pulleys, Motor, Sensor, Planning, and LEGO Experience are on a binary scale but may show as decimal numbers since they consist of the mean values. All of these were judged as present (1) or not present (0).

We can see that, with a few exceptions, there are not significant differences between the grade 2 and grade 6 values. Grade 6 students completed their warm up task more quickly than grade 2 students. The number of computer program steps was higher for grade 2 students, but because the number of steps were so few overall, this number is not meaningful. Grade 6, but not grade 2 students, showed attention to symmetry in their designs. Only grade 6 students used gears. Only grade 2 students (n=2) produced planning artifacts either before build or post-make. Self-efficacy was slightly higher in grade 2 students but not necessarily accurate when the overall ratings were examined. These results were surprising; greater differences were expected between grade 2 and grade 6 students.

Even fewer differences were seen for gender. See Figure 35.

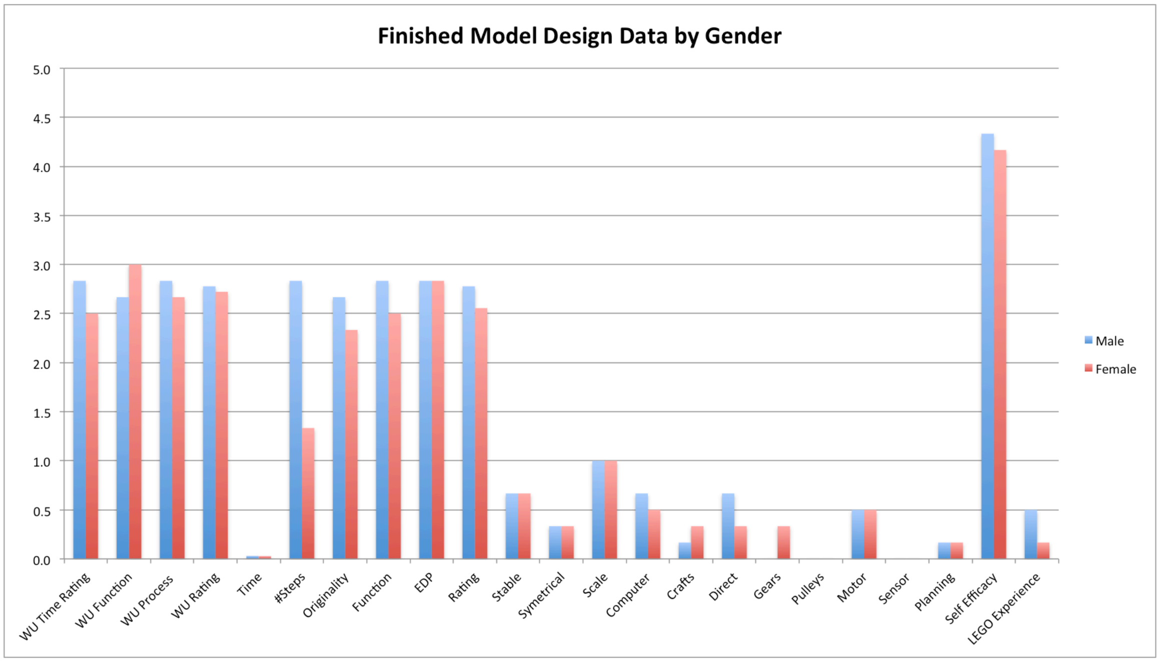


Figure 35. Final model design data by gender.

As for grade level, the number of steps was not meaningful. LEGO experience was greater for the male students. Overall, these results are encouraging and show, at least in this small sample, the gender does not play a role in the final products of male and female students in the context of a yearly K-6 robotics program. It is certainly plausible that the existence of the program helps to ameliorate cultural pressures for girls not to be good at mathematics, science, and engineering.

The final model design ratings were compared by gender and by grade level and no correlation was found. Similarly, the EDP graphs were grouped together by gender and by grade level and were visually inspected for patterns and, again, no pattern was found. (See Figure 34 and Figure 35.) However, there were significant differences in the builds (as measured by the final model design ratings and EDP timelines). If neither gender nor grade level was the primary factor in the differences in final models and EDP, what was? In observing the students, there seemed to be some differences in their knowledge of LEGO connecting techniques and their engineering process that was affecting their ability to realize design ideas. I looked at the final model design data by the new LEGO experience variable and by the EDP rating to see if more significant differences would be shown to verify my emerging thesis that factors other than gender and grade level were playing significant roles. If so, more analysis would be needed to find out exactly what was going on.

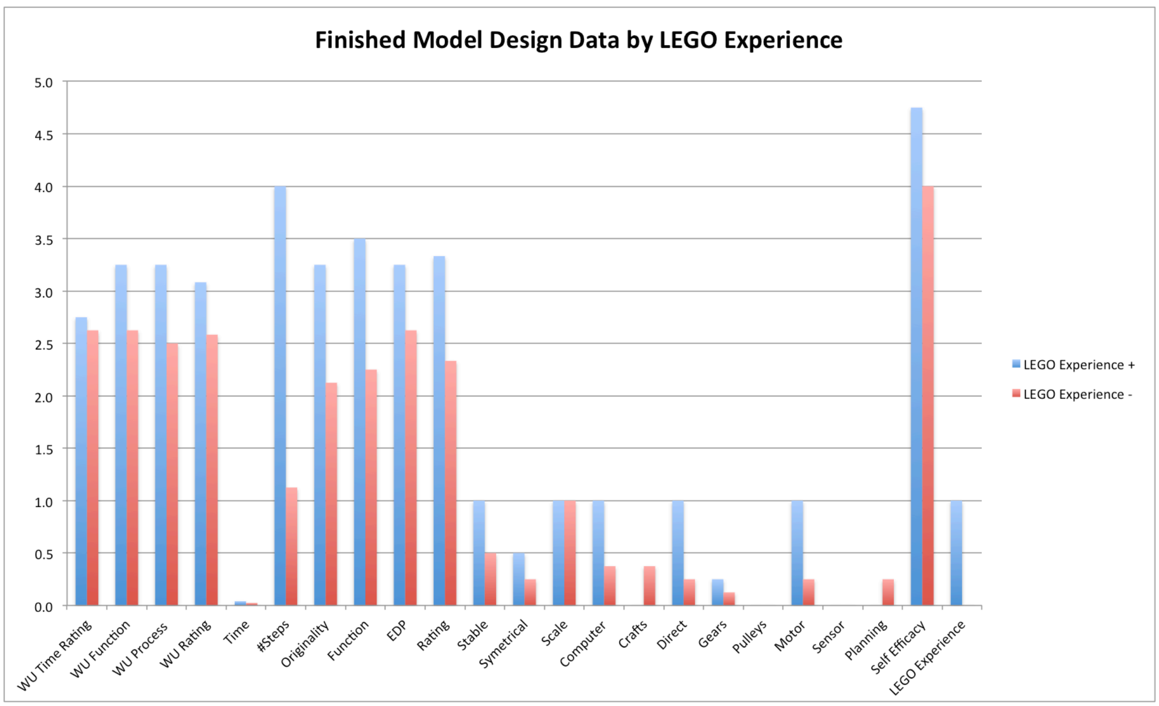


Figure 36. Finished model design data by LEGO experience.

In contrast to the grade level and gender graphs, there is an across the board increase in rating for those students with LEGO experience for both the warm up task and the main task. Greater LEGO experience could point to greater structural and domain specific process knowledge as being significant factors in the differences in final products and engineering design processes.

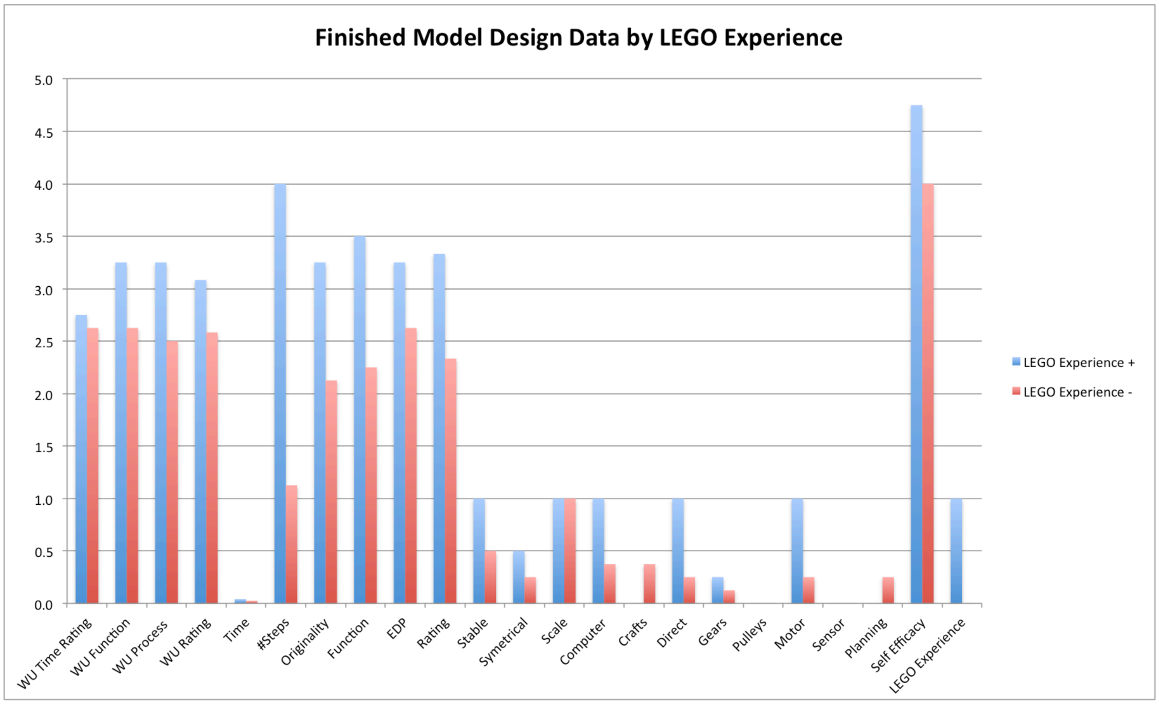


Figure 37. Finished model design data by engineering design process rating. This graph shows students with the highest possible EDP rating (EPD+ in blue) versus students with lower ratings (EDP-) in red.

As with LEGO experience, students with the higher engineering design process ratings (as judged by Appendix E - Finished Model Design Quality Rubric) showed similar gains. This suggested that an in-depth analysis of the students' engineering design processes could shed light on the factors that were influencing the students' final designs.

Individual Builds

In this section, I review the EDP Timeline and EDP phase frequency, time, and average duration graphs of each student. A photograph of each final build will also be shown. The basic story of each build is described as well as any interesting moments that occurred that had relevance to the research questions.

Boy 6. Second grader and experienced LEGO builder Boy 6 had a somewhat complex ride and a sophisticated parallel program. Creative play was very important to Boy 6 and he was very intent on making a "spooky ride." Boy 6 talked a lot about his interest in LEGOs. He added many creative details such as the ride operator shown in Figure 38. Boy 6 showed some good EDP skills such as testing regularly as he built and asking problem scoping questions. Boy 6 generally built serially, that is, he created as he went along without expressing an overall plan for his ride. He explicitly showed some good cognitive flexibility at 09:05.

> [00:09:05] Boy 06: Maybe if it doesn't work, I'll try a different idea. [IMPORTANT]
> (Shows cognitive flexibility)

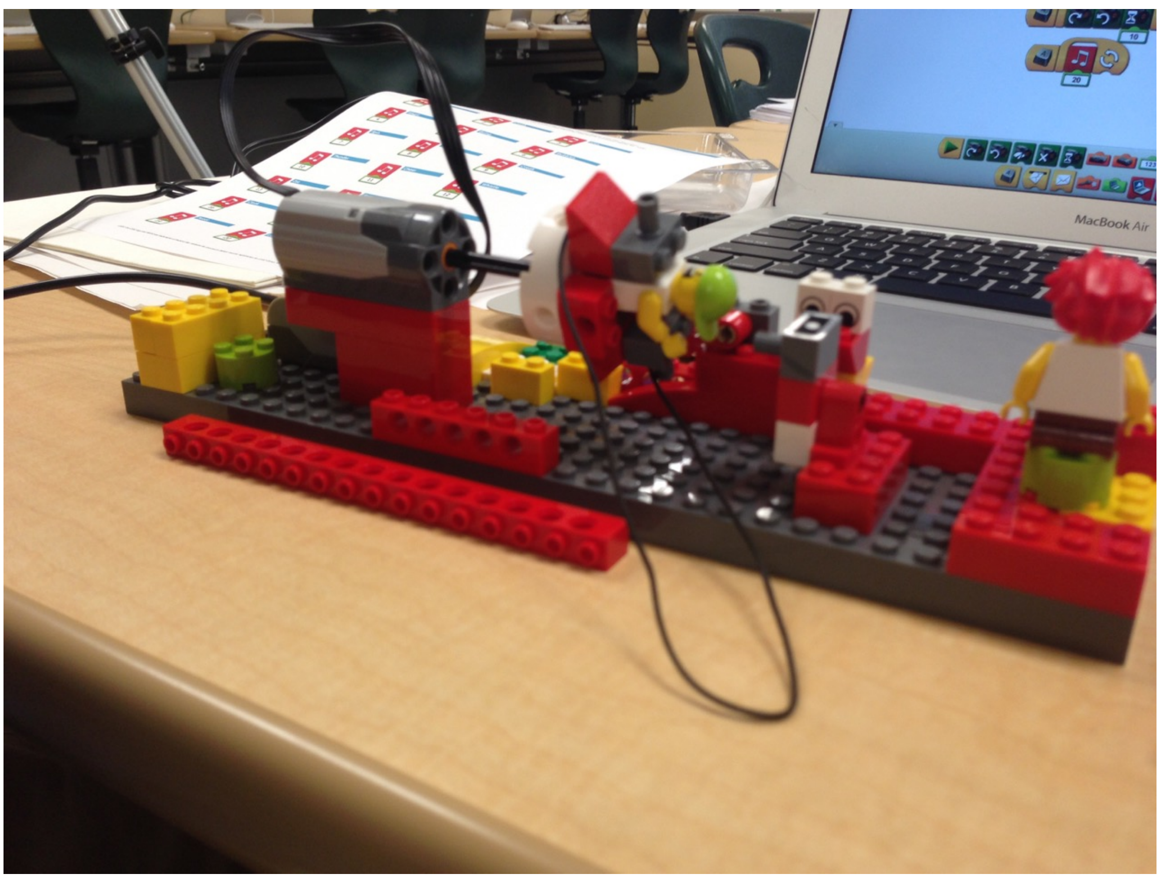


Figure 38. Boy 6 finished ride.

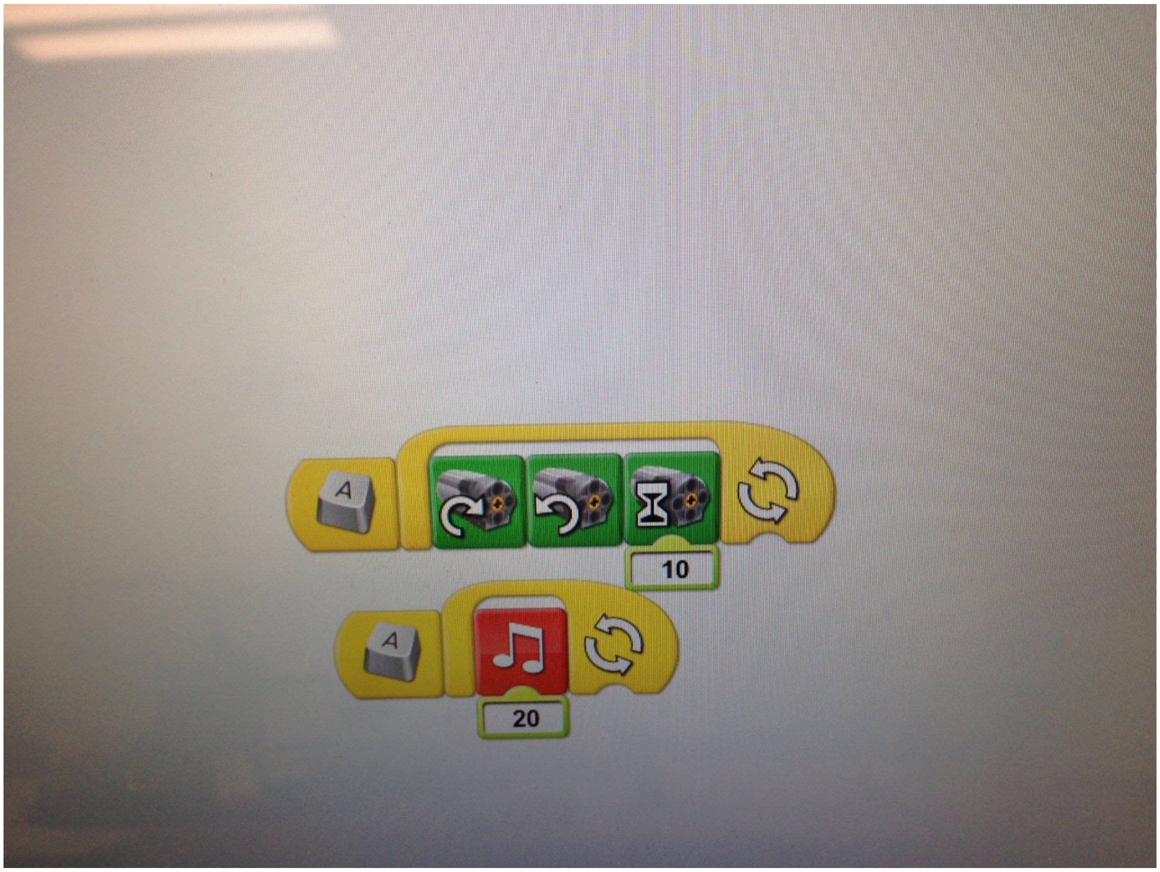


Figure 39. Boy 6 parallel program for his ride.

In terms of process, Boy 6 had a good mix of EDP phases with some up front planning and research and ongoing planning and testing. He had a long programming time but once completed, he did not need to come back to it. Boy 6 showed a fairly typical EDP profile with perhaps a little less research and evaluation than others.   See Figure 40 and Figure 41 for visualizations of his EDP. Note that the dark lines on the time itself in Figure 40 show where the subject was doing nothing, waiting for the researcher, etc.

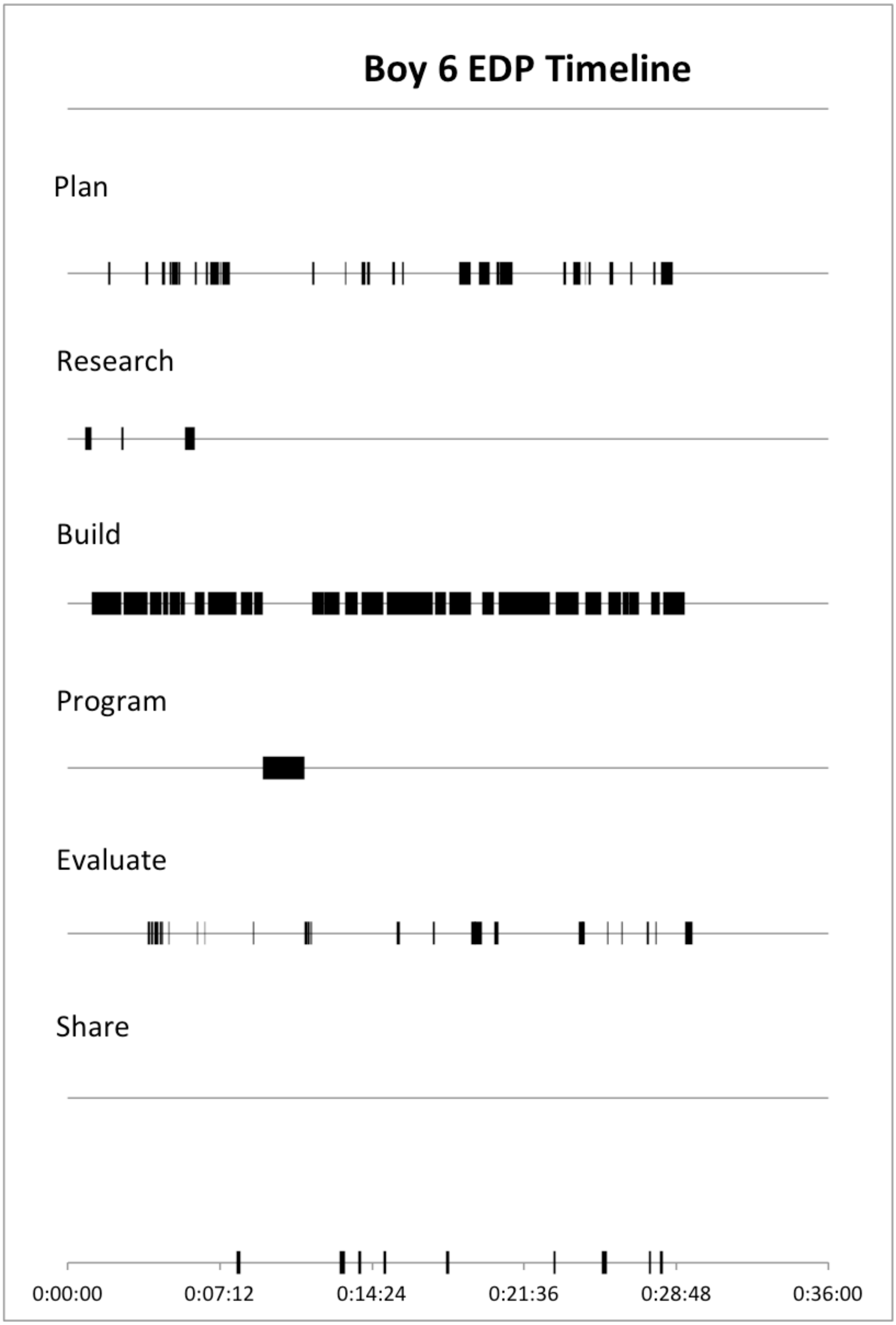


Figure 40. Boy 6 EDP timeline.

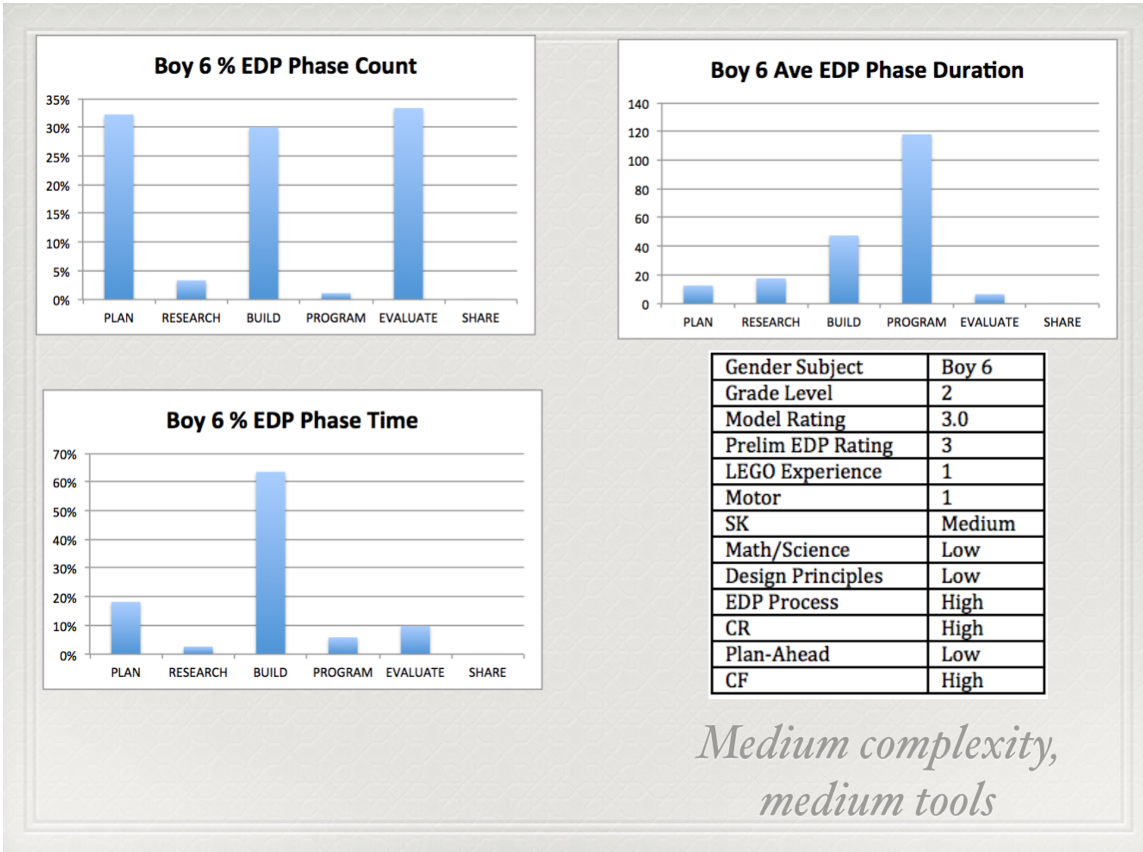


Figure 41. Boy 6 EDP frequency, time, and duration graphs.

Boy 7. Second grader Boy 7 showed a similar final product and similar EDP process as Boy 7 but was a little less sophisticated in his EDP. Boy 7 showed a mix of skills in predicted the effects of his design design decisions. For example, he did not know that a LEGO cross pattern is needed for axle insertion to get a solid connection and hence needed to hand start his ride when there was a load on it, a problem he never corrected.

[00:18:10] Boy 7: I thought it would be too heavy. [IMPORTANT] (Blames free spinning of beam attached to motor on weight rather than connector choice, which is true in a way but not the root cause of the issue.)

As discussed later, there is a question in this type of case as to whether this shows difficulty in causal reasoning, lack of structural knowledge, or a combination of both.

This also shows that children, at times, have no issues with filling in problems with a "hack" that adults might find objectionable. This could be considered to be an example of a lack of cognitive flexibility, which I also call non-optimal persistence, since he never corrected the root cause of the problem. Note also his simple program never ends, which violates the safety constraint. Overall, his build was borderline complex with many subsystems and creative ideas. Examples of this are the lights he built, the ride operator, and the turntable the ride sits on. See Figure 42 and Figure 43 for photographs of his ride and program.

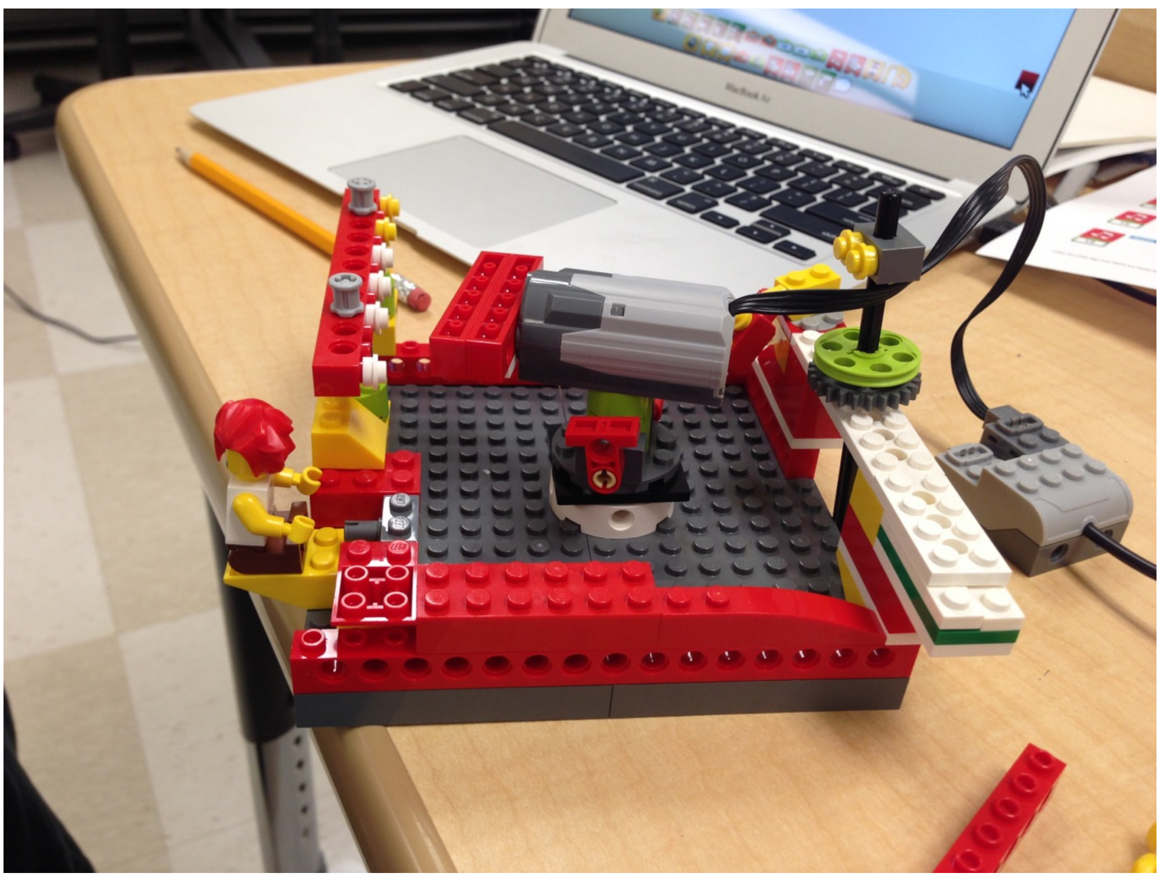


Figure 42. Boy 7 final ride.

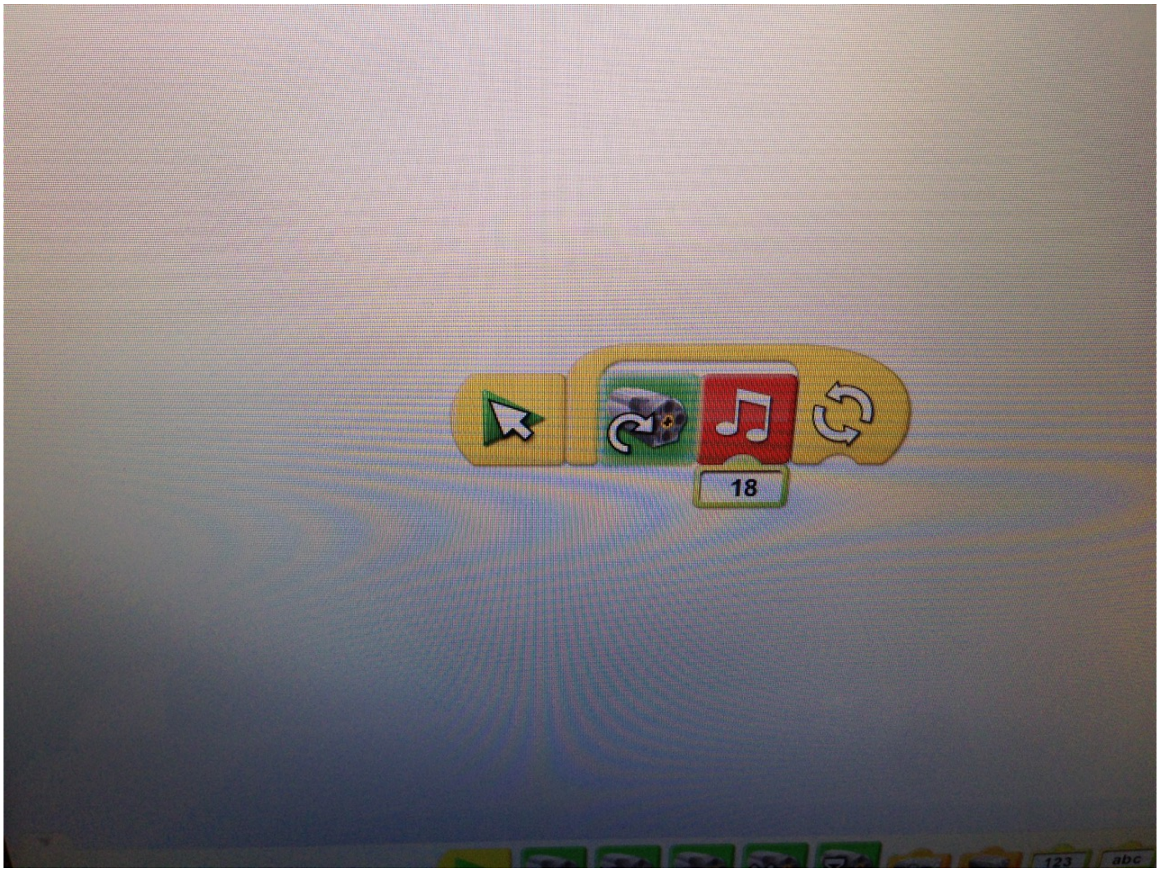


Figure 43. Boy 7 final program. Note that ride never ended.

Boy 7 showed a serial building style; he never indicated an overall plan for his ride but had a lot of build/evaluate cycles, which further shows a tinkering style (Resnick & Rosenbaum, 2013). This is also shown in Figure 44 and Figure 45, which show that Boy 7 spent the vast majority of his time building with not much time planning or researching. He did show some evidence of controlling variables (COV) when he takes the mini-figure off the beam when it does not spin. Overall, Boy 7 showed a build heavy EDP but with some planning, research, and a fair amount of evaluation.

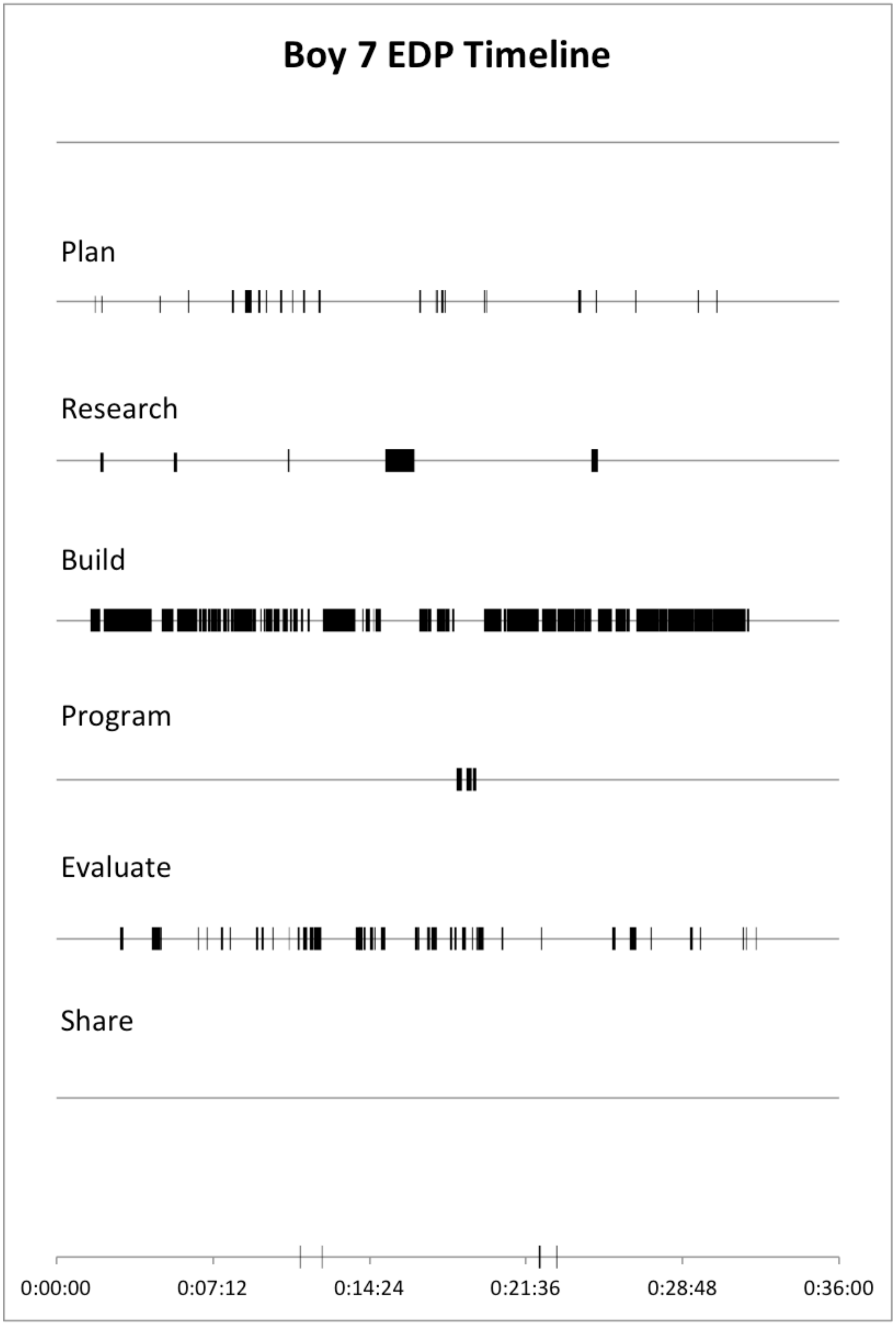


Figure 44. Boy 7 EDP timeline.

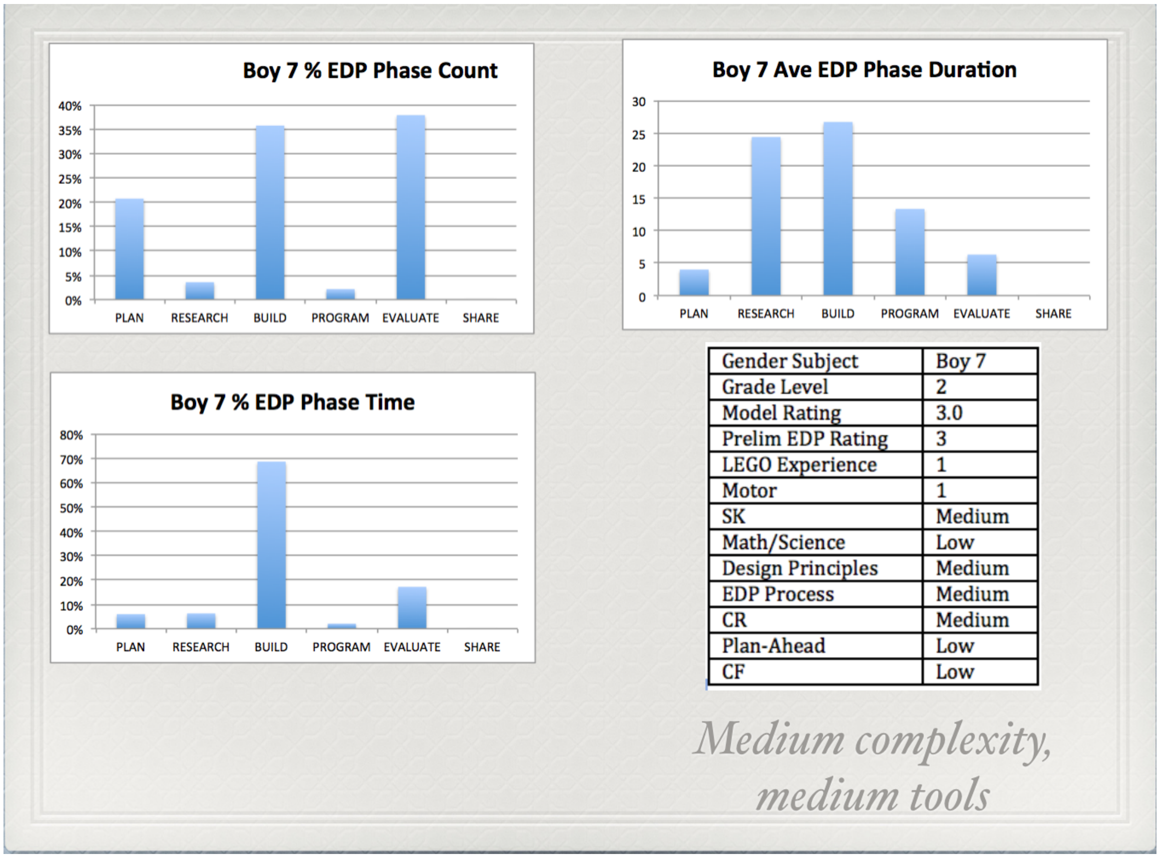


Figure 45. Boy 7 EDP count, frequency, and average duration graphs.

Boy 8. Second grader Boy 8, our last grade 2 boy to discuss, was an interesting and atypical case. Boy 8 showed a real mix of high and low skills and knowledge. His ride was also quite interesting and reflected his mix of knowledge and skills. He attached the motor to his ride seat (rather than a tower structure), which resulted in the cord being tangled up when the ride actually ran. See Figure 46 for a photograph of his ride. Like Boy 7, he did not initially attach the axle to a cross piece. Because that was critical to his ride, I did eventually provide some scaffolding so his work could continue. Boy 7 had a simple 3-step program as shown in Figure 47. Even more interesting than his fairly complex, atypical ride was his engineering design process.

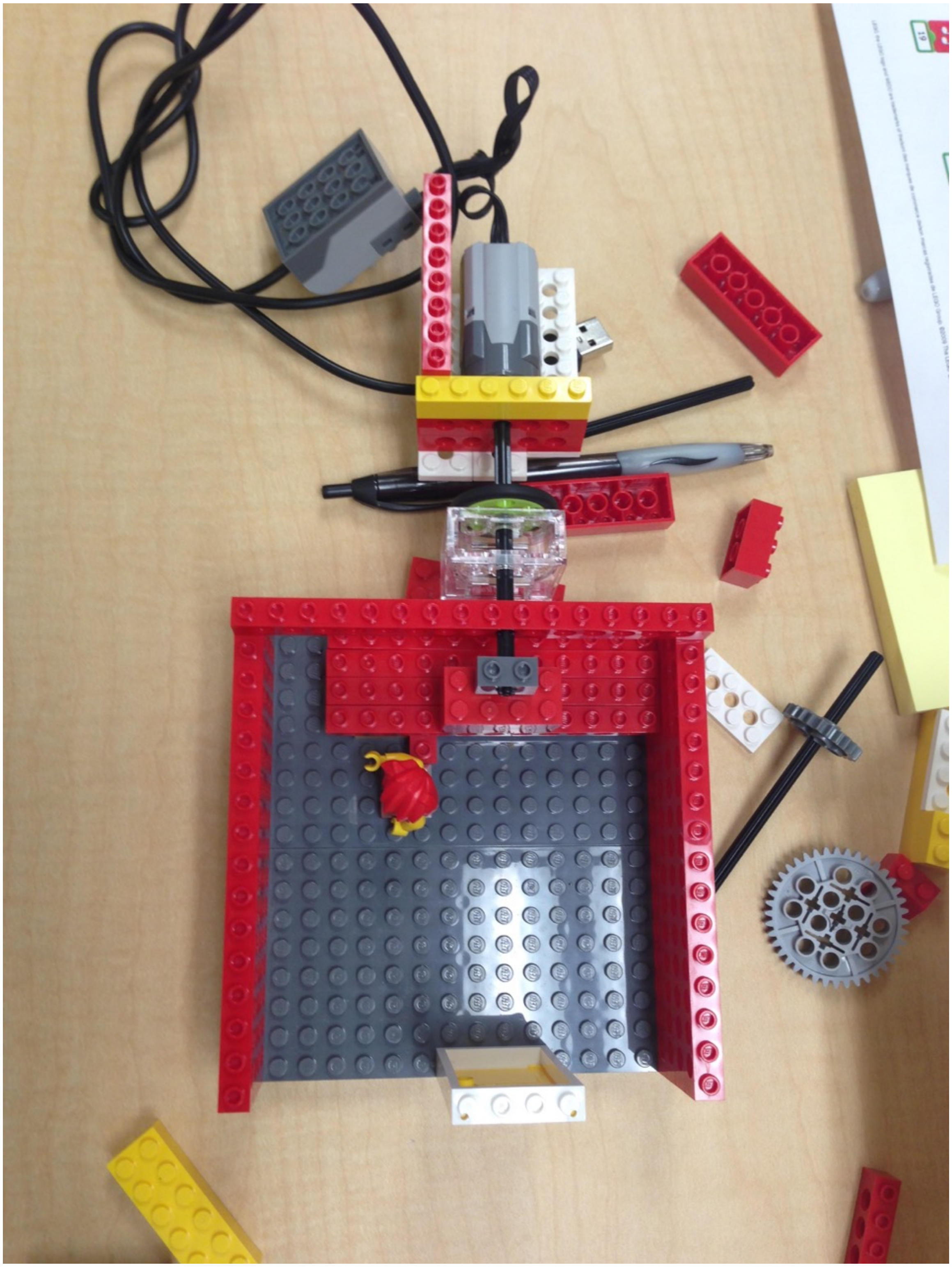


Figure 46. Boy 8 final ride. Note motor on seat and tangled cord.

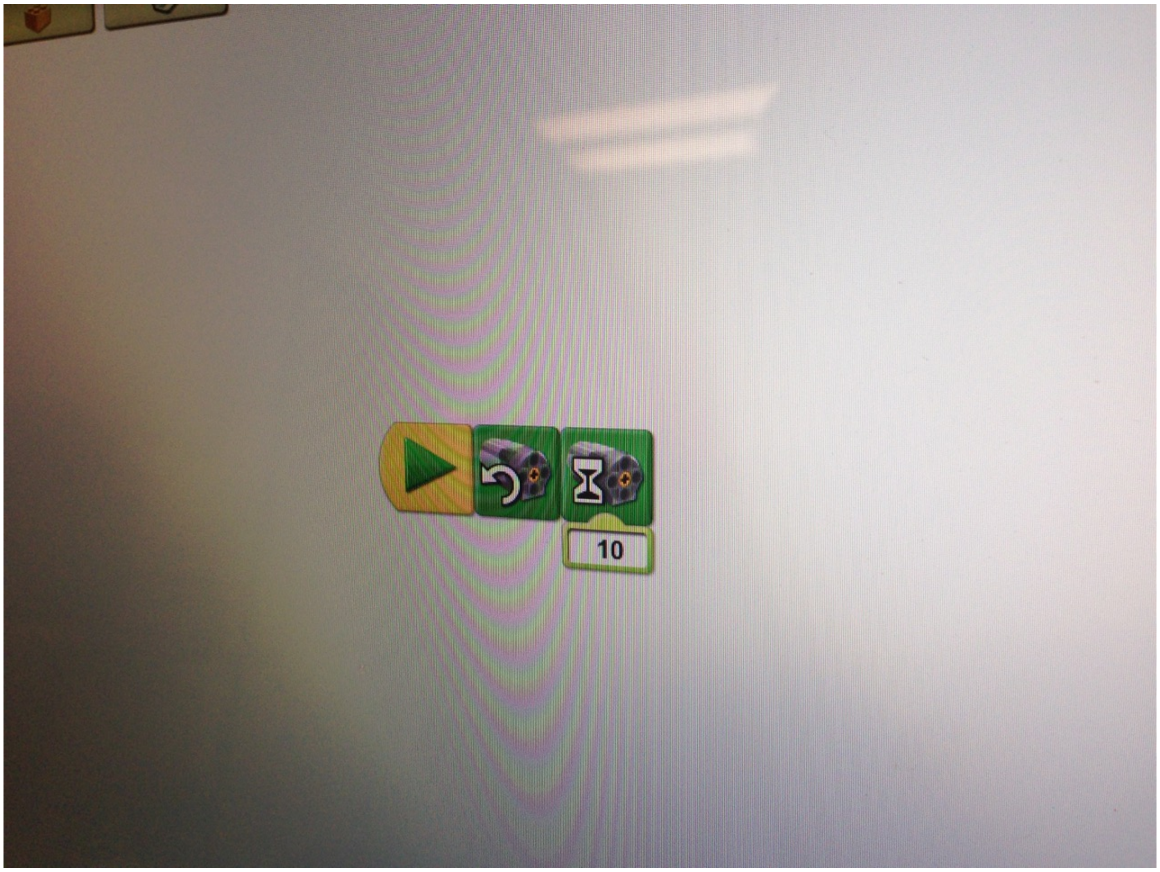


Figure 47. Boy 8 program.

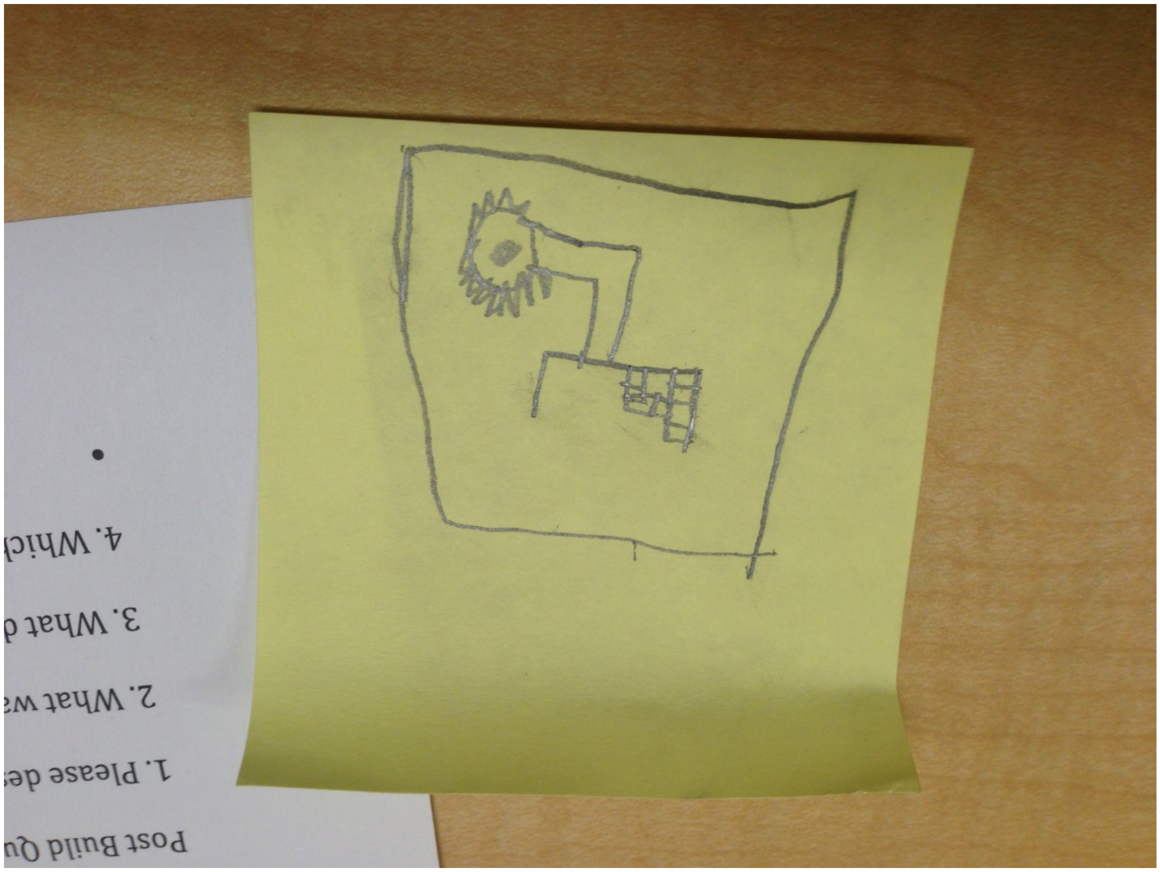


Figure 48. Boy 8 initial ride plan.

Boy 8 was one the few students to use produce a plan ahead of time as shown in Figure 48. He continued to use drawing as a way to plan. His relevant executive function in the form of causal reasoning was less developed than other grade 2 students. One example of this was that he did not see that attaching the motor to his seat rather than the structure would cause the cord to become tangled. However, he did show cognitive flexibility, which helped with lack of causal reasoning and structural knowledge. Here is an example of his cognitive flexibility, which he also can articulate.

> [00:10:28] Boy 8: Maybe I should make the roof lighter, because it keeps falling down because I'm making that wall. [PERSISTENCE+] (Decides to take difference approach in light of persistent difficulty) [IMPORTANT]

An example of his lack of structural knowledge was his confusion about the purpose of motors. While he did not use design principles of stability, symmetry, and scale, he did have good engineering design process knowledge, he applied mathematics to help his design, and he planned ahead with an overall system design. He also attended to the design constraints. Because of his strengths of cognitive flexibility and a good EDP, he was able to largely overcome his lack of structural knowledge and causal reasoning given sufficient time. An example of this is when he eventually figures out, with sufficient testing, that the axle must be solidly attached to the wall in order for the seat to spin.

> [00:36:19] Boy 8: Wait, I don't think I actually make something to move. I just need something to stick it into, because then you'd still be stopping it and then… [IMPORTANT] (Learning moment)

Examining the EDP Timeline, as shown in Figure 49, we see a more advanced EDP with significant up front planning and research. However, his overall time is longer than other grade 2 students because his lack of causal reasoning and structural knowledge caused more time to be needed to work out design problems. Figure 50 confirms a good mix of planning, research, building, and evaluation in the % EDP Phase Time graph. Now that the grade 2 boys have been examined, let's look at the products and processes of the grade 2 girls.

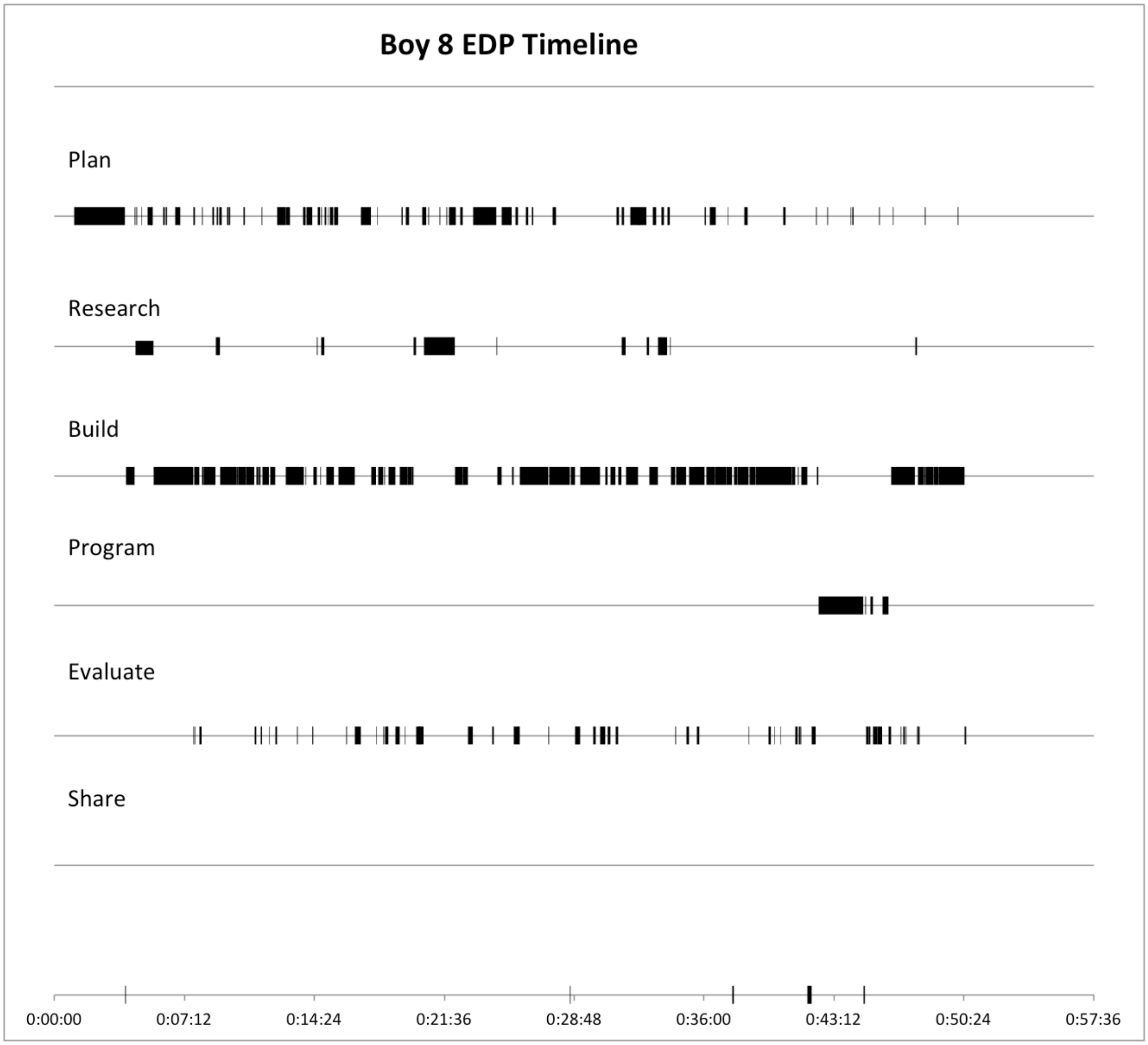


Figure 49. Boy 8 EDP timeline.

Figure 50. Boy 8 EDP phase frequency, time, and average durations.

Girl 6. Second grade Girl 6, like Boy 8, made drawings of her design, but they were post-make drawings. She pointed to the prototype and then the drawn parts so she had a 1-to-1 correspondence with drawing and model. Girl 6 made a simple LEGO ride that did not use a motor or a computer. See Figure 51 for a photograph of her finished ride. Note the green and yellow stairs on the side of the ride. The ride had a small number of parts but did rotate manually with a long ride beam rotating on an axle. Figure 52 shows her accurate post make drawing. Now that a short description of her fairly simple ride has been given, let's examine her engineering design process.

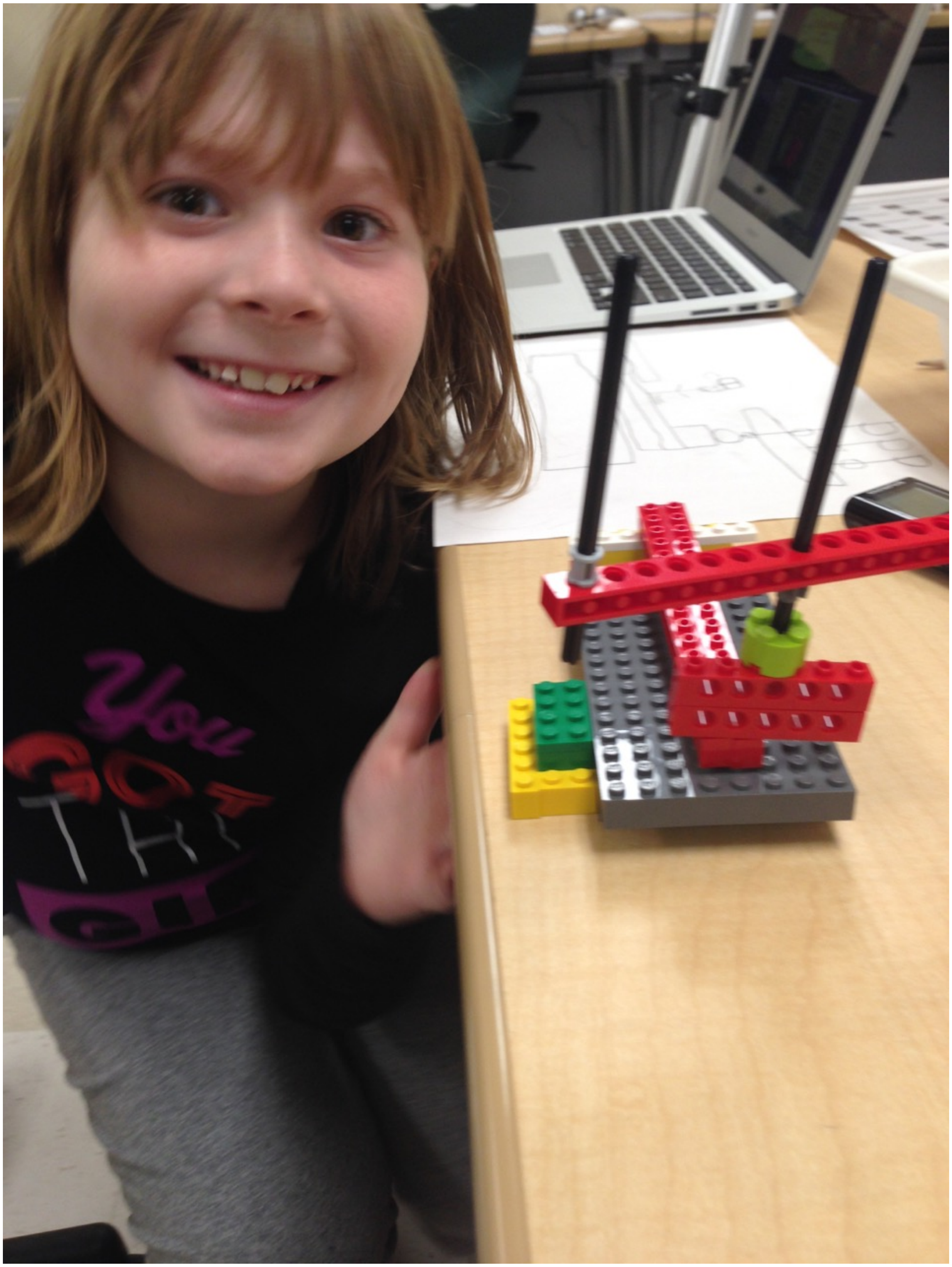


Figure 51. Girl 6 finished ride.

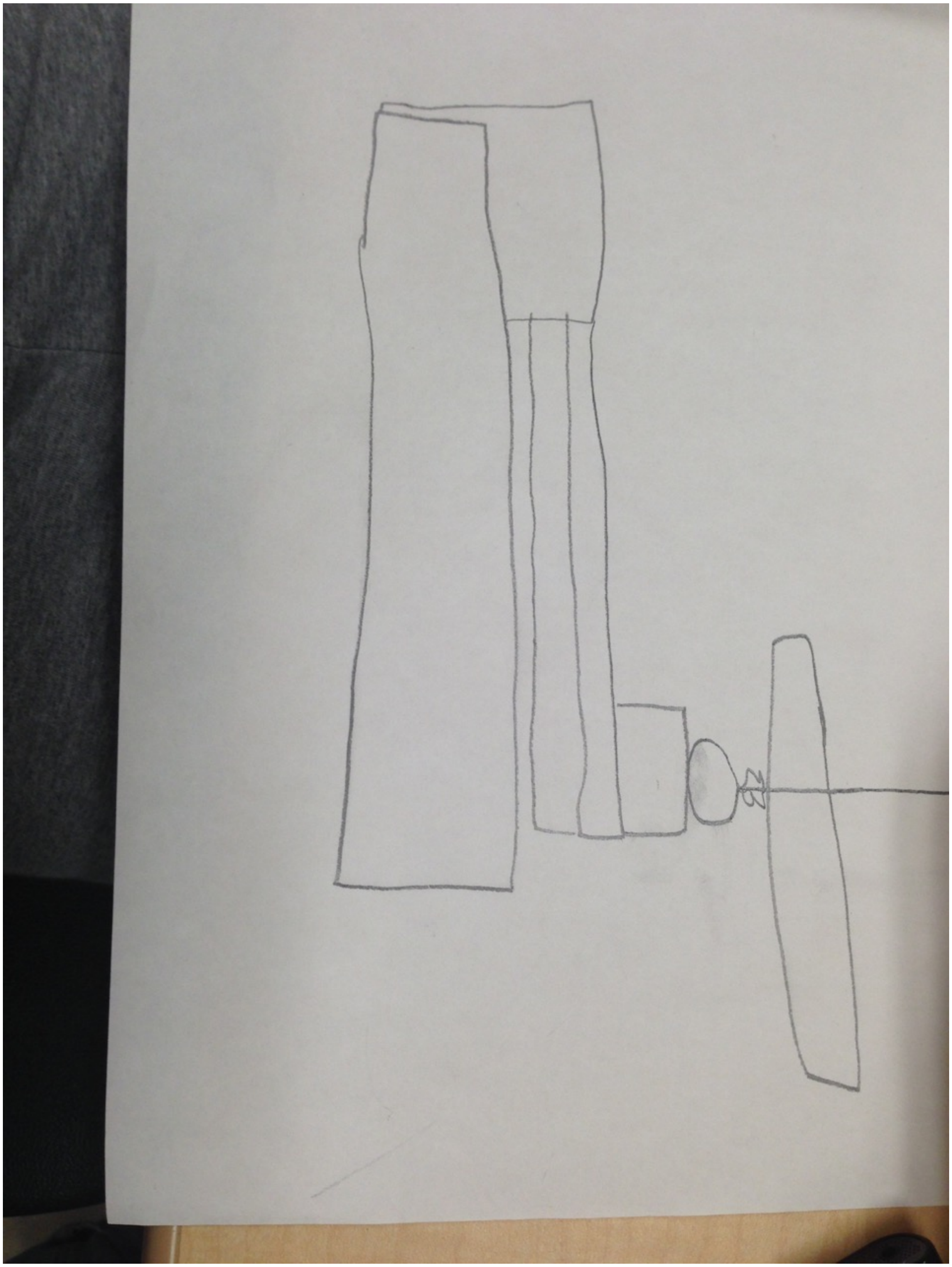


Figure 52. Girl 6 post make drawing.

In terms of her process, we see from Figure 53 that Girl 6 jumped right into building. She initially asked about using drawing as a plan, but when I told her it was her choice, she skipped the drawing and jumped right into building. Girl 6 had low causal reasoning and structural knowledge. For example, she repeatedly tried to attach a long beam to another long beam at at 90-degree angle using a single connection point. Again, since these seem to go hand-in-hand, there is some question as how much is lack of structural knowledge, how much is causal reasoning, or how much is a combination of both. Girl 6 also showed evidence of low cognitive flexibility (non-optimal persistence) in terms of persisting with unstable design ideas. However, she did change her larger ideas of about what her ride could be. An example of this is shown below.

> [00:06:09] [PLAN] Girl 06: Even though I was going to try to make it go up like this and then go down, or there was this ride where it was a dragon ride. It went side to side, and then it started to go up, up, and then it started to go higher and higher, so I might make the dragon ride too. [IMPORTANT]

During the coding process of Girl 6, I started to wonder if the complexity of the designs such as this one might be affecting the corresponding engineering design process. Her simple design was build heavy and she chose not to explicitly plan the ride on paper.

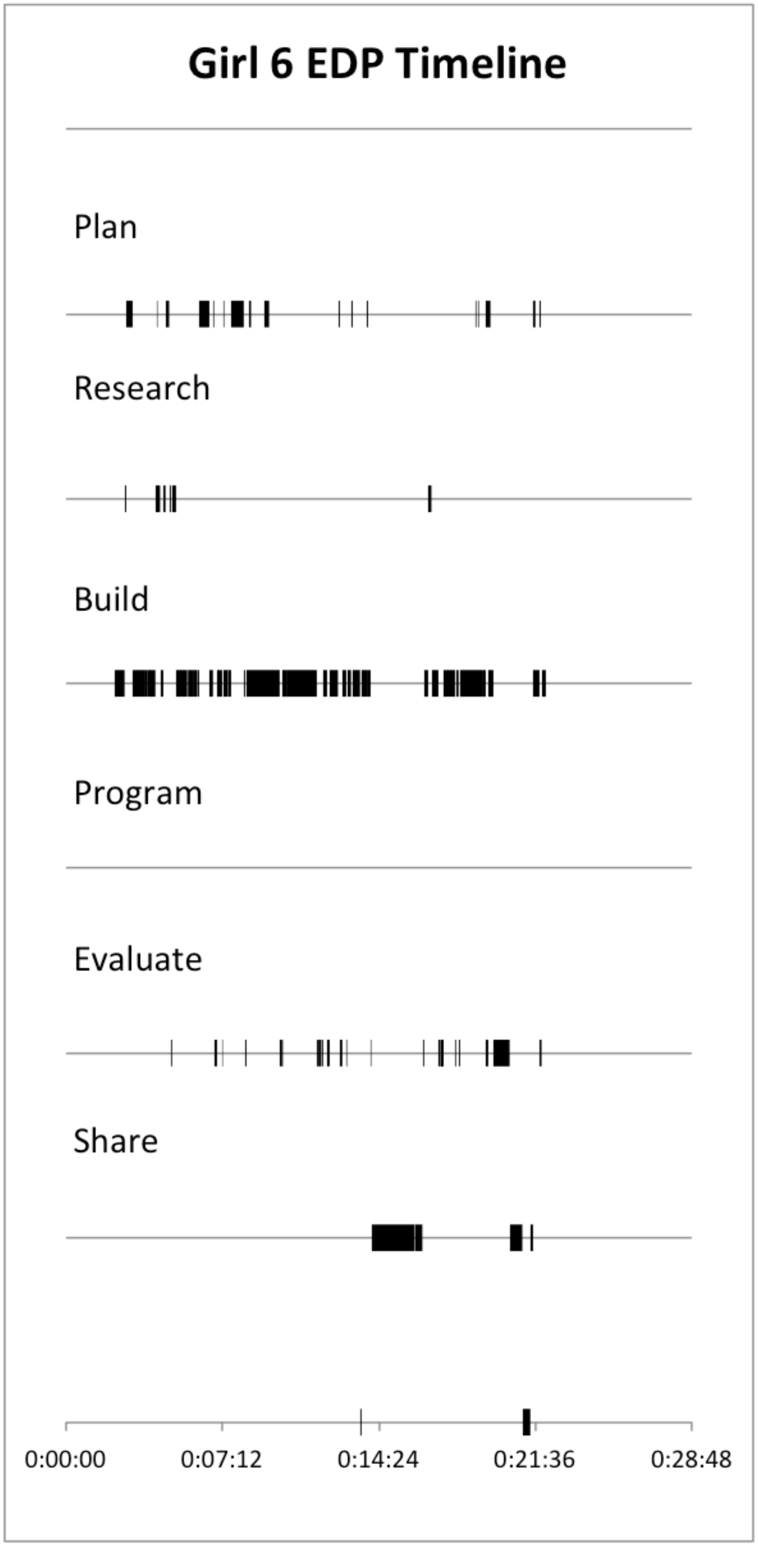


Figure 53. Girl 6 EDP timeline.

As shown in Figure 54, Girl 6 spends a large proportion of her time building, which supports the previous contention that her EDP process was not advanced. She spent very little time researching but did do some amount of planning. Now, let's see how Girl 6 compares to the other second grade girls, Girl 8 and Girl 9. Recall that Girl 7 was not used since she did not verbalize sufficiently.

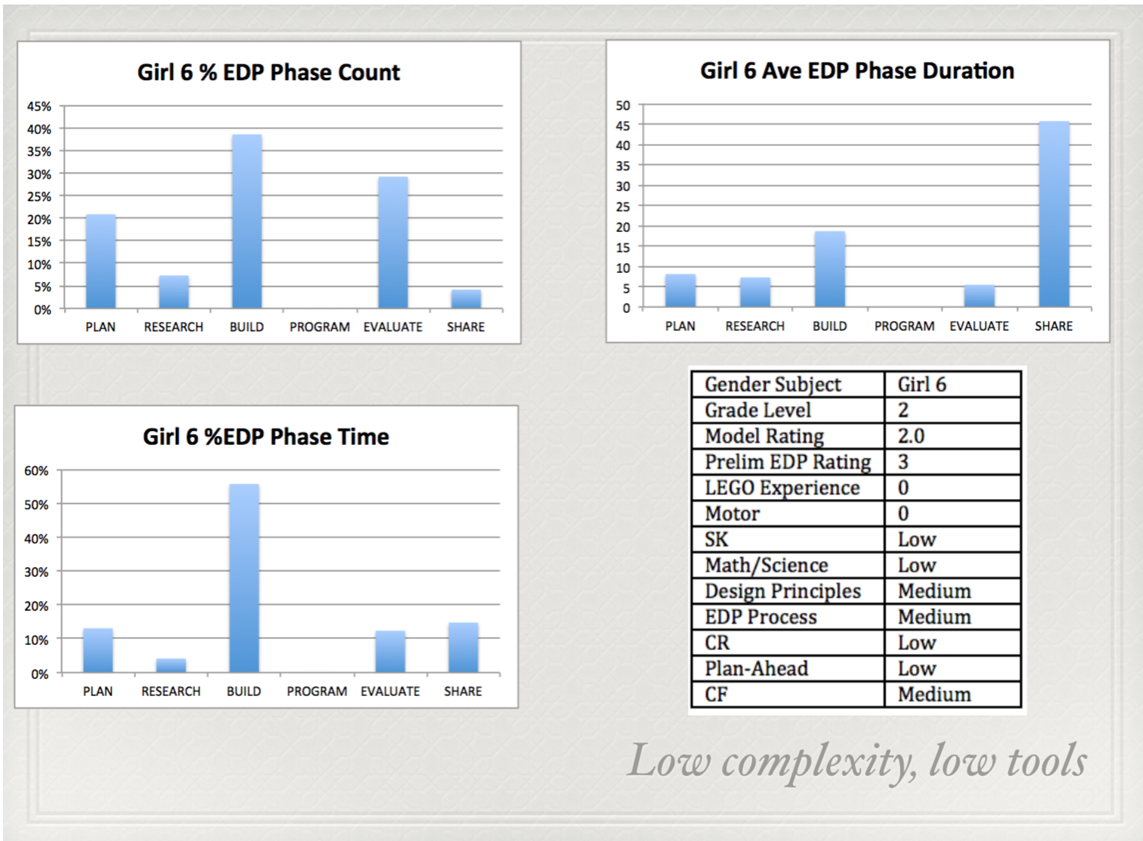


Figure 54. Girl 6 EDP frequency, time, and average duration graphs.

Girl 8. Girl 8 is a very interesting and atypical case. She had advanced engineering and executive function skills, which she demonstrated in both the warm up task and the main task. However, she chose a low complexity design, as shown in Figure 55, which resulted in a very unique EDP timeline. Girl 8 chose to make a roller coaster, which she planned very precisely ahead of time (see Figure 56).   The ride did not use a motor or computer.

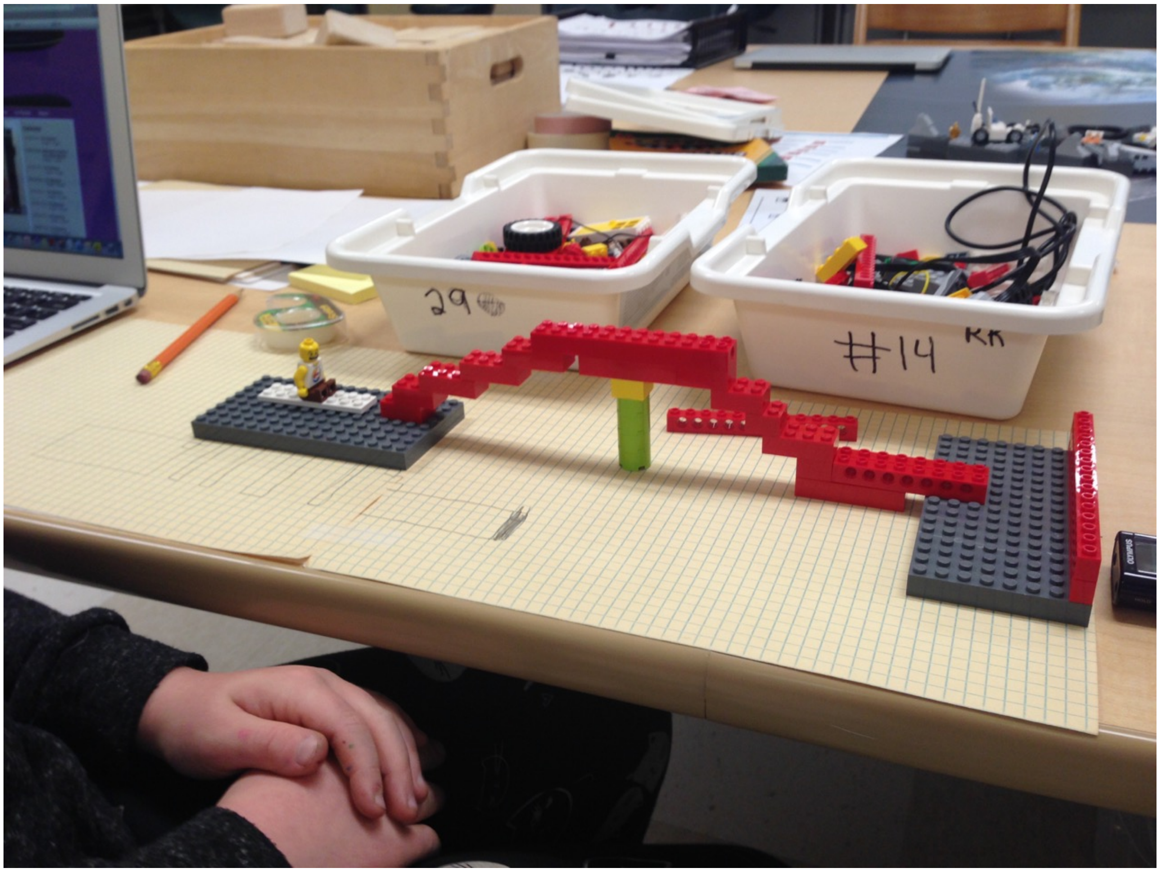


Figure 55. Girl 8 final ride.

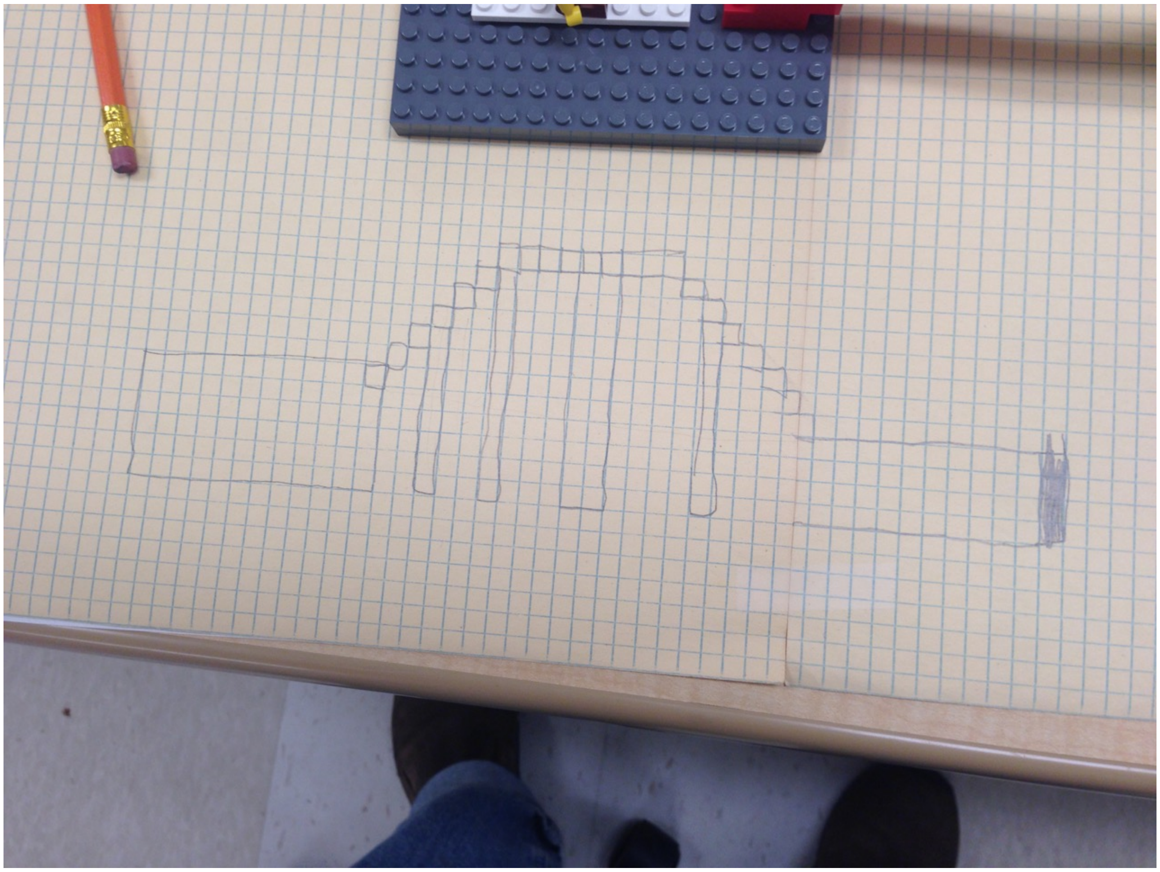


Figure 56. Girl 8 ride plan.

Girl 8 had a very interesting engineering design process (see Figure 57). She completely planned out her ride ahead of time and needed very little iteration. She spontaneously planned without teacher prompting. In other words, her ride worked as planned without the need for very much rework. She did no research and needed very little evaluation (testing) of her ride as shown in Figure 58. Note also that she did not need much time to complete her ride. She did use some simple math in the form of counting to help execute her plan. She seemed to be idea first, systems (as opposed to serial) builder. In other words, as her drawing shows, she planned out her complete ride ahead of time. Girl 8 showed through her verbalizations that she drew on previous experience. An example is shown below.

[00:03:50] Girl 8: Yeah. It's going to be this, and then it's going to keep going up. Then I have to have one of these so it can stay, like a board, so it can stay holding down, and up. I have to keep adding ... I can't remember if I did this this year with the cars or something, but me and Jackson we kept taking little ones and piling them on top of each other. [IMPORTANT]

As she drew, she was clearly visualizing the building process, which indicates good structural knowledge and good causal reasoning in the form of prediction.

[00:04:31] {drawing}

{00:04:40] Girl 8: Make it stay holding.

[00:04:50] Girl 8: Now I'm adding a flat part.

Researcher: Yup.

[00:04:54] Girl 8: It needs to be these. This one's going to be a little thicker so it can hold up better. [IMPORTANT]

I wondered if the combination of low complexity and high skills and structural knowledge resulted in such a unique EDP, similar to early, theoretical, idealized EDP models as described by Welch (1999). Girl 9, on the other hand, seemed to be somewhere between Girl 6 and Girl 9 in terms of build complexity and process.

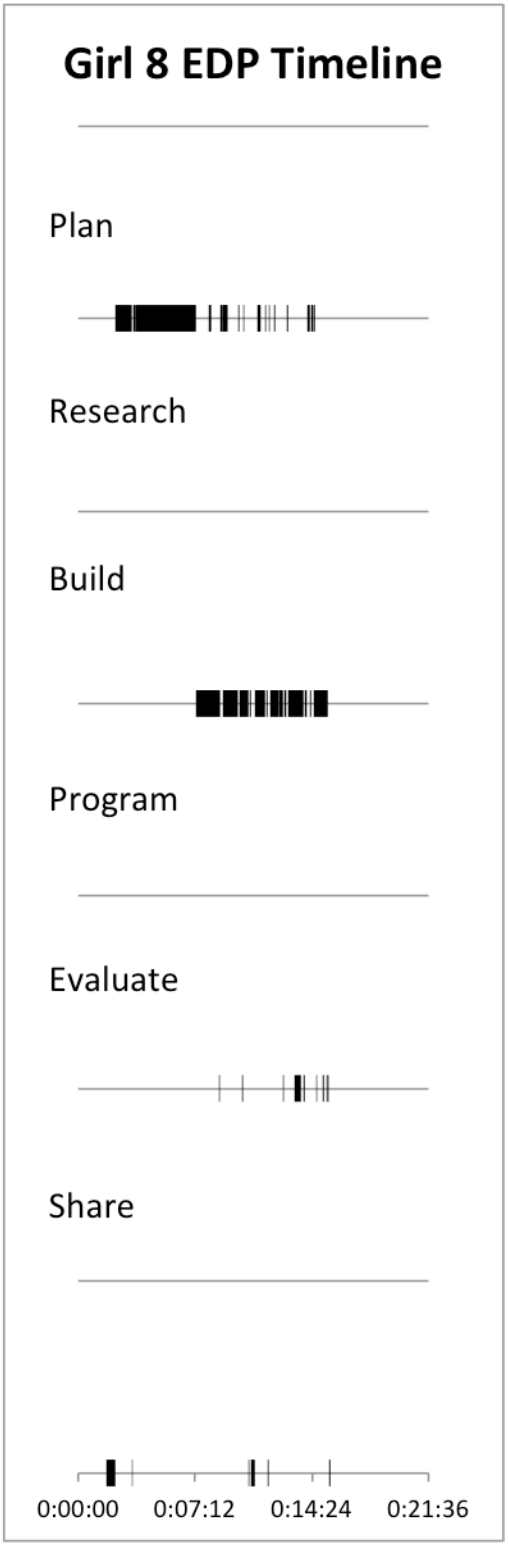


Figure 57. Girl 8 EDP timeline.

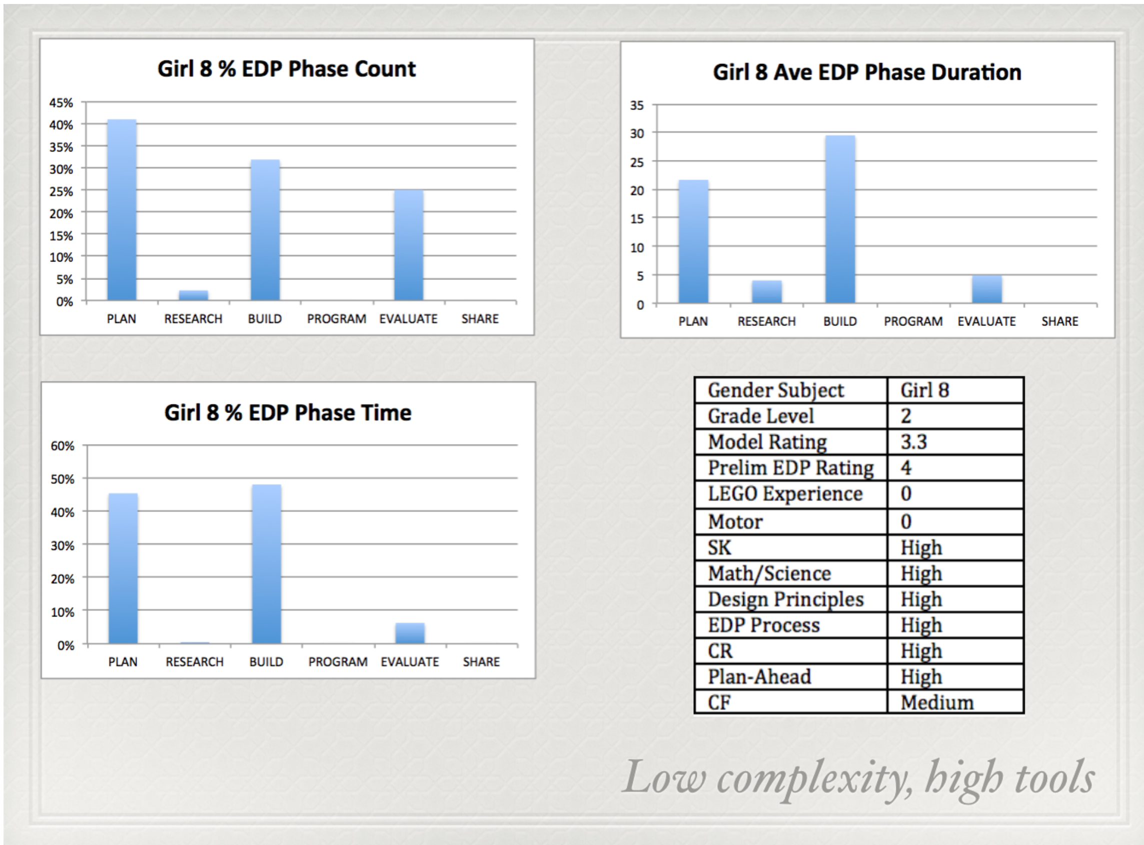


Figure 58. Girl 8 EDP frequency, time, and average duration graphs.

Girl 9. Girl 9 was very creative in her ride. She readily "filled in" mentally the parts of her ride she could not actually make. As shown in Figure 59, the motor does not actually turn anything. Also note in her program (see Figure 60), the Wait For Motion Sensor block is not functional, though the program still runs. She did have many imaginative details such as the "grass" she made for her ride.

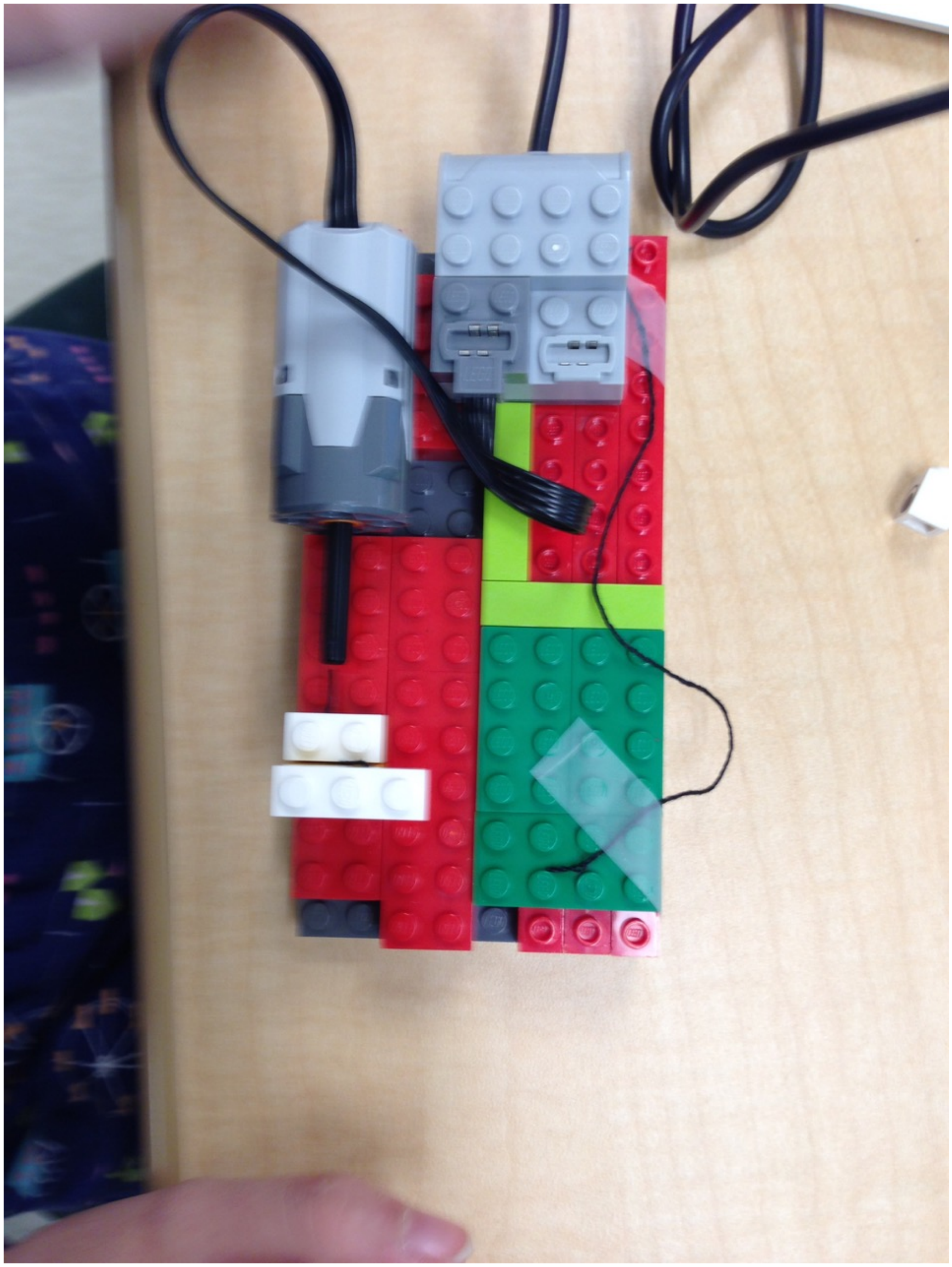


Figure 59. Girl 9 finished ride.

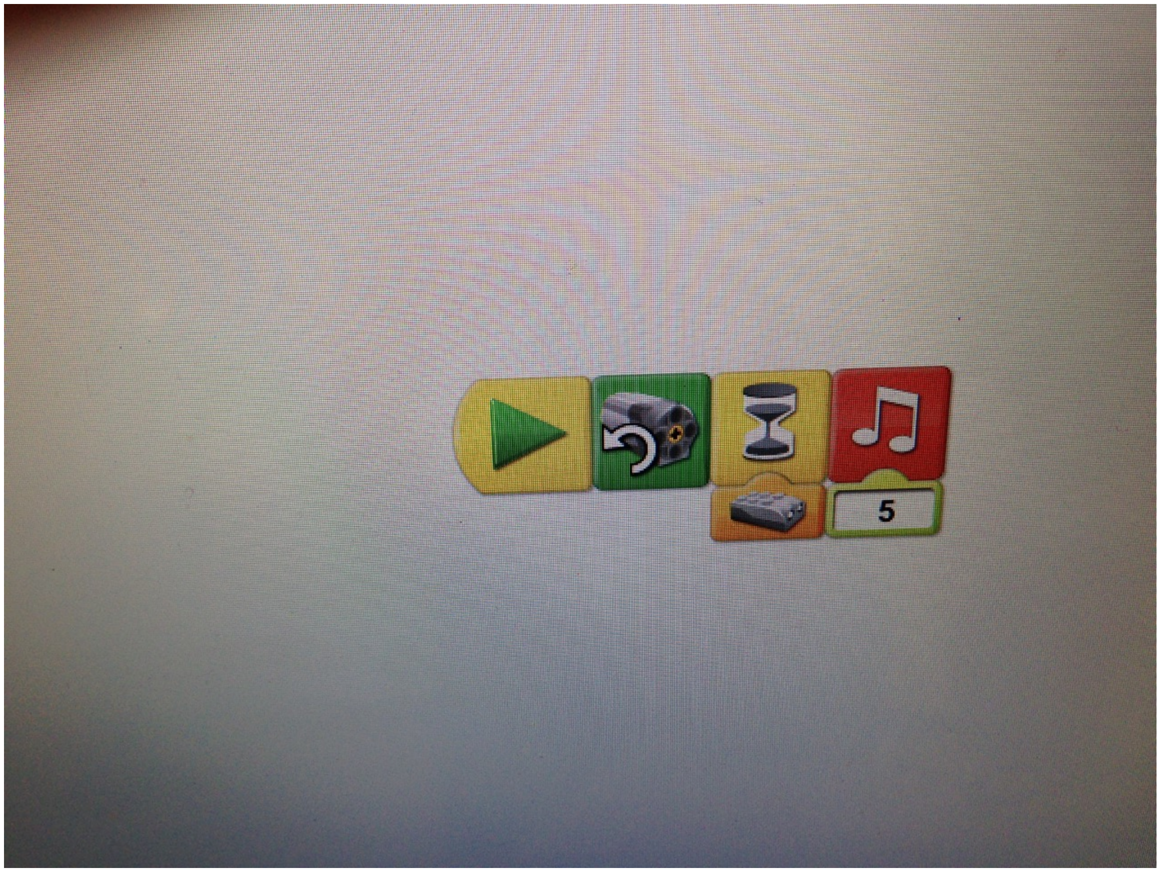


Figure 60. Girl 9 ride program.

In terms of her process, she lacked structural knowledge. A few (of many) examples of this were: she did not have good knowledge of how LEGO pieces connect and she was unclear on the difference between the motor and USB hub. She also had some misunderstandings about her program. She did use mathematics when she measured the string before cutting it. She was very much a serial builder who did not have an overall plan for her design up front.   She did consistently describe her next step. Because she had generally good cognitive flexibility, causal reasoning, and engineering design process knowledge, she happily finished her ride leaving some - what adults might consider incomplete - parts of her ride to her imagination. Here are some of her comments on this.

[00:25:18] {no_activity} [2:PLAN] Girl 09: I might want to make it so this looks kind of connected. I'm going to grab another piece and try to connect them…

[00:26:22] [2:PLAN] Girl 09: I couldn't find a long enough piece so now I'm just going to add more grass.

In the post interview, she describes her ride and process this way.

Girl 09: Sure. The motor helps this turn, the handle turn. The seat you can move. I had to move it because it needed enough space. It doesn't latch on because I couldn't find a piece to latch it on. This rope, I put the little pieces on it for it to stay until I put on the tape.

Her use of tape with LEGOs also shows cognitive flexibility but also a lack of structural knowledge. Adults and experienced LEGO builders might find the use of tape objectionable to their own design sensibilities.

Figure 61 and Figure 62 show that she builds without much initial planning but plans as she goes, suggesting a serial or tinkering style (Resnick & Rosenbaum, 2013). She did do some research and testing as she built. Unlike other students who seemed to lack both casual reasoning and structural knowledge, she had good casual reasoning skills but clearly lacked structural knowledge. However, her causal reasoning skills helped her ***gain*** structural knowledge during the build. Now that the second grade builds have been discussed, the sixth graders will be examined next.

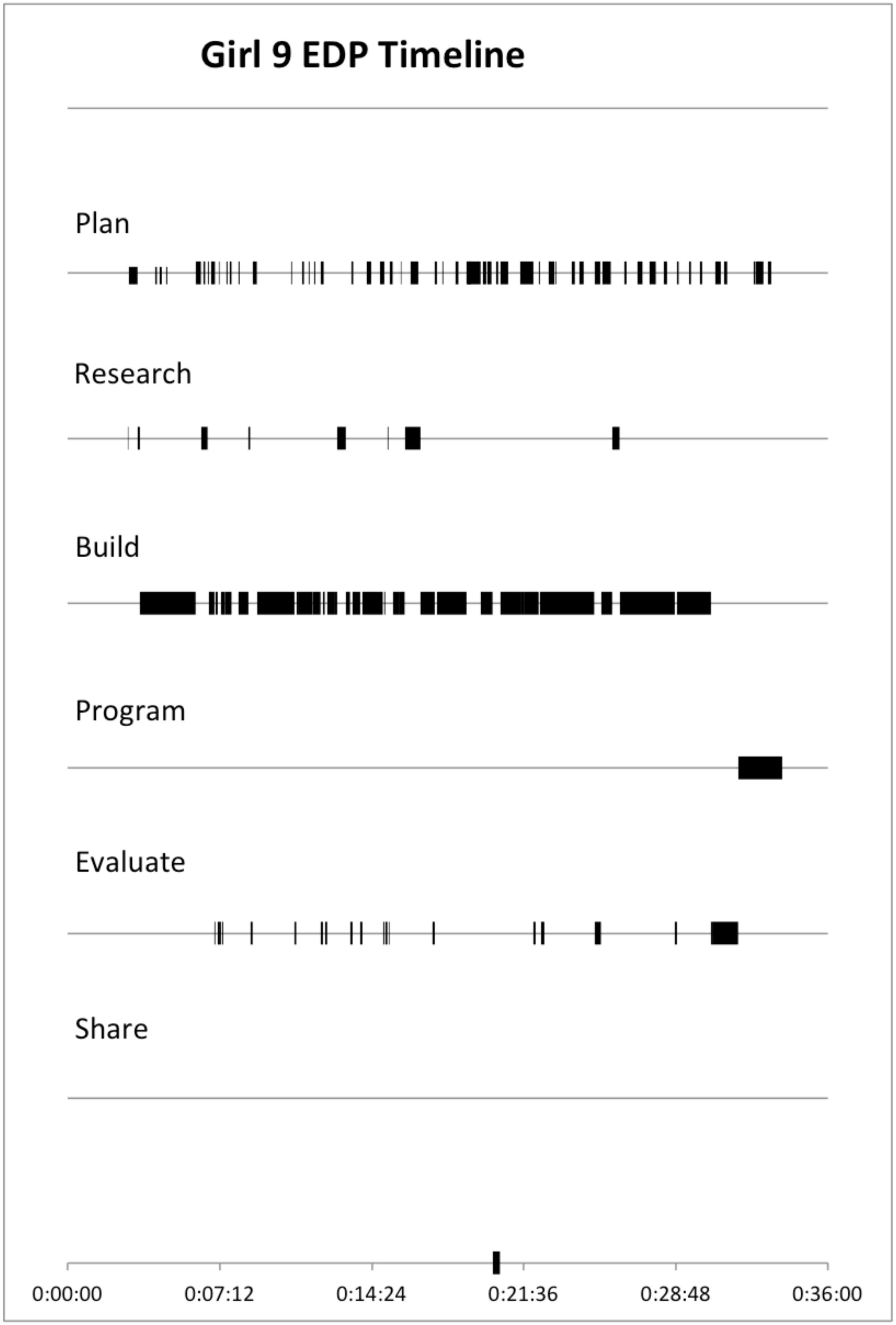


Figure 61. Girl 9 EDP timeline.

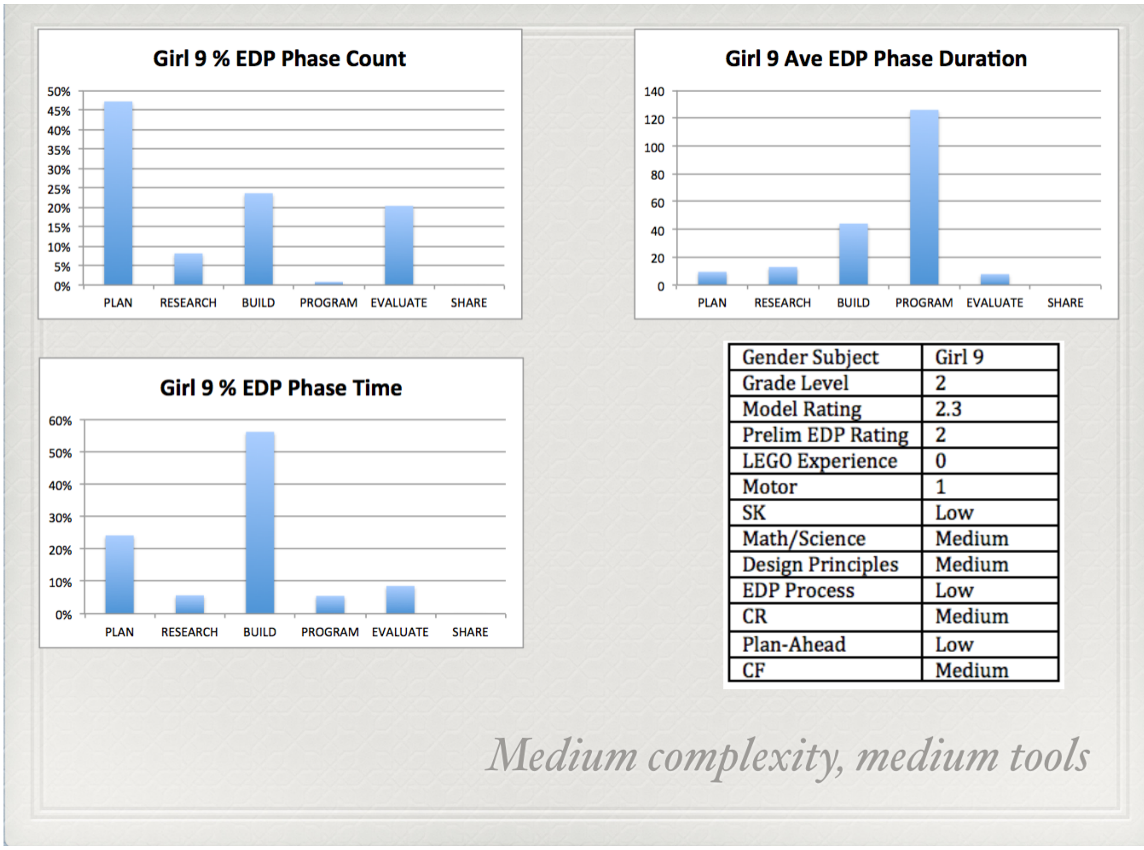


Figure 62. Girl 9 EDP frequency, time, and average duration graphs.

Boy 3. Boy 3 initially built a roller coaster completely out of blocks. I decided that I should have required LEGO blocks to be used and I asked him to try again. Somewhat surprisingly as shown in Figure 63, he chose to build the same ride idea - a roller coaster - using wooden blocks and LEGOs. Most of the LEGO pieces were not even connected and, furthermore, not even lined up (see Figure 64). This again shows the children will readily “fill in” what adults or experienced LEGO builders might find objectionable in terms of LEGO design sensibilities.


Figure 63. Boy 3 finished ride.

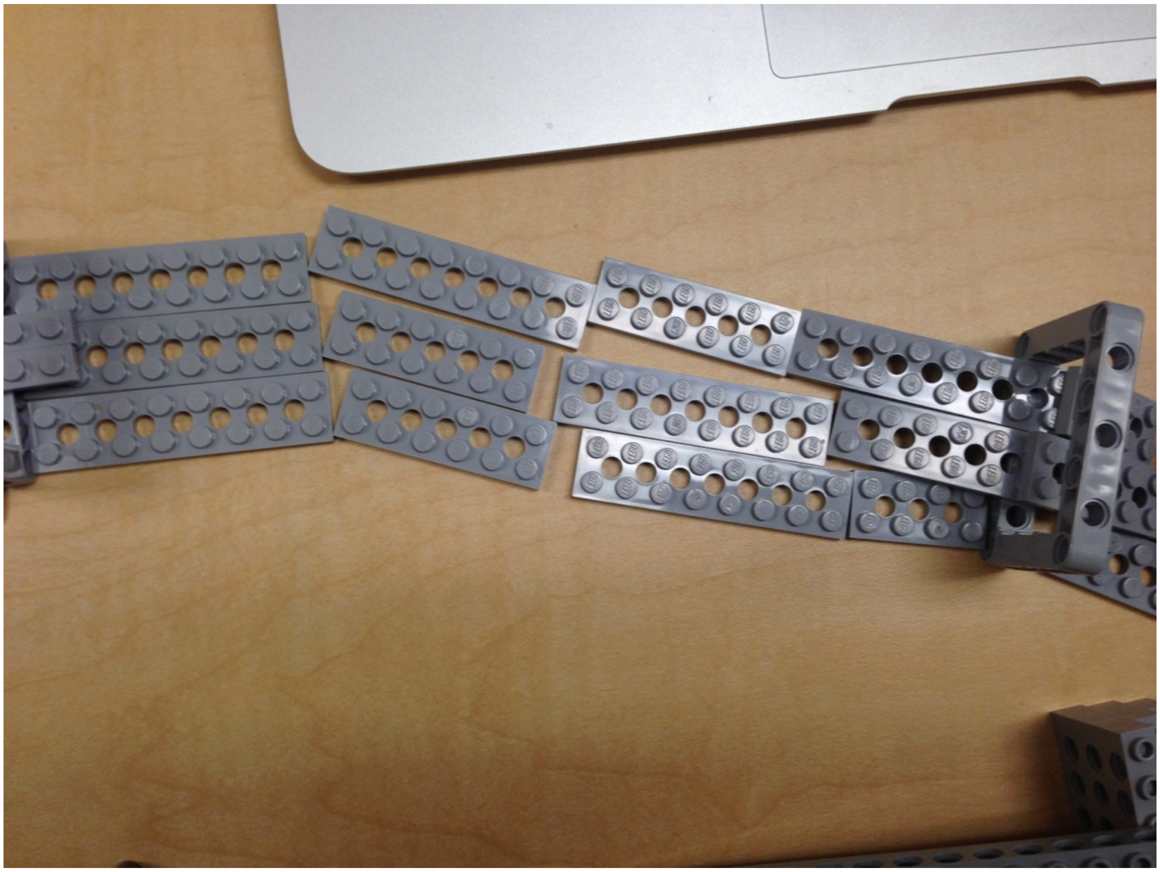


Figure 64. Boy 3 ride section.

Boy 3 chose a low complexity build and his process reflected that. He did not need very much testing or research as shown in Figure 65 and Figure 66. After some initial planning, Boy 3 built his roller coaster and did some planning as he went using a serial building style. He did not show application of mathematics or science or much structural knowledge. It is somewhat unclear how much this is a function of his low complexity build choice. He did show some evidence of cognitive flexibility by essentially using LEGO pieces as blocks in such a unique way. He also showed some causal reasoning skills when the secondary EDP codes were examined. The short build time and overall EDP seem to indicate low complexity and low overall structural knowledge and process skills. Next we look at Boy 4 also chose a roller coaster design, but with significant differences in final product and process.

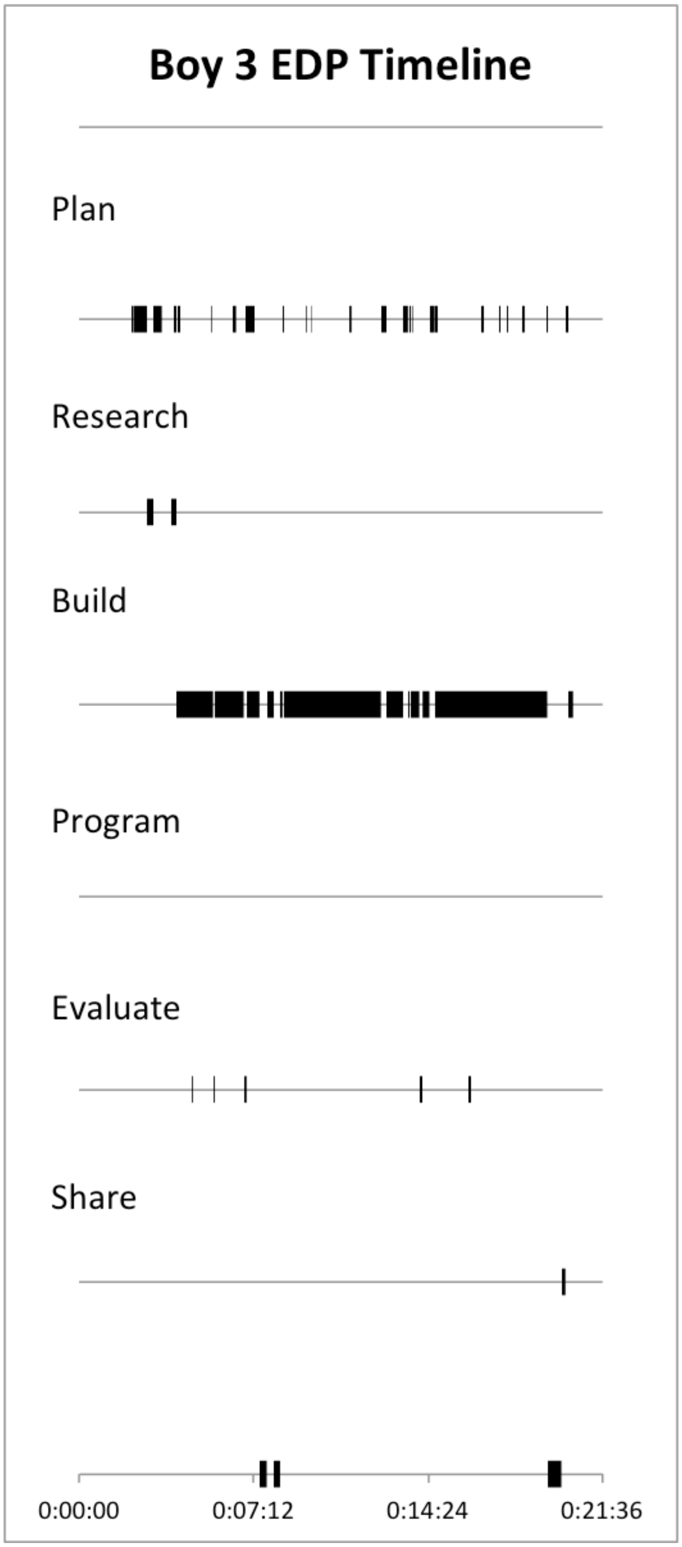


Figure 65. Boy 3 EDP timeline.

Figure 66. Boy 3 EDP frequency, time, and average duration graphs.

Boy 4. Boy 4, like Boy 3, built a non-motorized roller coaster. However, as can be seen in Figure 67, his design is much more sophisticated - in terms of his use of LEGO connection techniques - than Boy 3's. See Figure 68 for a sampling of some of his LEGO connection techniques. We can see that structural knowledge, in the form of LEGO connection techniques, seems to be emerging as an important factor in elementary engineering of LEGO and LEGO robotics. Note also that his design is also symmetrical and much more stable that Boy 3's roller coaster.

Let's look at Boy 4's engineering design process now, especially compared to Boy 3 since they made the same ride idea and are the same age but choose very different levels of complexity and exhibited much different structural knowledge of LEGO connection techniques.

Figure 67. Boy 4 final ride.

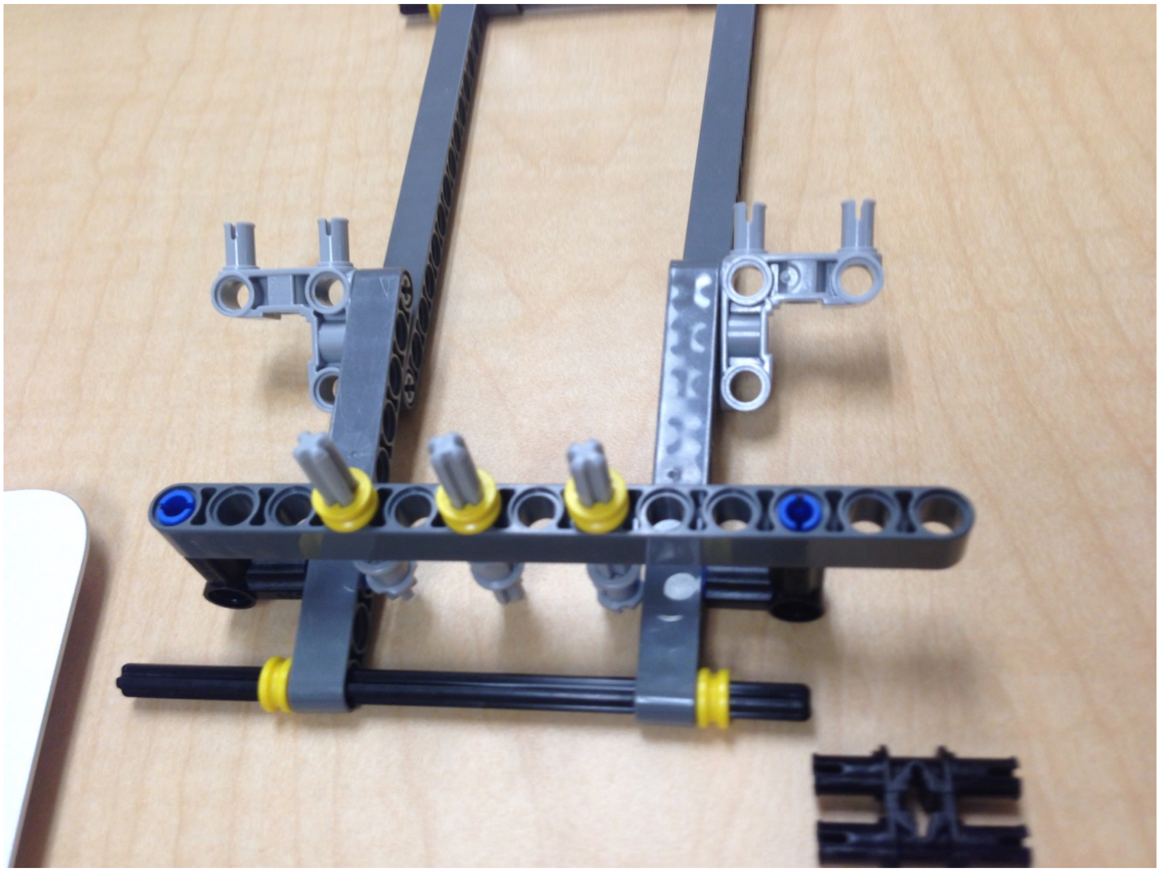


Figure 68. Close up of Boy 4 LEGO connection techniques.

Figure 69 and Figure 70 show much more typical engineering design process than Boy 3. This is seen with the greater amount of time and a more even distribution of EDP phases, most notably evaluation and research. His build time was also longer and more typical of medium complexity builds.

Boy 4 articulated a parts first orientation at one point in his design.

> [00:26:51] Boy 04: I'm just looking for parts to see if they give me any inspiration for something new. [IMPORTANT]

However, he seemed to have an overall plan in mind at the start of his process. He could not precisely articulate why he builds symmetrically at 11:02 but he did consistently build symmetrically. He also was able to articulate concerns about stability explicitly, in both cases, showing use of engineering design principles.

[00:11:02] [2:EVALUATE-VERBAL] Boy 04: So it's not like ... if there is like a car going on it, it could turn one way instead of the other, but I wanted it to be one way. It just works better, I think. [SYMMETRY+]

[00:27:45] [BUILD-NORMAL] [2:PLAN] Boy 04: I'll just put this on this one too, so it's a little more stable. [STABILITY+]

At 21:48, does some disassembly to enable some reassembly, which shows cognitive flexibility. He also uses an impromptu wheel as a cart when asked to demonstrate ride at the end showing both cognitive flexibility and the ability to "fill in" missing parts of a design with his imagination.

In summary, Boy 4 has good LEGO structural knowledge and generally higher process and executive function skills than Boy 3. Just listening to the way he talked shows a higher level of sophistication that Boy 3. Here is an example.

[00:10:26] [BUILD-REBUILD] [2:PLAN] Boy 04: I have to put the axle piece so I can fit it with other piece.

I felt that Boy 4 could definitely have been pushed to do more - as I would have had he been in the classroom setting. His higher structural knowledge, process skills, and somewhat more complex build seemed to result in a richer, more balanced EDP. In contrast to Boy 3 and Boy 4, the other sixth grade boy, Boy 5, chose a complex build and had the structural knowledge and process skills available to accomplish his design idea.

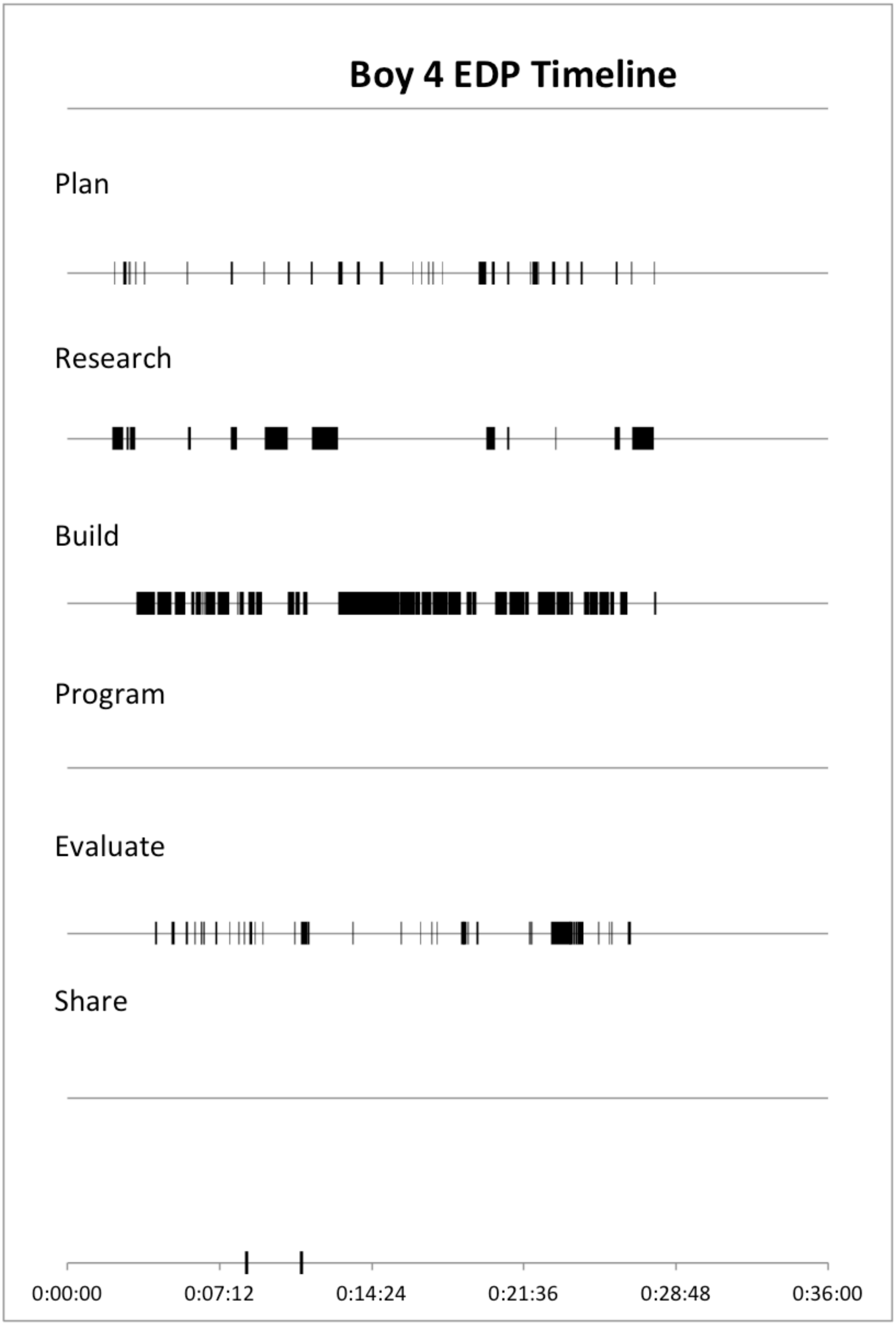
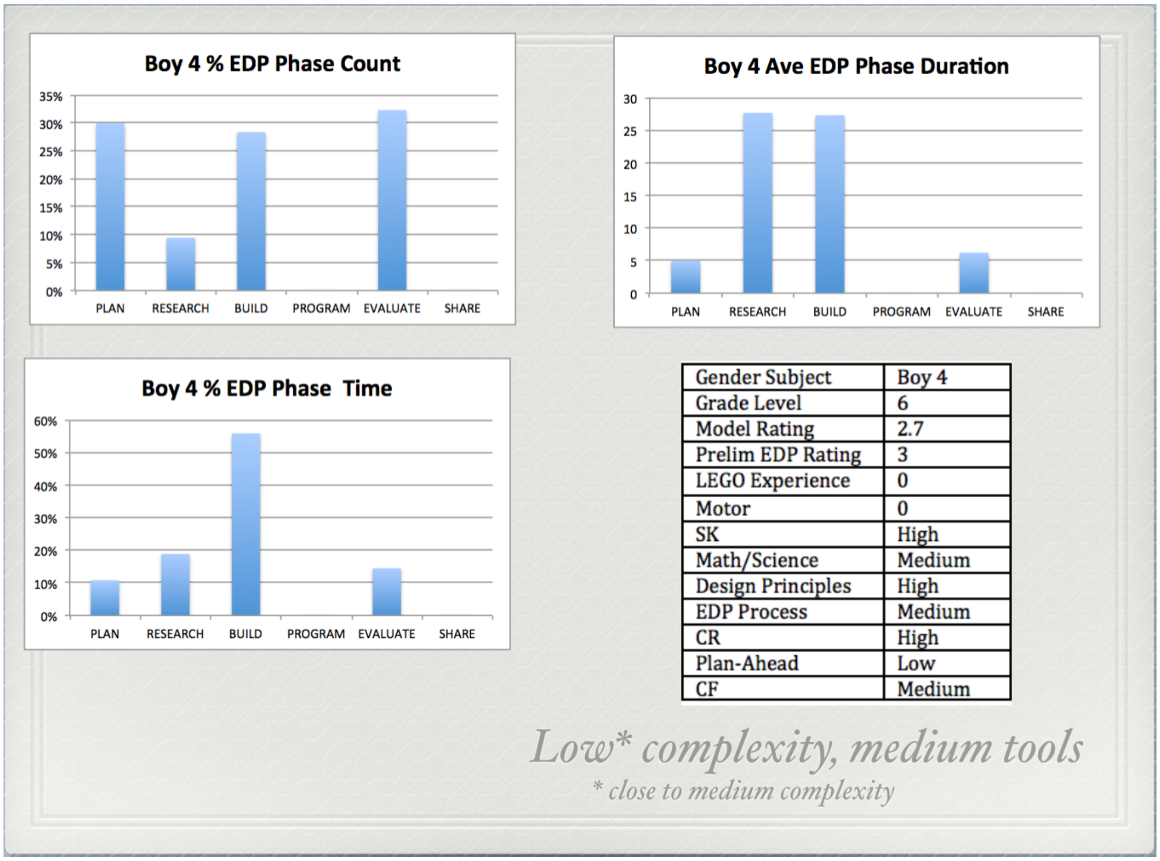


Figure 69. Boy 4 EDP timeline.



Gender Subject	Boy 4
Grade Level	6
Model Rating	2.7
Prelim EDP Rating	3
LEGO Experience	0
Motor	0
SK	High
Math/Science	Medium
Design Principles	High
EDP Process	Medium
CR	High
Plan-Ahead	Low
CF	Medium

Figure 70. Boy 4 EDP frequency, time, and average duration counts.

Boy 5. Boy 5, in contrast to Boy 3, chose a complex build and he also possessed the knowledge and tools accomplish his design idea (see Figure 71). His ride is an example of advanced ride structure that was also seen in the pilot study sixth grader and with Girl 5, as we shall see. These designs all consisted of four subsystems - which were built in order - of base, tower, rotating arms, and seats - with an overall system plan in mind. Note that not all the seats were built by Boy 5, as suggested by the researcher, in the interest of time. Boy 5 and Girl 5 planned ahead having a complete idea of the whole system in their mind before starting. In contrast, Girl 3, a serial builder, started with seats, and was never able to subsequently connect the seats to a larger structure. Boy 5's ride, when running, features seats that push out due to angular momentum, just like in a real swing ride. Boy 5 used a simple one block motor block to program his ride. We have seen that Boy 5 was able to build a complex ride. How did his EDP reflect that?

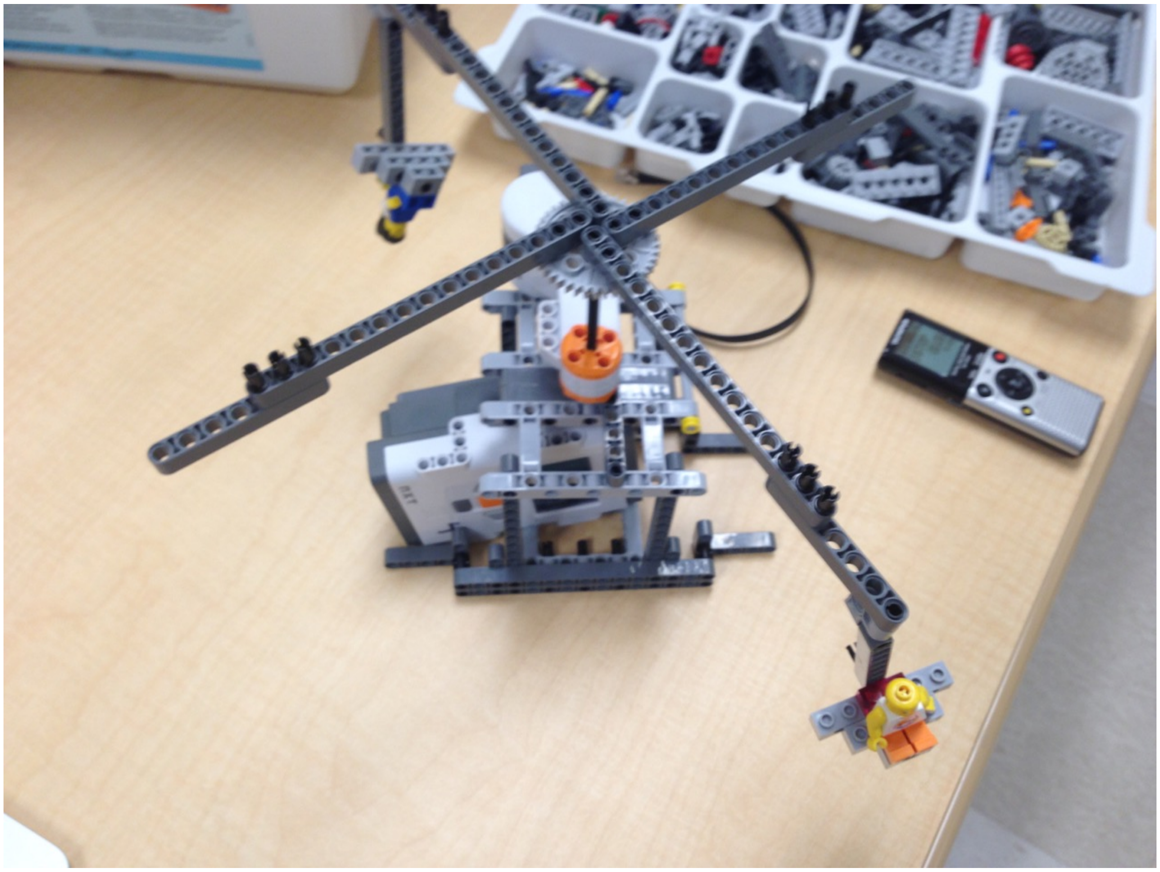


Figure 71. Boy 5 finished ride.

As shown in Figure 72, the EDP timeline of Boy 5 shows a long, dense, and balanced EDP. Also note the significant planning and research cycles that occurred before building commenced, which shows a good knowledge of the engineering design process and also a plan ahead or system style. Evaluation also occurred throughout the engineering design process. Figure 73 shows his EDP phase frequencies, time spent, and average duration graphs. The % EDP Phase Time graph, which seems to be the most useful for analysis through this study, shows a stair-like pattern (with evaluation going back down) that is typical of students with advanced EDP. In other words, planning, research, and building go up in a fairly linear fashion with the total evaluation time nearly the same as the planning time. Time spent programming was found not to be significant in this study and Boy 5 is typical of this.

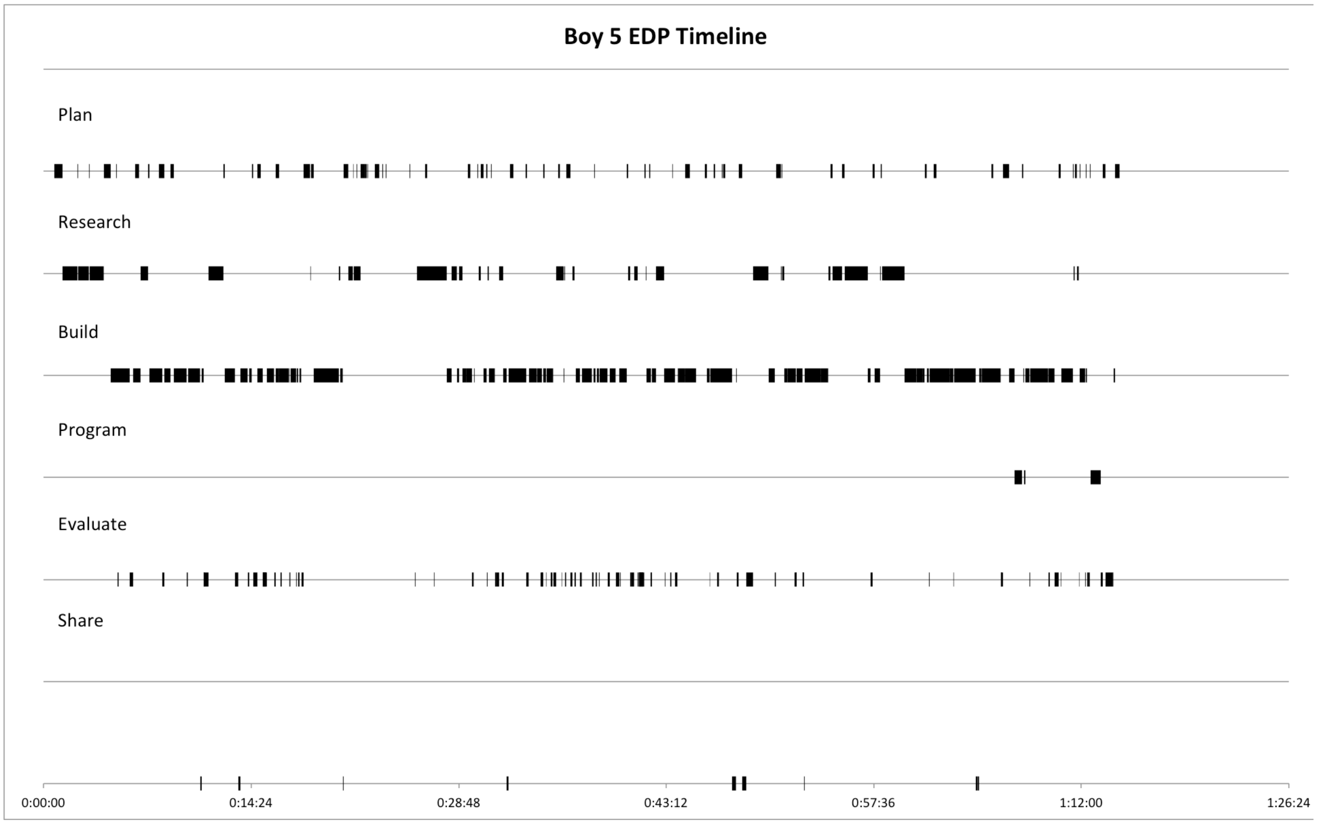


Figure 72. Boy 5 EDP timeline.

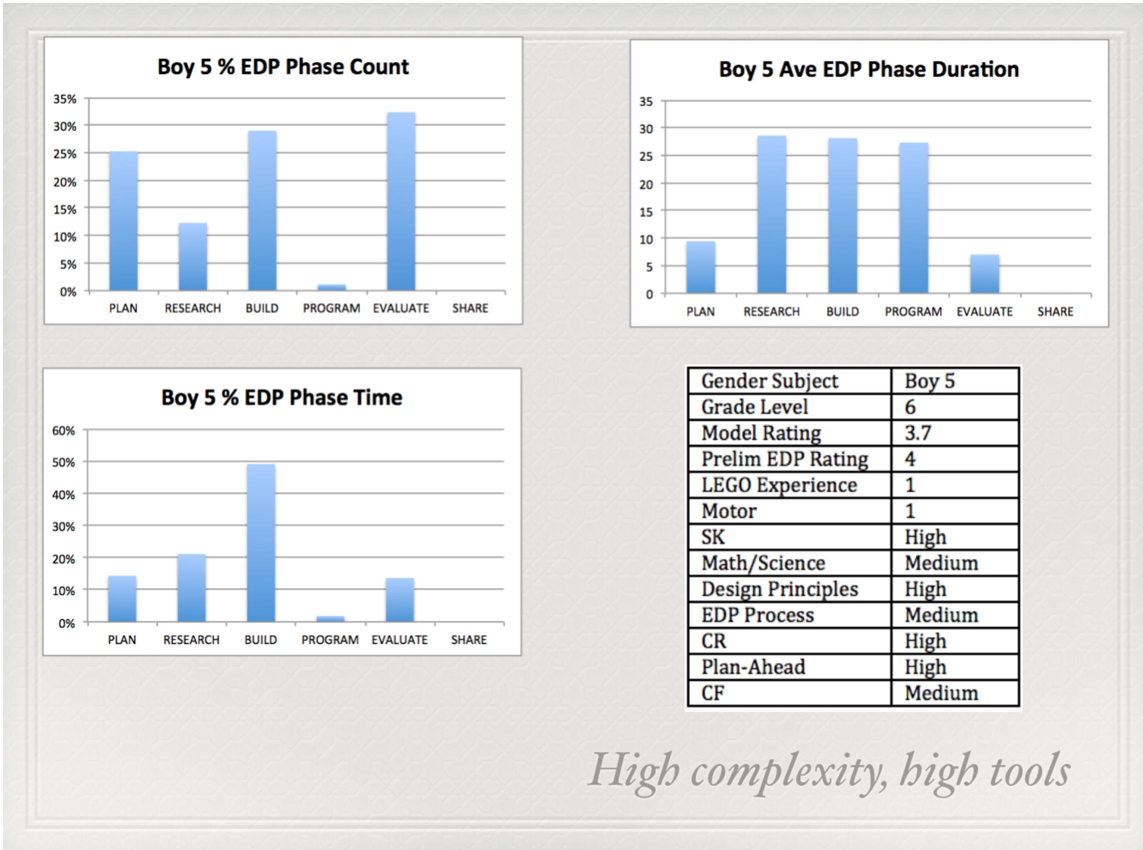


Figure 73. Boy 5 EDP frequency, time, and average duration graphs.

Boy 5 showed evidence of strong, across the board, structural knowledge, domain specific, and relevant executive function skills. Boy 5 considered using wheels and tracks to built a roller coaster, but ended up not using it. This showed good cognitive flexibility and good causal reasoning, since he considered many ideas and then picked one based on either mental projection or by physically trying out ideas. Contrast this with Boy 3 and Boy 4, who persisted with their roller coaster designs. He consistently used prediction and inference in his design processes. As one example, he moved the motor (in advance mentally) on the top of the tower so it was centered enough that the swings would not hit the sides of the tower showing very good prediction (causal reasoning). He also had many correct inferences and projections in his system testing. Recall that prediction and inference are key causal reasoning skills for engineers.

Boy 5 consistently talked about and incorporated the design principles of stability and symmetry. He gave accurate projections of what would be stable. Here is an example of his use of symmetry and stability. He also provides a description of how they are related (the latter is example of structural knowledge since he knows how different concepts are connected).

> Researcher: I notice you're keeping your design so that it's usually the same thing on the other side, all the time.
>
> [00:17:32] {gesturing} [EVALUATE-VERBAL] Boy 05: Yeah, so it's not off balance. If it's off balance, it has more likely to tip over. [PROJECTION+] [IMPORTANT][SYMMETRY+] [STABILITY+]

In the post interview, he mentioned that is was sturdy so it was safe, which showed that he attended to the engineering constraints, a sign of a strong knowledge of EDP.

> Boy 05: It's for people who really like getting dizzy and it's really sturdy so it's really safe.

Another example of his strong EDP is his use of mathematics in the form of frequent measuring. He can also articulate why he is using mathematics.

> [00:09:55] {moving} [EVALUATE-PHYSICAL] Boy 05: I'm now trying to see [by measuring] if they're lined up properly.

Boy 5 showed an advanced knowledge of LEGO connection techniques. He was also able to figure out connection problems if he encountered a new connection problem. He could also articulate his structural knowledge of LEGO connection techniques.

[00:16:26] [2:EVALUATE-VERBAL] Boy 05: That's when these pieces come in useful if you want to connect three things. These only connect with two. [IMPORTANT] [CONNECTOR-META+]

Another example of strong structural knowledge is his use of three connector pegs to attach two beams to each other.

Researcher: Why'd you use three [connector pegs]?

[00:31:05] [2:END] Boy 05: So it's more sturdy. [CONNECTOR-META+] [PROJECTION+] [IMPORTANT]

Boy 5 spends a good deal of time exploring how to attach beams to other beams in a rectangle so they don't move, that is, they stay at 90 degrees. He persisted and tried many different techniques and eventually shored up the tower by using multiple horizontal beams. Some scaffolding on the use of trusses would have been useful in the classroom setting.

He shows persistence and curiosity about solving problems. He expressed in the post interview that he liked building more than programing.

Researcher: Really good? Okay. What do you like better, the programming or the building part?

Boy 05: Building.

Researcher: Okay, why?

Boy 05: It's fun to find different ways you can build things and how you can use different parts in different ways.

Boy 5 always seems to have a clear idea of where he is going even if the problem is not solved yet.

Researcher: What's your next part? What are you thinking you're going to do next?

[00:11:36] {moving} Boy 05: Maybe make this from not moving. I just don't know how yet.

At several points, he clearly pauses physical activity to plan, which was generally seen as and indicator of planning. Another sign of advanced EDP is when he reveals that has been looking at the time on the audio recorder and keeping track of time so he could finish his build within the allotted time frame, something I was not aware of until he mentioned it.

When he had attached the motor, he first wanted to know which way the motor would turn, but stated he would try one way first, which is a good troubleshooting strategy, an example of the causal reasoning skill of inference. He clearly had a strategy of trying things out first as research.

[00:59:12] Boy 05: I'm just trying out how to make the actual seat.

Overall, we see that the many tools Boy 5 brings to the task allows him to successfully build his complex design idea using a rich, balanced, and lengthy design process. As we will see next, this contrasts with Girl 3, who has a similar design idea but does not have the tools needed to accomplish her design idea.

Girl 3. Girl 3 was the only student who did not finish her design. After a long work period, I asked her if it was all right if she did not finish and she agreed. I could see that she would either need extensive time or help to finish her design idea and that continuing would result in frustration. Her partially completed ride is show in Figure 74. In contrast to Boy 5, Girl 4, and Girl 5, who had the similar ride idea of making a swing or Ferris Wheel ride, Girl 3 started with the seats and build serially without showing evidence of planning ahead a complete system. She states this clearly.

Researcher: When you are thinking about your Ferris wheel do you plan just the first part and then worry about the rest later or do you have an idea in your head about what the whole thing is going to be?

[00:04:36] Girl 03: I usually just start with one thing and see how it goes. [IMPORTANT] [PARTS-FIRST]

And also here.

> [00:53:48] Girl 03: I just try to look at the parts and try to think of how it'll work. [IMPORTANT] [PARTS-FIRST]

The other builders, who showed evidence of complete system plan, started with a tower structure, then build a rotating structure to hold the seats, and built the seats last. Girl 3, building the seats first, could never find a way to connect the seats to a rotating seat holding structure. What differences in her processes and knowledge might explain some of these results?

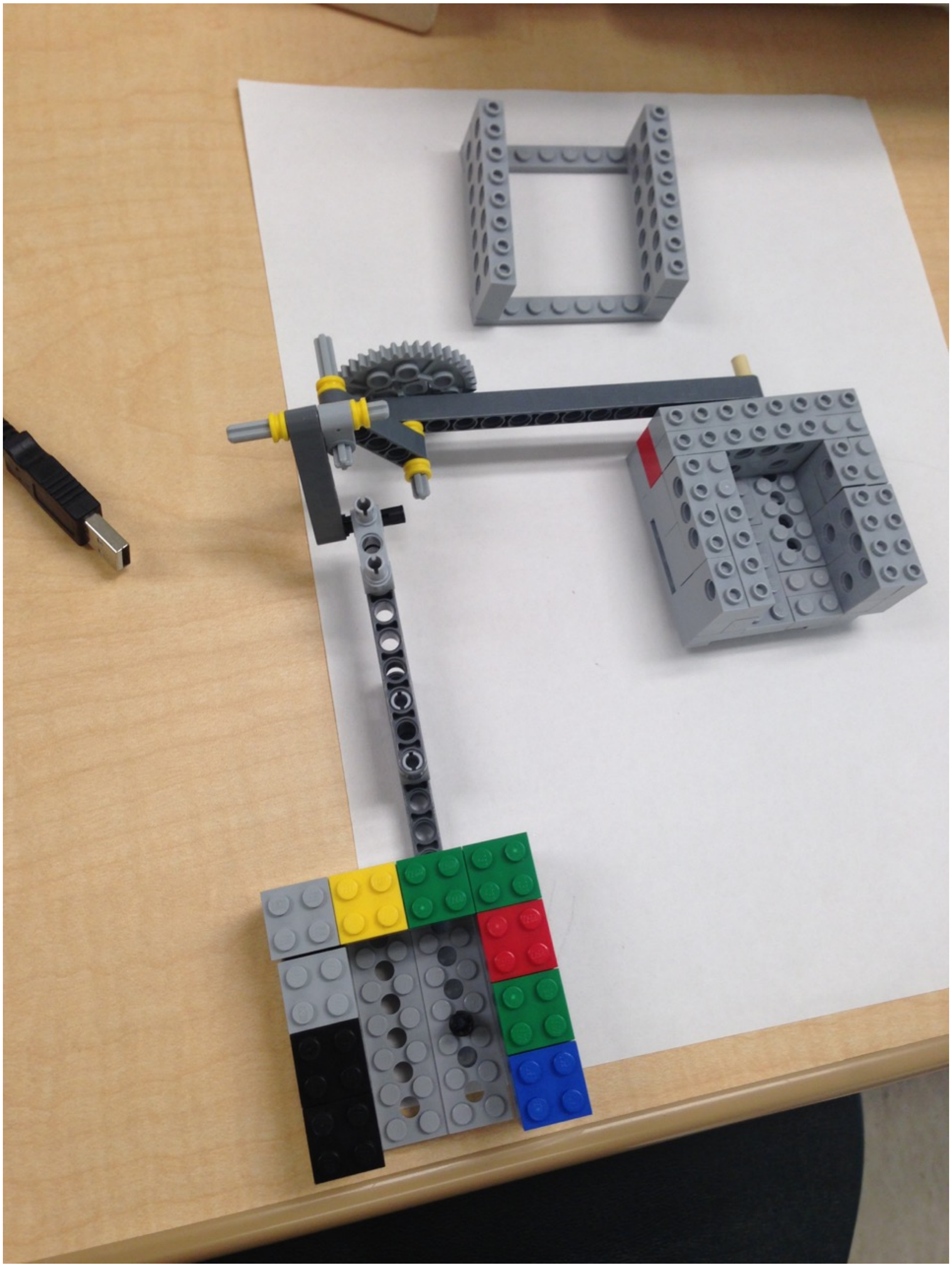


Figure 74. Girl 3 partially completed ride.

Girl 3 had low structural knowledge of LEGO connection techniques, which put her at a real disadvantage in trying to realize her complex build idea. Examples of this are shown in Figure 74 and Figure 75. The technique of using the thin yellow collars and axles is a common sixth grade technique but does not result in high stability designs. At one point, her seats spun but she did not see that it would not turn because it was circle-circle connection rather than a cross-axle connection. She spent lots of time looking for and trying different way of connecting things. She seemed to miss easier and more direct and more stable ways of connecting parts. As shown in Figure 74, she has difficulty in figuring out how to change the direction of her subassemblies in a stable way. While she has a good EDP, her less developed executive function skills of planning ahead, causal reasoning, and cognitive flexibility put her at a disadvantage. She also did not apply mathematics or science knowledge nor did she show evidence of using the design principles of symmetry, stability, or scale.

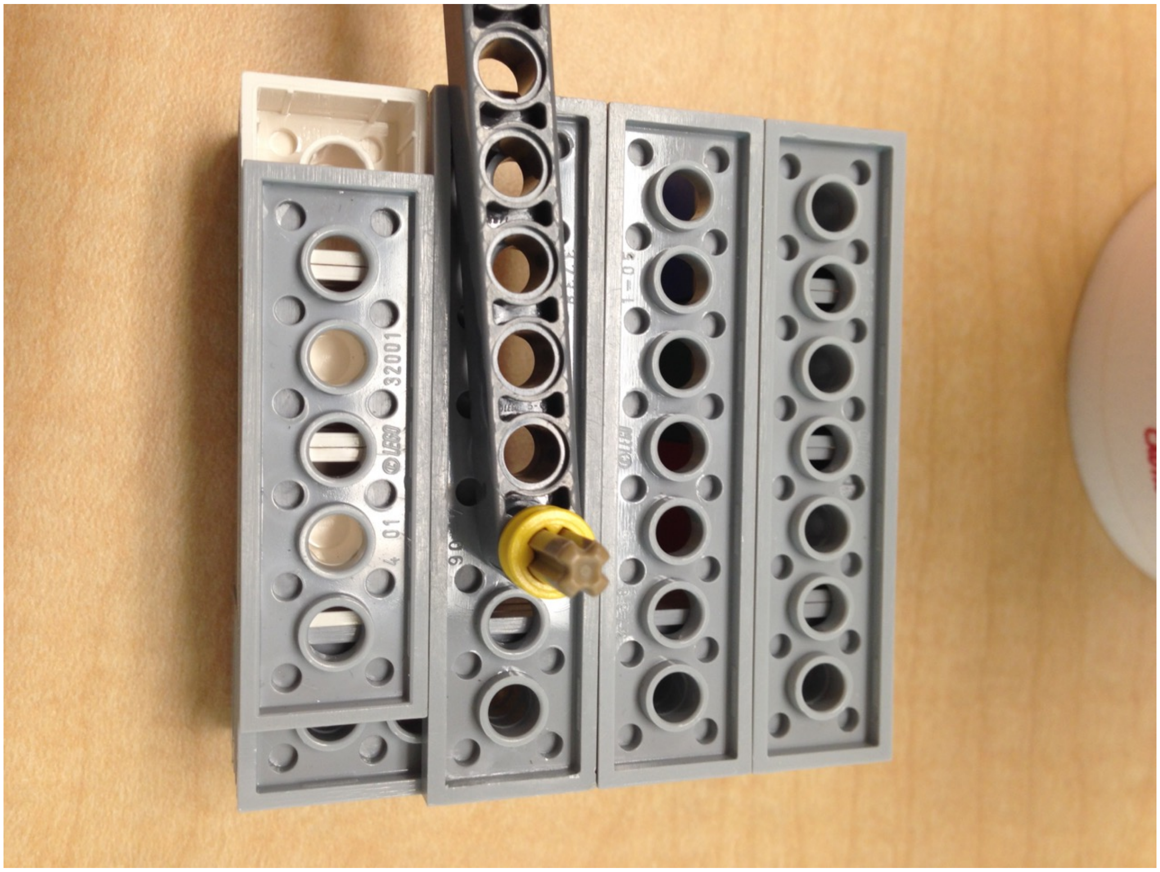


Figure 75. Girl 3 example LEGO connections.

While her EDP timeline looks fairly typical as show in Figure 76, a closer look reveals that she got struck in a research/built/evaluate cycle that never resolved. This is evident in the research heavy second half of her build. A symmetrical design would have helped a lot with the beams. One seat kept falling apart, which shows evidence of a lack of cognitive flexibility or non-optimal persistence.

She does show some EDP strengths. For example, she got out all the pieces ahead of time to make second seat.

Researcher:	It looks like you're getting a bunch of pieces ahead of time?

[00:17:21] {connecting} Girl 03: Yes.

Researcher:	Why is that?

[00:17:23] Girl 03: I'm going to make sure that there's actually enough of the pieces to see if I can build this. [IMPORTANT] [PROJECTION+]

Also, she does do a lot of physically trying out ideas without actually connecting anything, which shows a good research strategy.

Girl 3 does not do as much evaluation as other subjects. This may result in some of her difficulties. Also, she does much less "cycling" than Girl 5, for example.

At 39 minutes into her design, I saw a real flimsy connection system that was obvious to me could never work. This shows a lack of causal reasoning and/or structural knowledge. She does eventually come to realize that structure to hold the seats up is needed and continues to articulate that need.

[00:41:45] [2:PLAN] Girl 03: Keeping this up somehow. [IMPORTANT] (She identifies the need for a base and tower after she has made the seat structure, unlike Boy 5 and Girl 5.) [IMPORTANT]

[01:04:52] {no_activity} [PLAN] Girl 03: No, I'm just trying to think of how to get it to be up.

[01:08:19] [2:PLAN] Girl 03: I want to build something to keep it up. Like a little structure or something. [IMPORTANT]

[01:11:47] [2:PLAN] Girl 03: I just thought of it. I was thinking of like how, as a real Ferris wheel, how it stays up. [IMPORTANT]

Overall, we see a good engineering design process. However, without sufficient structural knowledge and executive function skills, she would need much scaffolding or a very long time to realize a complex design idea. Her serial building style was a major impediment to building this particular design. Girl 4 and Girl 5 were much more successful in building similar ideas, to different extents, as we shall see next.

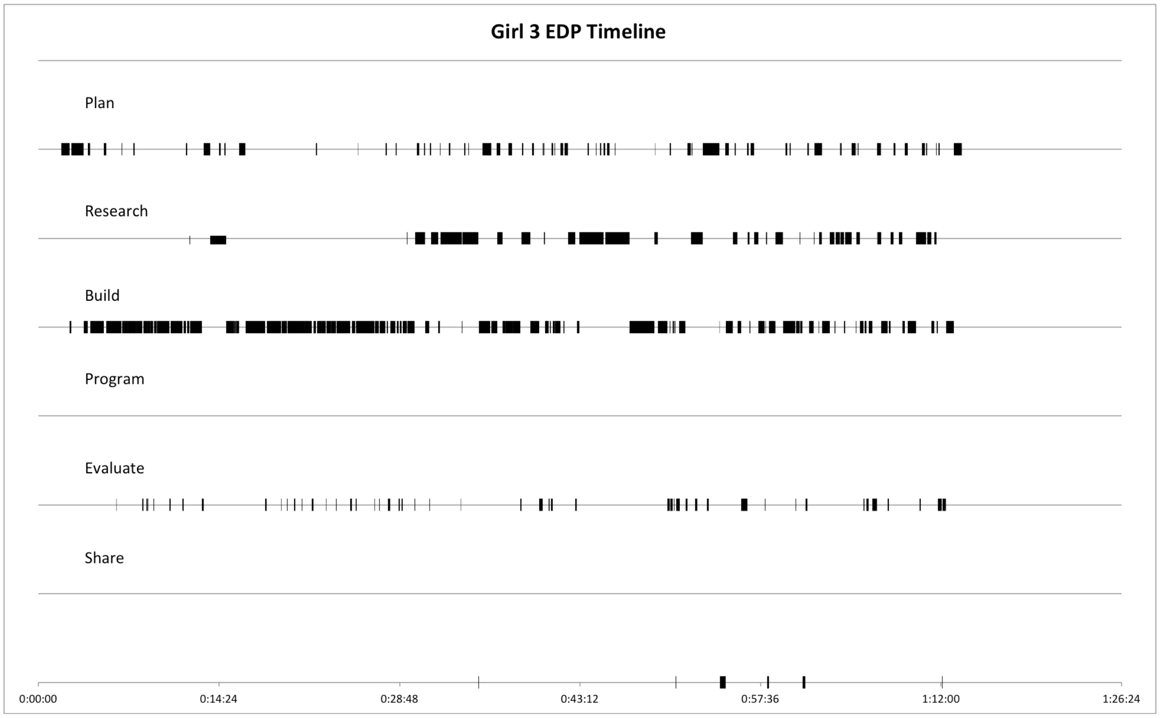


Figure 76. Girl 3 EDP timeline.

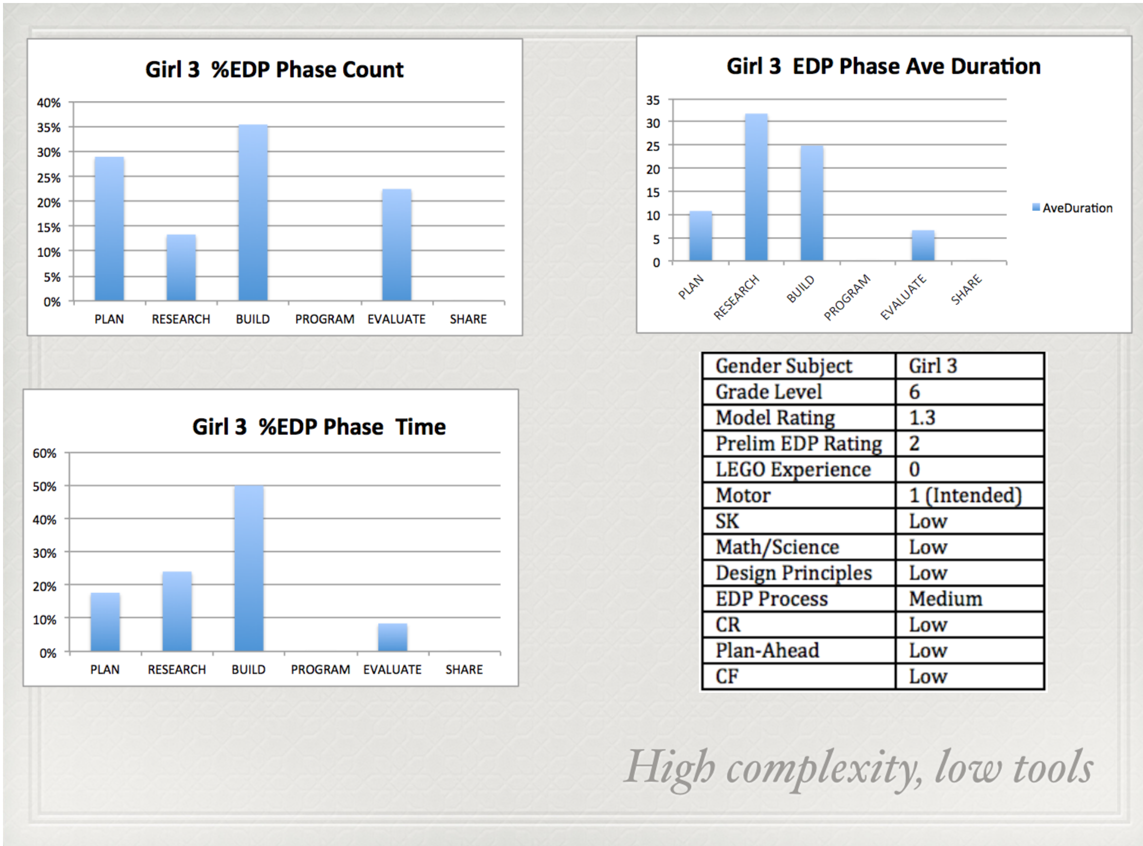


Figure 77. Girl 3 EDP frequencies, time, and average duration graphs.

Girl 4. Girl 4 made a ride that was simple in some ways (the tower) but complex in other ways (the gears). She used whatever materials worked in her tower such as blocks and wheels as shown in Figure 78. Girl 4 initially built a very simple non-motorized version of her ride with the three major subsystems of tower, rotating seat structure, and seats (see Figure 79). When she decided to use a motor, she largely rebuilt her ride but retained the three subsystems. Her planning seems to be mostly serial with a small plan-ahead window though she builds the base first but she also seems to have an idea about complete system. She can be seen as a unique mix of serial and a plan-ahead, systems builder.

Once she built her gear assembly, she spent a good deal of time developing a tower of the correct height to support it. So while she had an overall system in mind, she did not build the tower first like more advanced builders such as Boy 5 and Girl 5. Figure 80 shows this intermediate stage of her ride. Since she was intermediate in her complexity, how did her process differ from more advanced builders such as Boy 5 and less advanced builders such as Girl 3?

Figure 78. Girl 4 finished ride.

Figure 79. Girl 4 initial ride.

Figure 80. Girl 4 intermediate state of ride.

We can see from her EDP timeline (Figure 81) and % EDP Phase Time graph (Figure 82) that she had a relatively short build time. She was also build heavy (as measured by time spent building) but did have some time planning and evaluating with very little research time. While her structural knowledge of LEGO connection techniques was also low, her much more developed executive function in terms of cognitive flexibility and causal reasoning combined to allow her to come up with relatively simple, unsophisticated but ultimately functional structures.

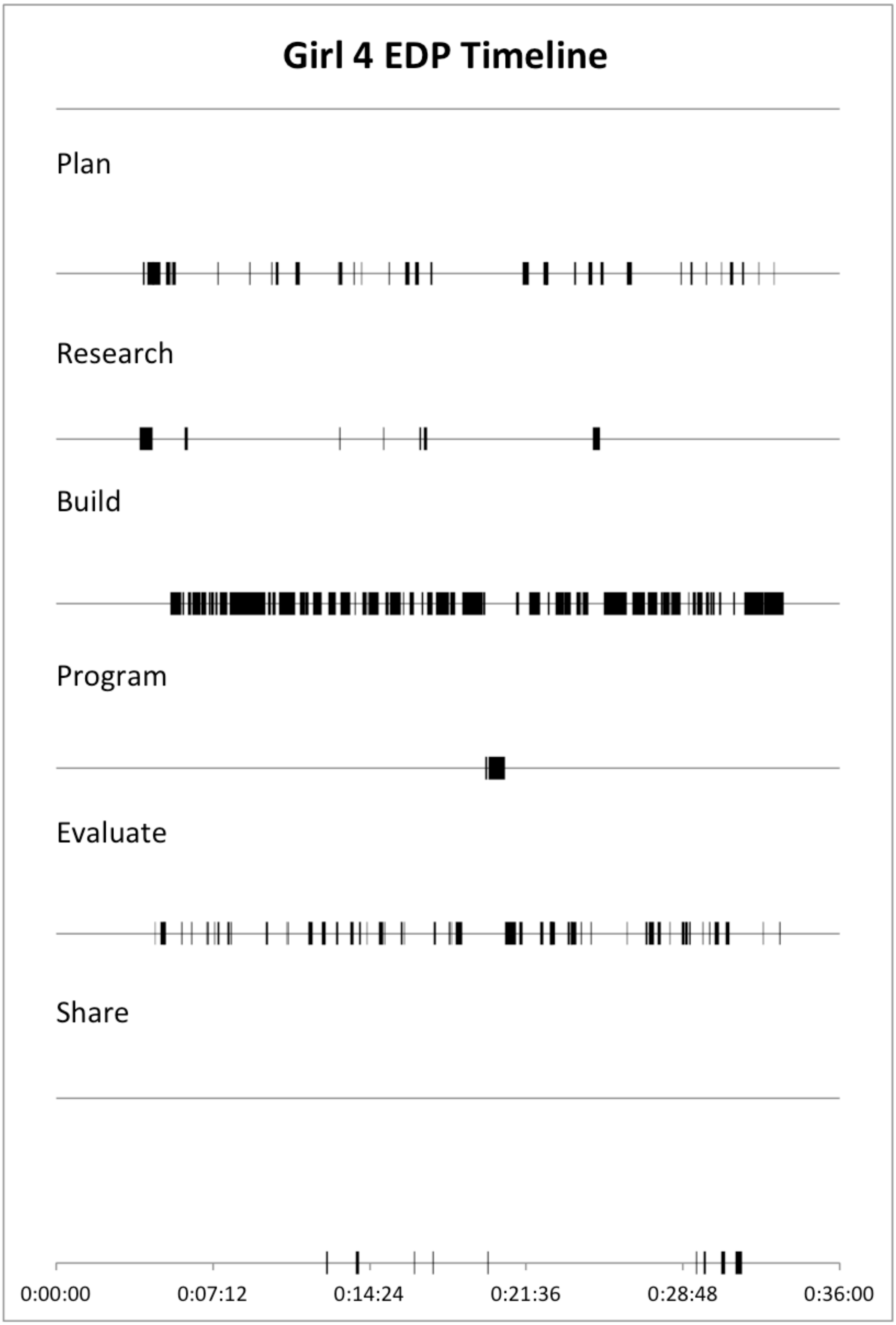


Figure 81. Girl 4 EDP timeline.

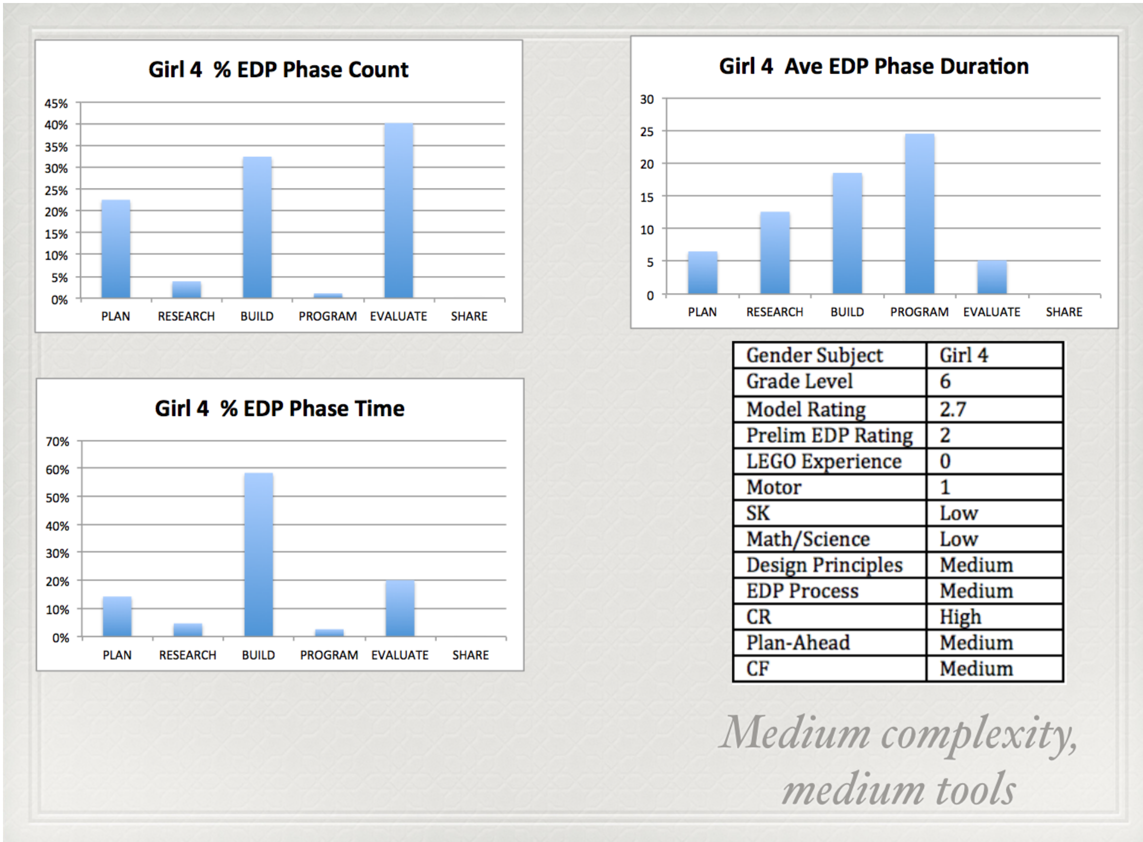


Figure 82. Girl 4 EDP frequency, time, and average duration graphs.

She showed evidence of non-optimal persistence in her frequently unstable tower but eventually finds a creative solution, which shows cognitive flexibility. As another example of high cognitive flexibility, she also made her own mini-figures when there were no more mini-figure bodies. As another example of cognitive flexibility, she mixed in wooden blocks to get the correct tower height. Her mix of wooden blocks and LEGO did not bother her like it might an adult or more experienced LEGO builder.

[00:29:35] {connecting} [2:PLAN] Girl 04: Maybe a block can help it stand up.

So overall she shows a mix of high and low cognitive flexibility.

Girl 4 figures out that that base needs to be more stable but did not see this ahead of time. She is not clear on solution either, at least right away. She does articulate a concern for stability. In general, she has a mix of correct and incorrect projections and inferences but shows overall strength in causal reasoning. Her system testing resulted in stability failures that she eventually worked through.

Overall, we see that her relative strengths in cognitive flexibility, EDP, and causal reasoning allow her to successfully overcome her low structural knowledge, unlike Girl 3, who did not possess enough compensating strengths. How does this compare with Girl 5 who built a complex system and had the highest structural knowledge and process skills in the research sample?

Girl 5. Girl 5 built a very sophisticated ride with base, tower, and seat structure as shown in Figure 83.   She used gears to increase the speed of one of the seats by using gearing up (see Figure 84). She built up starting with the base, built an ascending, gradually widening tower with an internal column for strength, a platform to hold the motors, and two rotating beam based seats. She used additional supports to hold the gear train as shown with the grey blocks and grey plate in Figure 84. She wrote a a simple one block motor block program to run the ride but frequently varied the parameters in her system testing. Girl 5 solved a number of interesting problems during the build and she had a very sophisticated process and good structural knowledge of LEGO connection techniques, one of which can be seen in Figure 85. Let's now examine in more detail her processes and knowledge that enabled her to realize her complex design idea.


Figure 83. Girl 5 finished ride.

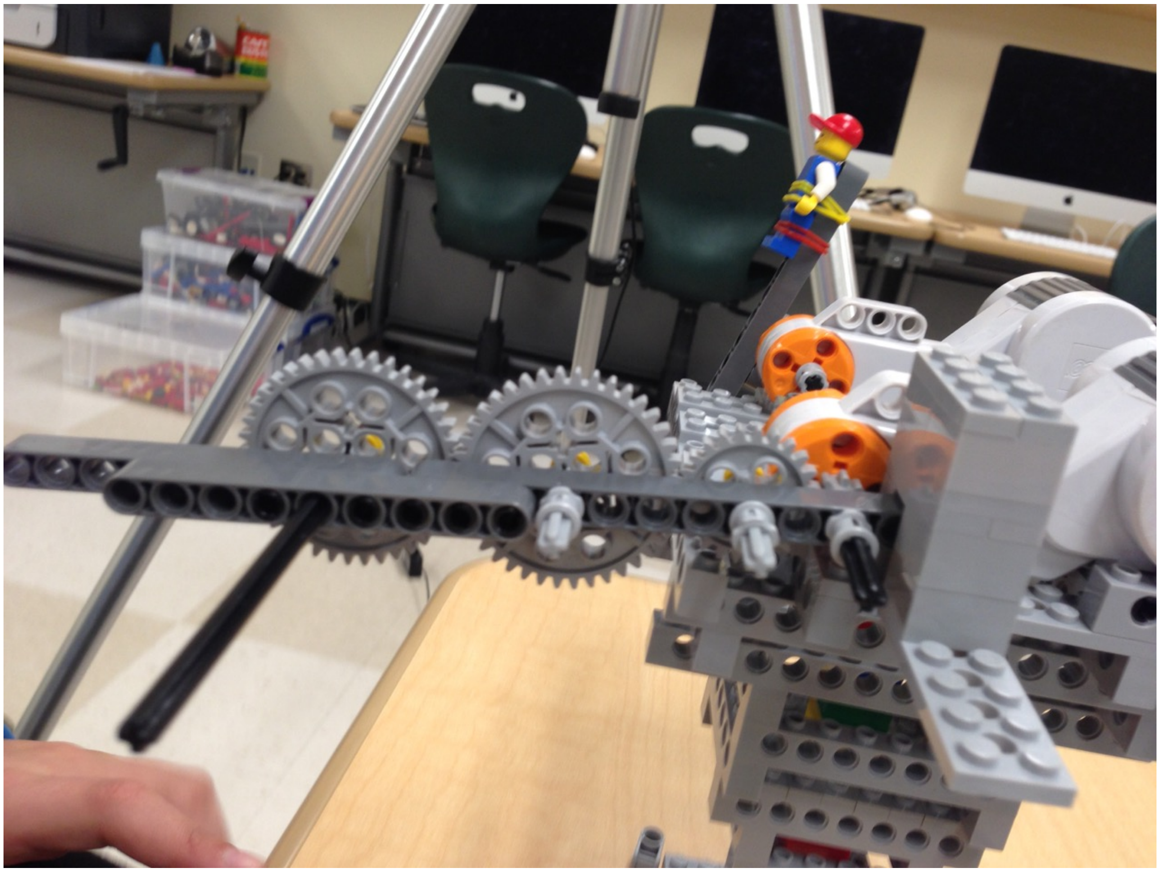


Figure 84. Girl 5 detail of gear train used.

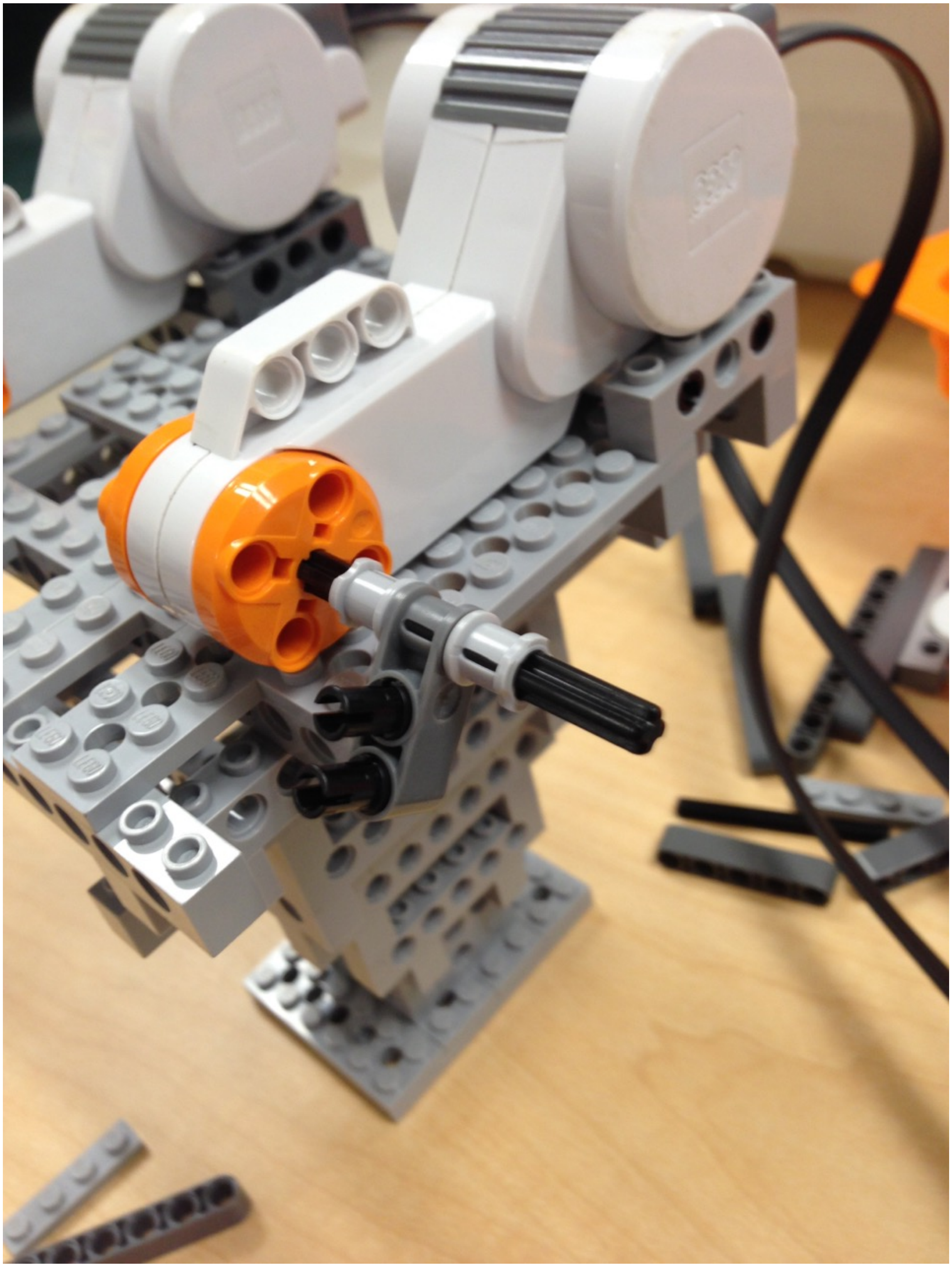


Figure 85. Girl 5 LEGO connection example.

An examination of her EDP time line shows a very long, dense, and balanced EDP. The only difference from other advanced EDP builders is somewhat less time spent in research and more time in planning and evaluation. She used frequent and short planning and evaluation phases. Some of the density seen could be from her very expressive use of the talk aloud protocol. Because Girl 5 was the strongest student overall, we will examine her strengths and processes in some detail below.

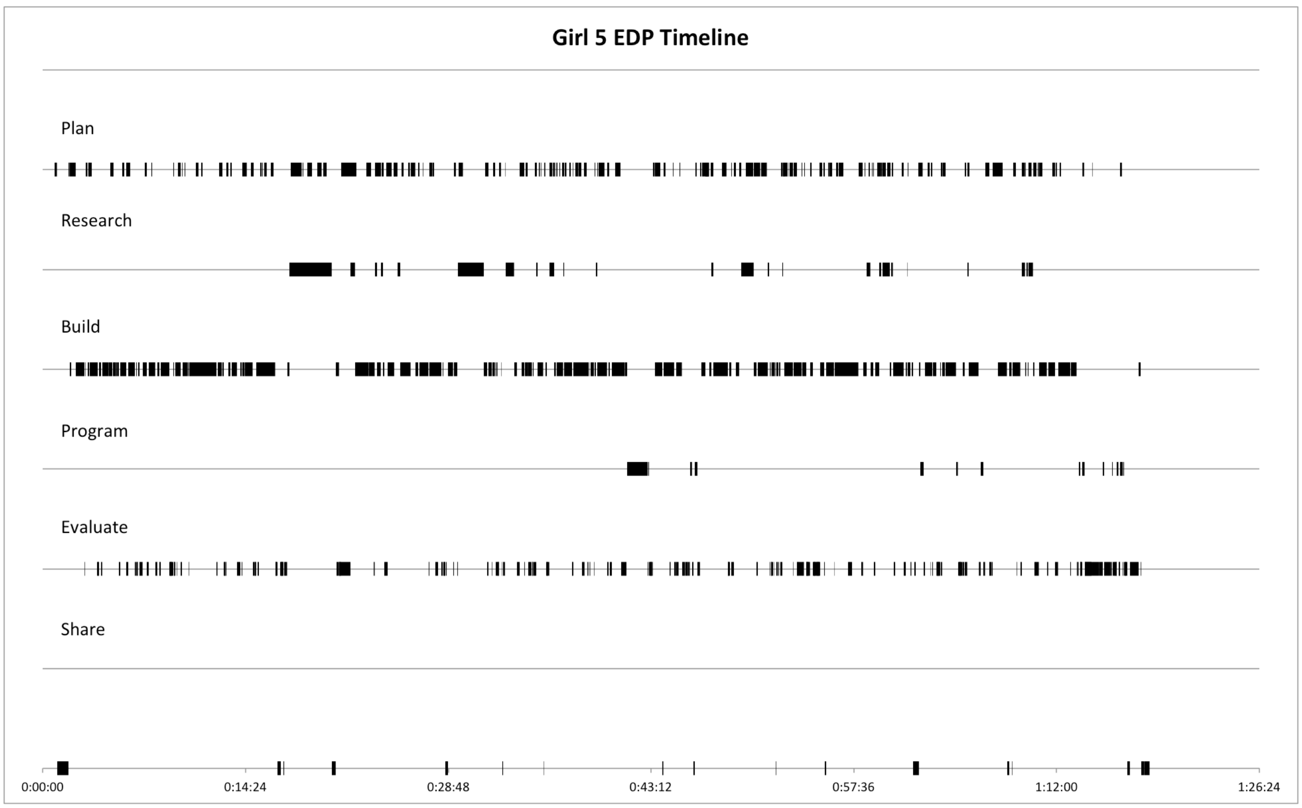
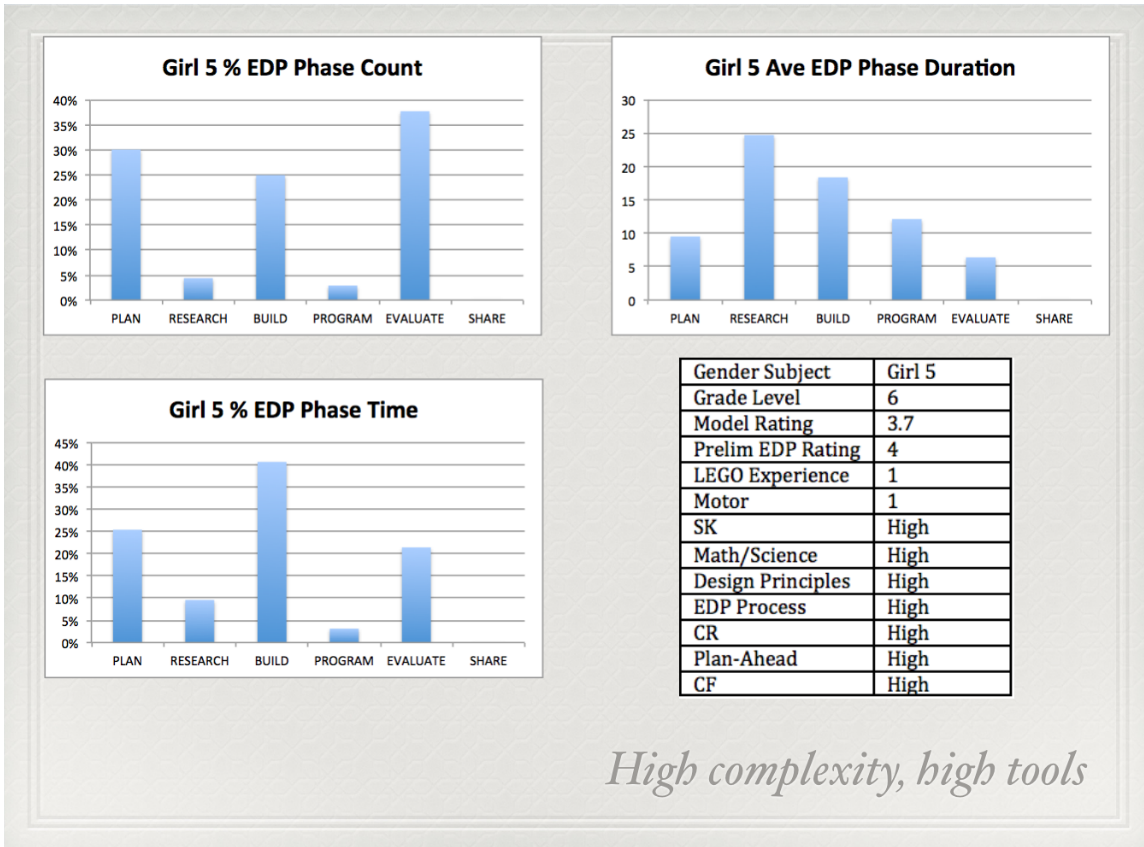


Figure 86. Girl 5 EDP timeline.



Gender Subject	Girl 5
Grade Level	6
Model Rating	3.7
Prelim EDP Rating	4
LEGO Experience	1
Motor	1
SK	High
Math/Science	High
Design Principles	High
EDP Process	High
CR	High
Plan-Ahead	High
CF	High

Figure 87. Girl 5 EDP frequency, time, and average duration graphs.

Structural knowledge. Girl 5 showed many examples of having strong structural knowledge of LEGO connection techniques. She clearly uses previous experience to help her connect pieces. The two separate examples below show this.

> [00:21:28] Girl 05: How am I going to attach it to that? I feel like there was a way. I remember that I can attach these to something, and attach that to the motor, so I've got the motor. I'm out of here, and put it right about there. Now I'm going to detach it first. I'm going to attach it with some of these, and first attach itself to those. [CONNECTOR-META+] [IMPORTANT]

> [00:25:13] Girl 05: I know there's a piece like that. It just slipped my mind what piece it is. [IMPORTANT]

Here she demonstrates structural knowledge of LEGO connectors by articulating the functional requirements of a piece.

[00:25:07] [2:PLAN] Girl 05: Make an axle from this go this way. [CONNECTOR-META+][PROJECTION+][IMPORTANT]

Here she uses collars and explains their purpose showing important LEGO structural knowledge.

[00:31:25] {connecting} [2:PLAN] Girl 05: Okay, so now I'm going to put a holder on this so this doesn't hit the other side and same for the other side. [PROJECTION+][CONNECTOR-META+][IMPORTANT]

Unlike other students, she does predict that putting axle through a circle will NOT create strong connection from axle to seat assembly. Not only does she have good structural knowledge of LEGO connection, she also gained more structural knowledge as she built and tested. The quote below describes something she learned.

[00:43:27] [2:PLAN] [BUILD-REBUILD] Girl 05: I'm going to take this off and replace it with a different one with two long so I can attach it two ways, and it'll be more sturdy. Because if it's one, then it just is free to wobble. [STABILITY+][CONNECTOR-META+][IMPORTANT]

As a final example of structural knowledge, Girl 5, like Boy 5, knows that using three connector pegs instead of two is more stable.

[01:00:37] Girl 05: Okay, so I'm going to attach this and attach this. First though I have to find a better side, and I'm going to need three of these just so it's extra stable. [IMPORTANT] [STABILITY+][CONNECTOR-META+] (Describes her building, not planning.)

Engineering design process. Girl 5 had a very strong engineering design process. For one, she observes carefully and tests as she goes along. Here she spots a subtle problem and fixes it.

[00:07:24] Girl 05: (Lifts structure) Wait a second.

Researcher: What did you notice?

[00:07:29] [EVALUATE-VERBAL] Girl 05: It's uneven.

[00:08:59] {moving} [EVALUATE-VISUAL] (Noting that she does a lot of visual examination of model.)

She is very adept at talking about one engineering design phase while doing another with her hands. At one point, she searches for two different parts simultaneously, one with each hand. These examples seem to point to an ability to engage is multiple processes at once. She also had the only example of systemic testing I found.

[00:37:24] [2:PLAN] Girl 05: Like an experiment with different speeds to see which one is the safest. [ATTEND-CONSTRAINTS+] [SYSTEMIC-TESTING+] [IMPORTANT]

Girl 5, also uniquely in the study, uses a control of variables (COV) strategy. She changes power and number of rotations when programming, but not simultaneously.

As an aside, she seems to do more visual (rather than physical) evaluation compared to other students. Another interesting and unique aspect of her process was the use of metaphor below.

[00:05:25] {moving} [EVALUATE-VERBAL] Girl 05: This is getting wider like an upside-down cake. [IMPORTANT][CREATIVE-PLAY]

In summary, Girl 5 uses a variety of advanced engineering design processes. She also attempts to use mathematics and science in her engineering design process, a basis for engineering, but not always successfully at first.

Application of mathematics and science. There were a few cases where Girl 5 tried to apply mathematics and science to her design process (in some advanced ways for elementary school) but she had to do some additional work to do so effectively. In the first example, she is trying to figure out which hole in a long beam is in the center of the beam so that axle can be inserted and the beam can rotate around the center. She has the right idea to count the holes in a long beam but does not take into account the hole with the axle in it.

[00:29:32] [2:PLAN] Girl 05: Okay, and now I'm going to put the ... We're going to find out how many there are. One, two, three, four, five, six, seven, eight, nine, 10 ... 15, so don't think I can divide that in two. [IMPORTANT] [MATH=]

The correct answer is to put the axle in the eighth hole so that there would be seven on each side of the center hole. She figures it out by physically putting the axle in the middle and then counting. Here's her description of the process.

[00:30:23] Girl 05: One, two, three, four, five, six, seven, eight, nine, 10, 11, 12, 13, 14, 15 holes. Can I divide 15 by two? No, I don't think so. I'm going to have one, two, three, four, five, six, seven, one, two, three, four, five, six, seven. Wait a second. Huh! so I can have ...

Researcher: Why did you say, "Huh?"

[00:30:55] Girl 05: {moving} Because I was thinking that I couldn't have even holes on each side, and now I can. Yay!

Researcher: Do you know why you can?

[00:31:06] Girl 05: 15. Oh yeah, because you can't divide it by two. If you could, then you wouldn't be able to have even amounts on both sides. Okay, yay. [IMPORTANT]

She later can easily replicate her previous finding about the beam center showing that she has integrated this into new structural knowledge.

[00:38:53] {measuring} [BUILD-NORMAL] Girl 05: So one, two, three, four, five, six, seven, so right there, right there. (Uses counting and her previous determination of beam center.)[IMPORTANT]

A similar process occurs when she decides to use gearing up to make one seat of the ride go faster. Although she correctly articulates that the smaller gear goes faster and why, she put the small gear on the motor, at least initially. [The smaller gear needs to go on the seat, not the motor if the seat is to go faster.] With a little prompting, she figures out that the gears are backwards. The prompting was that I pointed out that she said previously, that she has stated that the smaller gear goes faster.

For the final example, as she does some system testing on the geared up and direct coupled seats, she does not understand initially why the geared up ride had 50 rotations when she programmed 10 rotations. I suggested she count the direct-coupled seat instead. This is another example where teacher scaffolding in the form of a neutral suggestion or question triggered learning.

Use of design principles. Girl 5 was very conscious of the design principles of stability and symmetry in her building. She clearly articulates symmetry and why it is helpful.

[00:16:51] [2:EVALUATE-VERBAL] Girl 05: That's a good question. If it's symmetrical, normally I build things and they're symmetrical on both sides. [IMPORTANT] [SYMMETRY+]

Researcher: Yeah, that's what I was asking, yeah. Why is the symmetry good?

[00:17:09] Girl 05: Because normally I do symmetrical sides and they tend to hold up better than things that aren't symmetrical. [IMPORTANT] [SYMMETRY+] [PROJECTION+] [STABILITY+]

She also expressed principles that help make structures stable as shown below.

[00:17:21] {searching} [BUILD-NORMAL] Girl 05: Now I'm going to get on to the Ferris wheel part, and I think I'm going to make it not a really long Ferris wheel because I don't want it to break. [IMPORTANT] [STABILITY+] [PLAN-AHEAD+]

She makes an interesting connection between symmetry and stability here.

[00:06:52] {moving} [EVALUATE-VERBAL] Girl 05: Because I don't want it to like ... If I have a heavier side on one side, then if I put that on the side that has more weight, it'll tip over. I don't want that to happen. [STABILITY+][SYMMETRY+] [IMPORTANT)

She tells a story of how she learned about stability here.

[00:11:26] Girl 05: I guess I just started to build something once ... Yeah. I started to build something once, and it looked really cool, and then all of a sudden it just toppled over. I got really upset, so I tried to figure out a way to not make it fall over, and then I figured out that I need to make more sturdy. [STABILITY+]

These examples and her finished design clearly show an advanced integration of the design principles of stability and symmetry in her building.

Cognitive flexibility. Girl 5 showed multiple instances of cognitive flexibility in her thinking and she was also very persistent. Here is an example where she both changes her idea, which shows cognitive flexibility and the ability to plan ahead.

[00:26:07] [PLAN] Girl 05: Oh, I know what I'm going to do. Instead of doing this, I'm going to do the same ride, but I'm going to make two Ferris wheel parts and have one on this side, one on this side, and they're just going to be two long. [PLAN-AHEAD+] [PERSISTENCE+] [IMPORTANT]

Here, she takes off the holding beam to strap the person on showing very flexible thinking and good building strategies. That is, she temporarily undoes the strap in order to accomplish a goal and then puts it back.

[00:37:49] {connecting} [BUILD-REBUILD] [2:PLAN] Girl 05: Okay, I know what I'm going to do. I'm going to take this off first, strap them down when it's not on the thing that I can break. That wouldn't be good. (Really good strategy for building.) [IMPORTANT] [PERSISTENCE+][PROJECTION+]

She shows a positive persistence even when she has to rebuild or change her idea.

[00:52:36] [2:PLAN] Girl 05: Hmm. I'm going to need to take off all of the things I just did and move this further over to there. [PERSISTENCE+] (Flexible, starts over).

She also frames her attempts in a positive way even if they may not succeed right away.

[00:55:51] {connecting} [2:PLAN] Girl 05: And make it extra stable by putting another four piece down here. It'll be like a ring around it, but I'm not sure if it'll work. [PROJECTION+] [PRESISTENCE+] [STABILITY+] (Flexible, try it attitude.)

[00:58:06] [2:PLAN] Girl 05: Yeah, that would be the same thing, and I'm going to see which one would work better, and it'll be a before and after. [PERSISTENCE+] (Flexible, positive thinking)

She calls things "interesting" when there are problems or when it gets hard, again showing positive persistence.

[01:03:01] [2:EVALUATE-VERBAL] Girl 05: This just got interesting. [PERSISTENCE+] (Views problems as interesting challenges). [IMPORTANT]

Plan-ahead. Girl 5 had an overall plan in her mind before building. That plan consisted of three subassemblies: base, tower, and seats. Here is one example of her clear plan when she articulates that a base is needed first.

[00:01:54] [2:PLAN] [BUILD-NORMAL] {searching} Girl 05: Okay, so I'm thinking on I'm going to build something different. I'm going to try and build particularly a really higher, slower merry-go-round that has the chairs instead of going with the actual motor. Like spin, so the person is always up, straight up. I'm just going to build a base right now. [IMPORTANT] [PLAN-AHEAD]

Causal reasoning. Girl 5 shows strengths in causal reasoning especially when she predicted what would be stable. Her causal reasoning is frequently related to design principles of symmetry or stability or based on structural knowledge of LEGO connection techniques.

In the first example, she correctly predicts speed of motor with no gears based on her knowledge of gear ratios. Note that before this, she successfully modified the gear train to gear up and not down.

[01:13:53] [2:PLAN] Girl 05: The other one's going to be like turtle. [PROJECTION+]

Here she correctly predicts how symmetrical building will produce a stable model.

[00:28:06] Girl 05: Going to need one of those pieces again. Okay, now I'm putting the other motor on, so now it's balanced. [IMPORTANT] [SYMMETRY+][STABILITY+] [PROJECTION+]

She also can make correct inferences about what caused problems after testing. Overall, her well-developed causal reasoning skills are successfully integrated with the other key process skills and are also integrated with her structural knowledge. If she does make a mistake, her process skills allow her to discover it and update her structural knowledge.

What Does It Mean?

Now that all twelve cases have been examined in some detail, what does it all mean in terms of what was seen and what it means for helping students with open-ended engineering design problems?

There was a lack of consistent EDP patterns by our original two independent variables of gender and grade level. This indicates that a clear developmental sequence in the Piagetian sense was not detected. Also, I did not see the "Ideal Project Envelope", a cascade pattern in EDP timelines as noted by Atman with expert practitioners (Atman et al., 2007; Atman, McDonnell, Campbell, Borgford-Parnell, & Turns, 2015).

Figure 88. Ideal project envelope. From "Using Design Process Timelines to Teach Design: Implementing Research Results" by C. J. Atman, J. McDonnell, R. C. Campbell, J. L. Borgford-Parnell, and J. Turns, 2015, Proceeding of the 122nd ASEE Annual Conference and Exposition, p. 26.1662.4. Copyright American Society for Engineering Education, 2015.

There did seem to be some correlation between the finished products with LEGO experience and EDP. Also, the build choice and resulting complexity seemed to be a major factor in students' EDP. Other factors emerged, some predicted by pilot study, some predicted by previous research, and frameworks: causal reasoning, design principles, cognitive flexibility, and structural knowledge. In the discussion section, all these factors will be integrated into a model that predicts EDP based on the structural knowledge, domain specific process skills (design principles, EDP, application of mathematics and science) and what seem to be the most relevant executive function skills in this domain (planning, causal reasoning, and cognitive flexibility). Additionally, more specific and specialized results and conclusions will also be reported.

CHAPTER 6

FURTHER RESULTS AND DISCUSSION

General Conclusions

If both the students' finished model design data and EDP timelines did not correlate with students' grade levels or gender, what did they depend upon? There did seem to be some correlation between the finished model design data with LEGO experience and the EDP rating (part of the finished model design data, see Appendix E - Finished Model Design Quality Rubric). A careful analysis of the different EDP timelines started to reveal some patterns. By sorting the EDP timelines in different ways, I eventually found a relationship between build complexity, the cognitive tools and knowledge the students brought to the task and the EDP timelines as show in Table 2.

Tools \ Complexity	**Low**	**Medium**	**High**
Low	Boy 3, Girl 6	Boy 8	Girl 3
Medium	Boy 4	Girl 4, Boy 7, Boy 6, Girl 9	
High	Girl 8		Girl 5, Boy 5

Table 2. EDP timeline, build complexity, and tools.

We saw that Girl 8 had a very idealized EDP where she planned her design up front, built is as planned, and needed very little rebuilding and iteration. This makes sense since she had very high skills and knowledge and she choose a very simple design. Girl 5 and Boy 5 had very dense, balanced, and long EDP processes, which reflected the complex designs they chose to build and high skills and knowledge they brought to the task. Girl 3, on the other hand, had some low skills and structural knowledge but chose a very complex design that she could not finish. Her EDP timeline was long and showed that she got stuck in a research loop never able to make progress towards a final product. Boy 3 and Girl 6 had build heavy designs, which makes sense since they had low complexity design ideas and low tools and hence could build without a lot of planning or research.   The other builders ended up in the middle and had typical, medium length, engineering design processes with a balanced mix of EDP phases. So a relationship was identified between EDP timelines, complexity, and what students bring to the task ("tools"). But what is meant by build complexity and tools? A summary rubric was created to precisely describe and rate these factors for each student as shown in Table 1 - Summary Rubric in Chapter 4 - Methodology.

The ratings for each student are shown below in Table 3.

Subject	Structural Knowledge	Math/ Science	Design Principles	EDP Process	CR	Planning	CF	Overall Knowledge and Process Rating (Tools)	Build Complexity
Boy 06	Medium	Low	Low	High	High	Low	High	Medium	High
Boy 07	Medium	Low	Medium	Medium	Medium	Low	Low	Medium	Medium
Boy 08	Low	High	Low	High	Low	High	Low	Low*	Medium
Girl 06	Low	Low	Medium	Medium	Low	Low	Medium	Low	Low
Girl 08	High	High	High	High	High	High	Medium	High	Low
Girl 09	Low	Medium	Medium	Low	Medium	Low	Medium	Medium	Medium
Boy 03	Low	Low	Low	Low	Medium	Low	Medium	Low	Low
Boy 04	High	Medium	High	Medium	High	Low	Medium	Medium	Low
Boy 05	High	Medium	High	Medium	High	High	Medium	High	High
Girl 03	Low	Low	Low	Medium	Low	Low	Low	Low	High
Girl 04	Low	Low	Medium	Medium	High	Medium	Medium	Medium	Medium
Girl 05	High	High	High	High	High	High	High	High	High

Table 3. Summary ratings. *= mix of high and low ratings.

There was a strong relationship between the tools the students brought to the task and the final product rating. This can be seen in Figure 89.

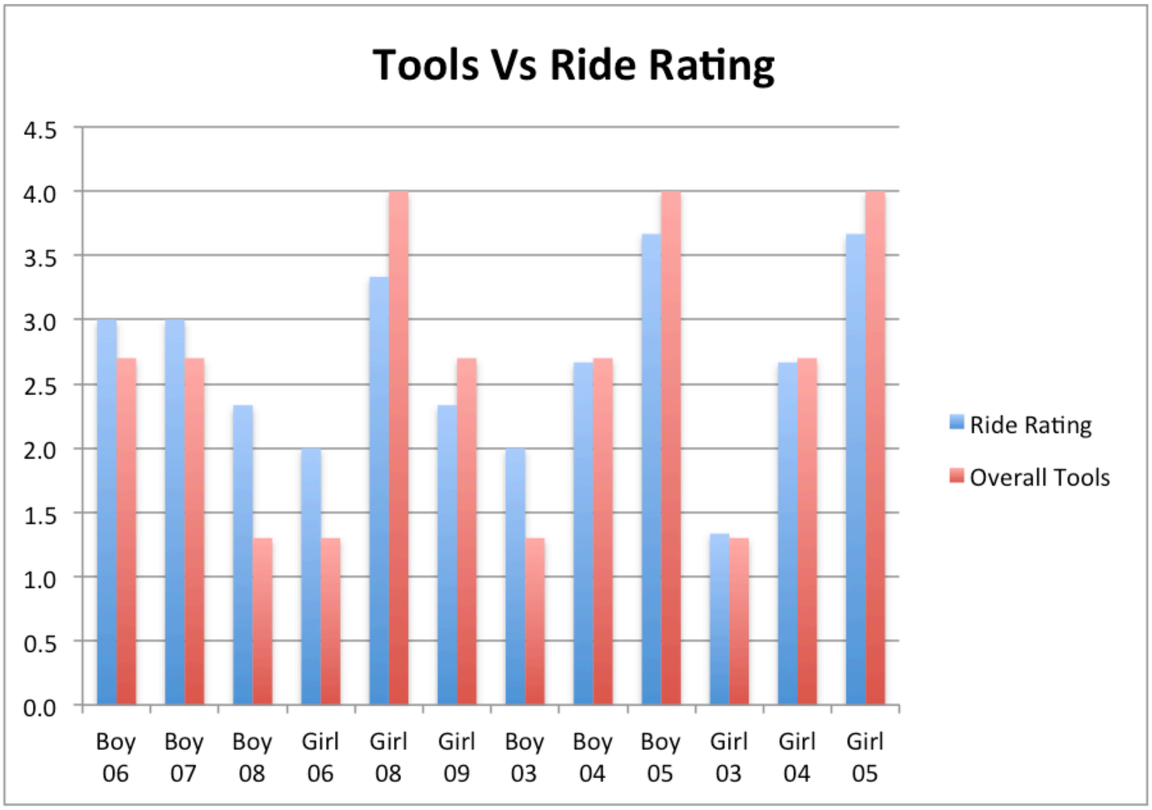


Figure 89. Tools versus ride rating by student.

Tools Students Bring to Task and Build Complexity

Recall that build complexity was defined in the summary rubric (see Table 1 - Summary Rubric) based on my years of experience seeing student rides, an examination of the twelve rides in this study, and also based on theoretical considerations. In the context of design problems such as the amusement part ride task, the most relevant aspects of problem (or build) complexity are the structuredness of the problem (ill-structured), the number of issues, functions, or variables in the problem (high), and the degree of connectivity between the variables (low) (Funke, 1991; Jonassen, 2000). Overall, students in this study are solving complex problems of various degrees, which I classified as low, medium, or high according the summary rubric. What emerged from the study were three different cases in terms of tools and complexity combinations:

1) higher tools than complexity: some students build low complexity designs that could have done much more sophisticated designs (Girl 8),
2) roughly matching tools and complexity: some students built designs within their current capabilities (note that Boy 4 and Boy 8 were very close to this class),
3) higher complexity than tools: at least one student (Girl 3) attempted to build without the needed knowledge and skills.

Teachers need to check proposed designs to try and avoid the first and last cases. In the *higher tools than complexity* case, making more required components such as a motor, computer, and sensor required would have make the increased the complexity enough to make the task harder for students who have the requisite tools for the task. Ideally, the required use of these components would make sense and not seem arbitrary to the students.

For the *higher complexity than tools* cases, teachers will need to provide significant, additional scaffolding to help these students realize their designs. For Girl 3 and Girl 9, additional scaffolding might have been: having them sketch out the overall design first, having them build the tower first, additional LEGO connection scaffolding in terms of direct instruction or additional building experience focusing on connection. In general, I do not recommend suggesting an easier design idea unless their idea is completely impractical. That way, the student can feel empowered to realize their design ideas albeit with teacher help.

LEGO Knowledge

Structural and domain specific knowledge about LEGO connection techniques emerged from the study as another key factor in the ability of students to realize their design ideas especially as the build complexity increased in some of the NXT (grade 6) designs. While the correlation to final ride rating is not as strong as the overall tools rating, it is still a significant factor (see Figure 90). Some students who had low structural knowledge compensated with other strengths (Boy 8 and Girl 9, for example).

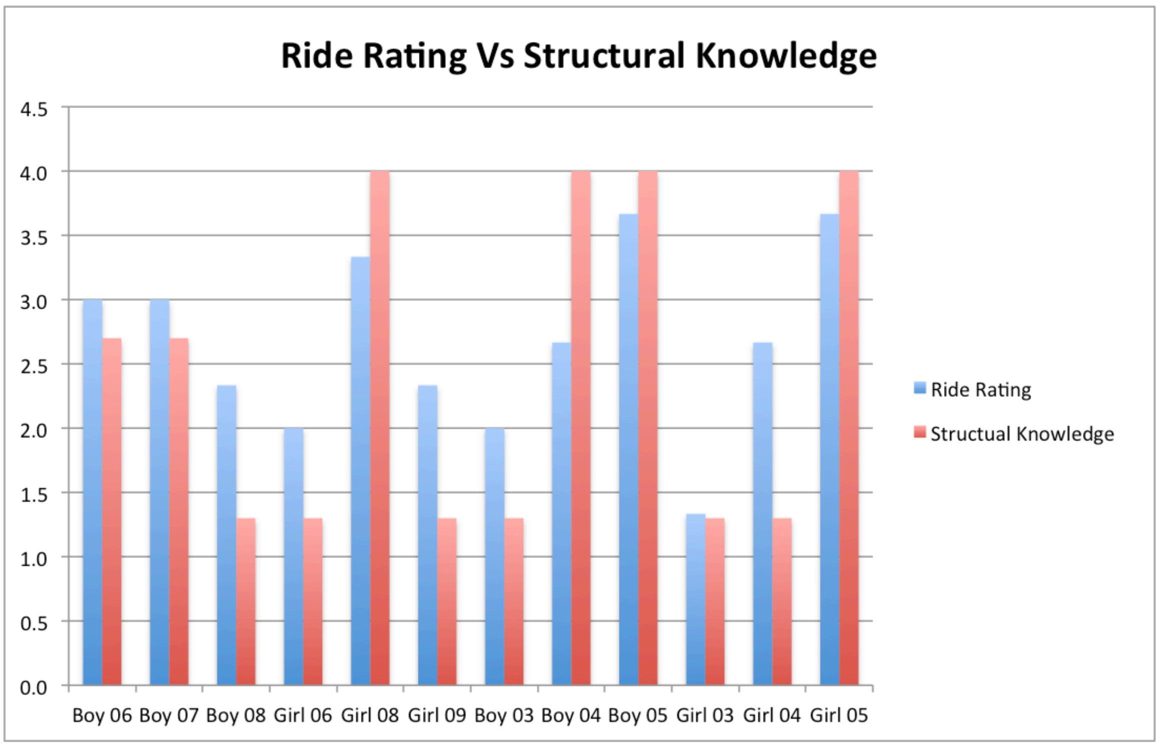


Figure 90. Ride rating versus structural knowledge.

Boy 5 and Girl 5, for example, had extensive LEGO connector knowledge - called domain knowledge - and but also possessed meta knowledge about how the various LEGO connection techniques were related to each other - called structural knowledge (Jonassen, 2000).

This study showed that some of the students needed more structural knowledge to be successful. While the curriculum used in this study (Heffernan, 2013) identifies key WeDo connector parts (see Figure 91), additional work is needed to map connection techniques and specifically when to use them for both WeDo and NXT/EV3. For example, many students in this study lacked the knowledge that to make an axle move a beam, a cross to cross connection is need as shown the bottom middle parts of Figure 91. Once connector pairings are mapped to their functions, activities need to be developed to help students understand which connectors might work - domain knowledge - and also gain structural knowledge of the relationship between the different connectors.

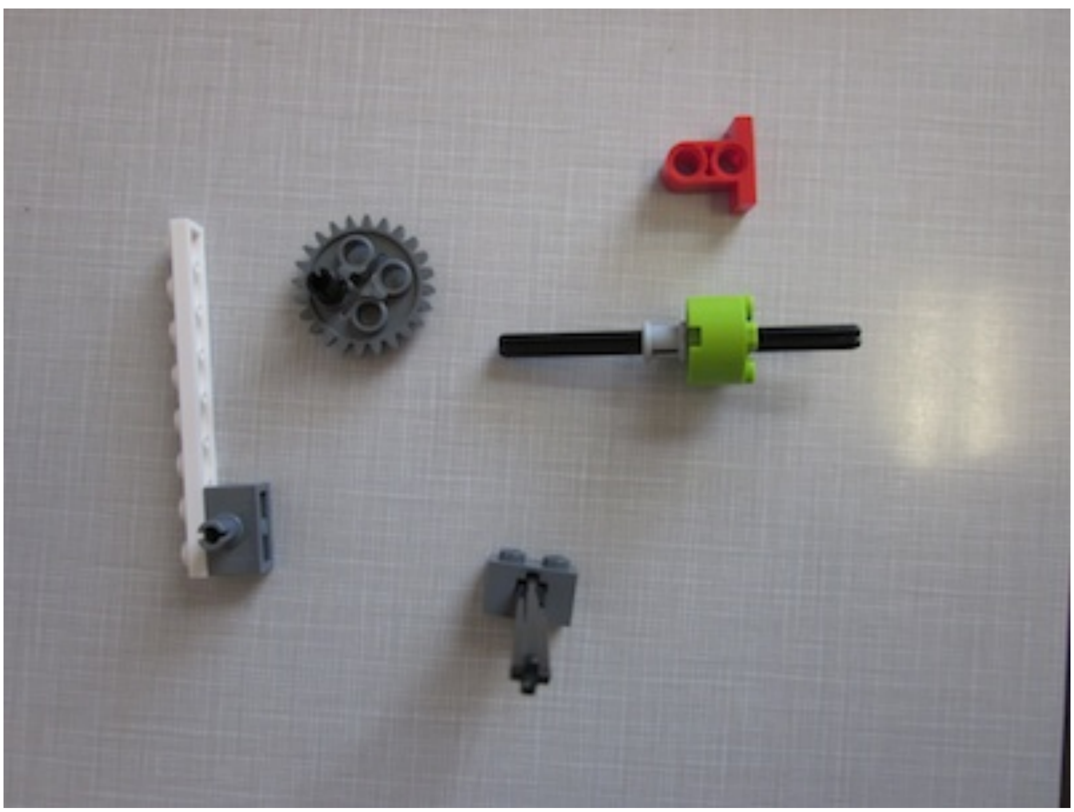


Figure 91. Key LEGO WeDo connection parts.

LEGO knowledge and build complexity emerged as two key factors that defined the EDP of elementary students doing an open-ended LEGO robotics task. I found six other key factors that can be thought of as process skills: three domain specific and three general executive function skills.

Engineering Process Skills

Three domain specific skills emerged as critical to the EDP and final product of students in this study. They are: the application of mathematics and science to engineering, the application of the design principles of symmetry, scale, and stability, and finally, knowledge of and the ability to use the engineering design process.

Design principles. This study revealed that students with the best designs and design processes attended to and understood certain design principles: stability, symmetry and to a lesser extant scale. One way to see this is in Figure 92. There is a high correlation between ride rating and the use of design principles. One exception is Boy 6, who chose a low complexity build despite having some key strengths.

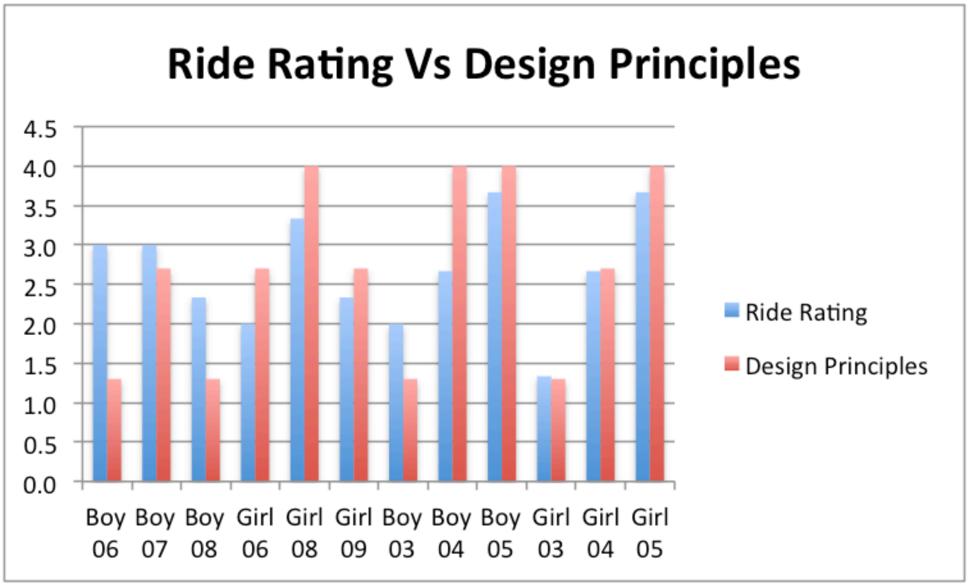


Figure 92. Ride rating versus use of design principles.

Examples were given in the Results section of students such as Boy 5, Girl 6, and Girl 8 who frequently cited and applied these design principles, while builders who had difficulty realizing their design ideas such as Girl 3, Boy 3, and Boy 8 did not. This shows that learning activities should be created that teach these principles to students, especially symmetry and stability. This includes the structural knowledge that symmetrical structures tend to be stable, the use of trusses such as those Boy 5 needed, and connecting beams in multiple places as shown by Girl 5 and Boy 5.

Application of mathematics and science. Similar to the use of design principles, some builders were able to apply mathematics and science to their designs successfully. We can see that the correlation is not as strong as some others as shown in Figure 93. This makes sense as not all rides at the elementary level require the application of mathematics or science to a significant degree. However, it remains an integral aspect of engineering to teach to younger students (Brophy et al., 2008; Crismond, 2001).

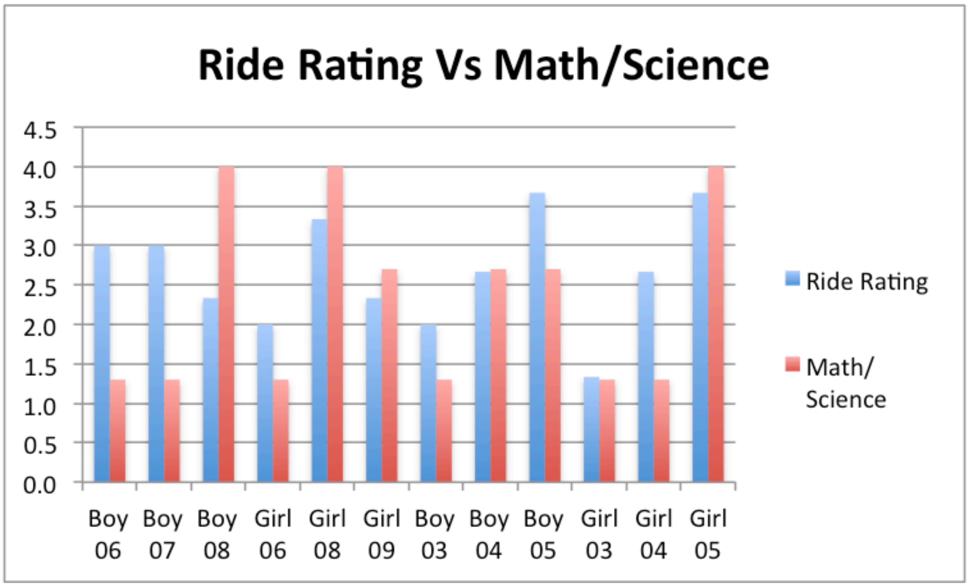


Figure 93. Ride rating versus application of math and science.

Girl 5, the strongest builder in the study, did apply mathematics and science to her design but needed some teacher scaffolding, in the form of a neutral question to figure out the difference between gearing up and gearing down. In her case, even though she could recite the domain specific science knowledge that the smaller gear goes faster, she initially applied it incorrectly.

> Jonassen (2000) explains this phenomenon this way: However, that domain knowledge must be well integrated in order to support problem solving. The integratedness of domain knowledge is best described as structural knowledge. (p. 69).

I had to restate her own statement about gearing up before she could correctly apply science knowledge to her design. This is consistent with other research that teacher or other scaffolding is needed to help students apply science in design problems (Crismond, 2001; Fortus et al., 2005; Puntambekar & Kolodner, 2005). Furthermore, the scaffolding should include helping students understand the relationship between domain different specific knowledge, that is, structural knowledge.

EDP process skills. Most students had good knowledge of the engineering design process itself (n=10 rated medium or high), Presumably this came from their exposure to the engineering design process due to yearly robotics units since starting in kindergarten.

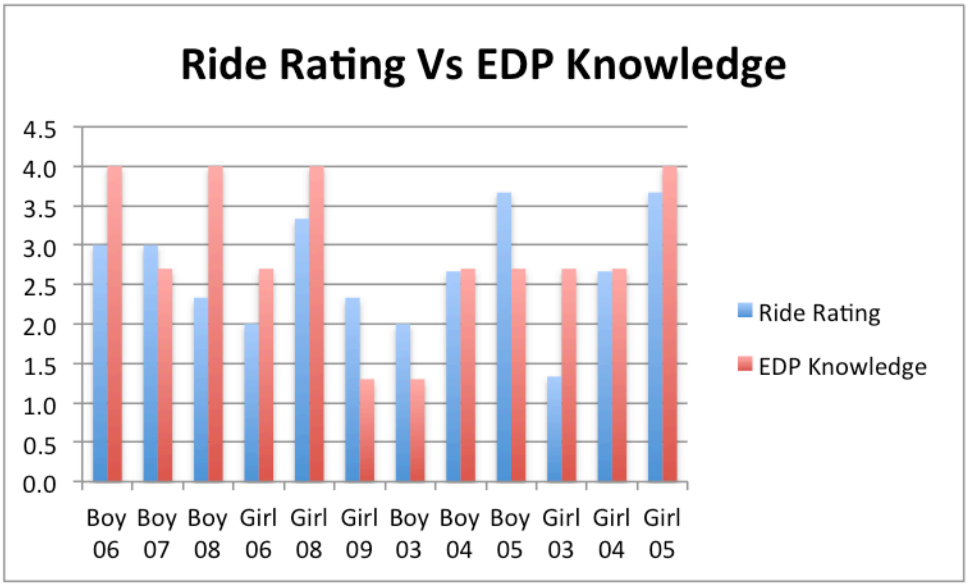


Figure 94. Ride rating versus EDP knowledge.

In some cases, having a strong EDP compensated for less developed executive function than other students. Both Boy 8 and Girl 3 were examples of this. Students with advanced EDP skills exhibited subskills such as: systemic testing (Girl 5), control of variables (Girl 5), troubleshooting tactics (Girl 4, Girl 5, and Boy 5) and, in general, a good balance of time spent in different EDP phases, most notably some up front planning and research (Boy 5, By 8, and Girl 8). While students showed good EDP overall, instructions in specific techniques such as control of variables or domain specific troubleshooting tactics will benefit students.

General Executive Functions Skills

While many executive functions (EF) are used in open-ended design problems, three in particular emerged as playing a key role in this study. See Figure 6 for complete taxonomy of executive function skills that may be involved in open-ended elementary engineering tasks.

Casual reasoning. As I hypothesized, causal reasoning (CR) in the form of predicting the effects of design decisions and inference in the form of inferring what went wrong when testing were key factors in this study (see Figure 95).

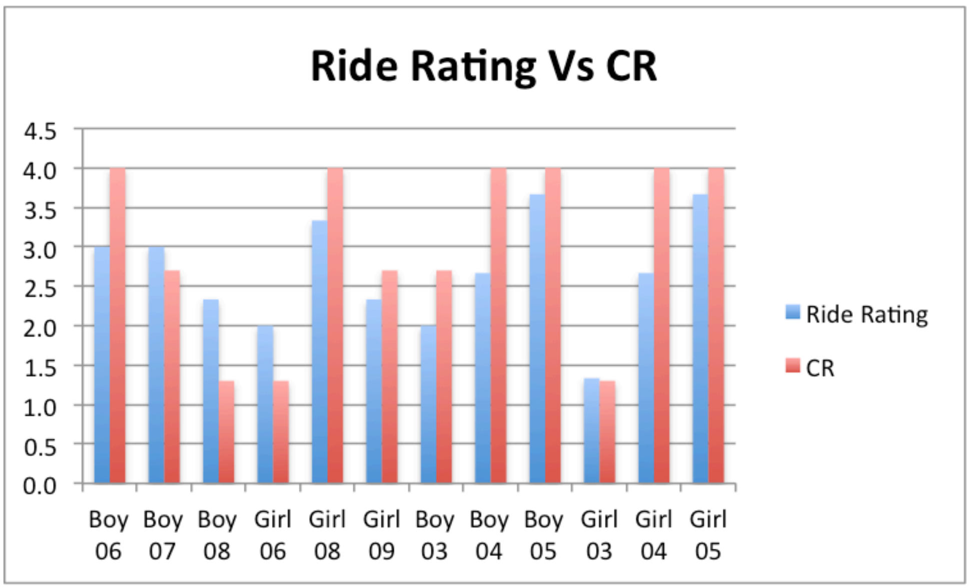


Figure 95. Ride ratings versus causal reasoning.

The most successful and advanced builders such as Girl 5, Boy 5, and Girl 8 had strong CR skills as measured by the summary rubric and secondary coding. Skill in prediction increased the likelihood of making productive design decisions more often than students with less developed CR skills. Good inference skills allowed faster determination of non-productive design decisions so they could be corrected. Boy 5 had very good prediction skills. In this example, he decides to use a gear piece as a connector to hold the seat assemblies.

[00:44:31] [BUILD-NORMAL] [2:PLAN] Boy 05: I would need to add a gear.

Researcher: Oh, gear. What's the gear do?

[00:44:40] Boy 05: It would turn the swings.

His successful projection (prediction) saved him time and effort and also worked well functionally. See Figure 96 for a picture of the gear and how it was used.

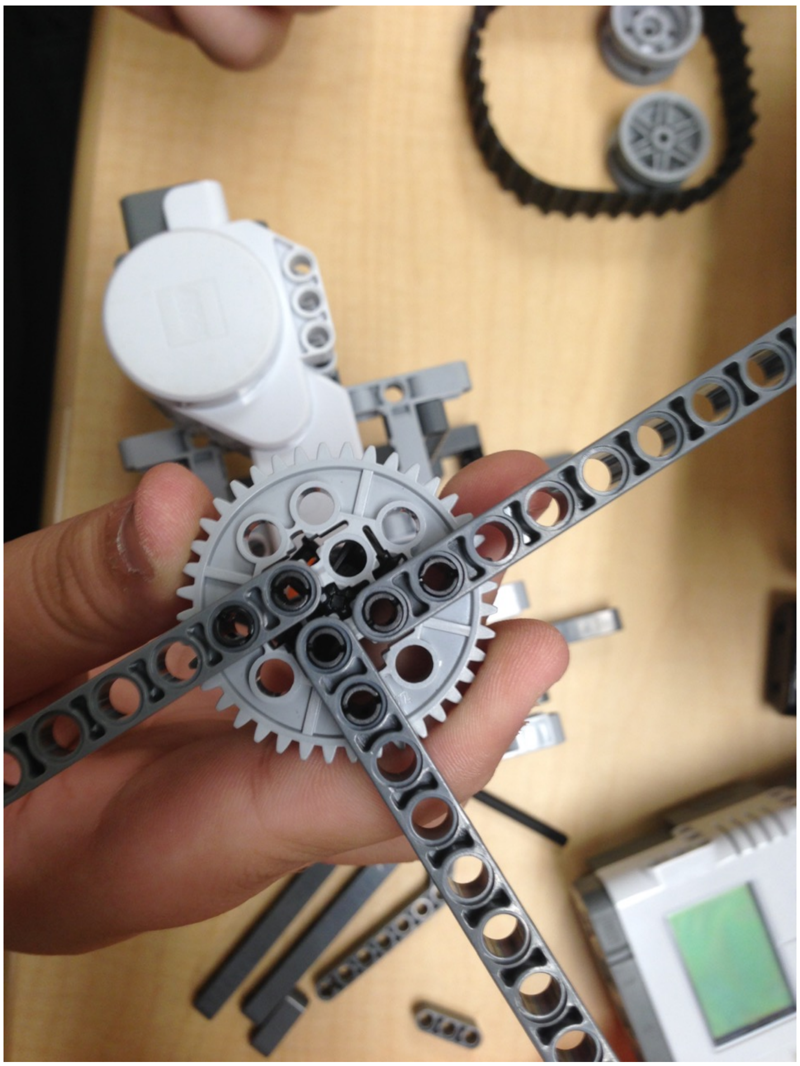


Figure 96. Boy 5 successfully predicted that this gear would work well as a connector for all the seat subassemblies.

I found that, in many cases, it was hard to determine if an incorrect prediction was a result of lack of structural knowledge or lack or CR or both. For example, if the motor is not connected to receive power, did the student not have the knowledge to understand that is needed to be connected or did they have the knowledge but did not have the CR required to use that knowledge? One interesting example of this was Boy 8, who put the motor on the seat rather than a tower type structure. He did not predict that the cord would become tangled even though it seemed obvious to me. See Figure 46 for a photograph. Note that if there is missing domain knowledge, there is no way that the student can create structural knowledge, which, by definition, integrates different domain knowledge. Again, this could be misinterpreted as a lack of causal reasoning skills.

There is some evidence to suggest causal reasoning and the lack of structural knowledge (SK) can be separated. Girl 4 scored high in CR and low in SK. Girl 9 scored medium in CR and low in SK. Girl 9, in particular, used good CR skills to compensate for low SK. It seems likely that lack of SK can appear to be lack of CR but that they are, in fact, two different phenomenon.

CR is generally considered to be developmental (Fuson, 1976; Piaget & Inhelder, 1969) and there were more high CR sixth graders than second graders. Open-ended engineering problems appears to be a good activity type to help develop CR in the form of prediction and inference as long as students also have the required structural knowledge as a basis for CR.

Planning. Planning was another key factor in elementary student engineering though its importance depended on a number of other factors. See Figure 97 for the relationship between planning and the final ride rating for this study.

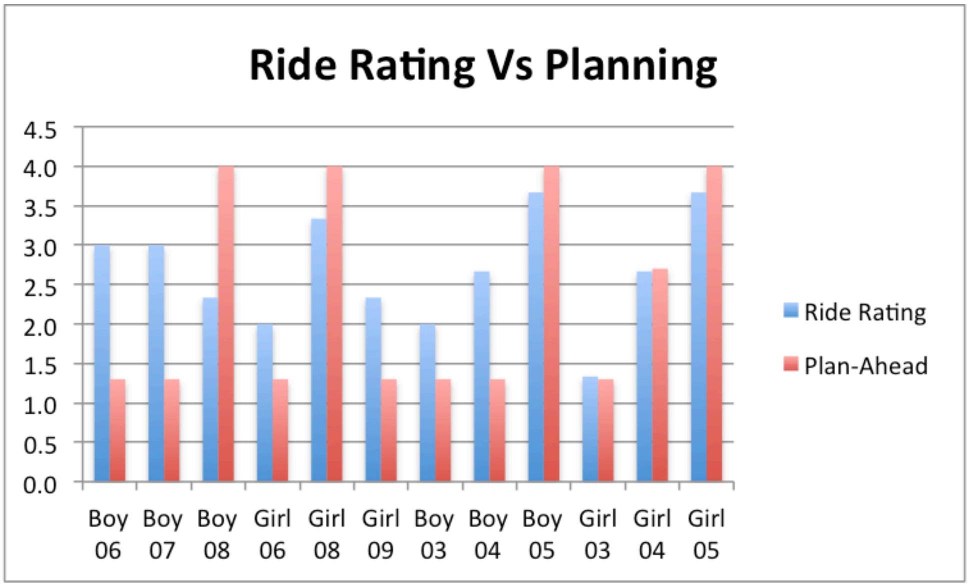


Figure 97. Ride rating versus planning.

Note that planning depends on causal reasoning, specifically, prediction (Jonassen, 2000). Most students had a clear planning style, which can be described as either a serial (Boy 6, Boy 7, Girl 6, Girl 9, Boy 3, Boy 4, and Girl 3) or systems approach (Boy 8, Girl 8, Boy 5, and Girl 5). Girl 4 had elements of both styles of building.

At 4:36, Girl 3 clearly states the serial building approach.

Researcher: When you are thinking about your Ferris wheel do you plan just the first part and then worry about the rest later or do you have an idea in your head about what the whole thing is going to be?

[00:04:36] Girl 03: I usually just start with one thing and see how it goes. [IMPORTANT]

In the case of Girl 3, who was unable to finish her ride, the lack of an overall idea before building caused her major problems in getting her subassemblies connected at a later time. Her ride, which is similar in concept to that of Boy 5 and Girl 5, would likely have been more successful with an overall system plan. Girl 5 and Boy 5 were able to successfully build the same ride concept as Girl 3 but had a clear plan of building a base, tower, rotating seat assembly, and seats ahead of time and in that order. However, there were many successful serial builders who choose less complex builds such as Boy 6 and Boy 7.

The implication for teaching is that the use of a systems approach is a useful tool to teach and will especially help students with complex designs and low CR skills. Also note that having immediate access to the building materials (LEGO pieces) may encourage a more serial or tinkering approach as opposed to a more formal pencil and paper engineering planning and design approach typical of engineering processes research at the undergraduate level (Atman et al., 2007).

Cognitive flexibility. Cognitive flexibility (CF) emerged as our final important EF factor in the study. I thought of this two ways: positive and negative. A positive CF in this context consisted of being willing to start over on a major part of an idea and having many different ride ideas or ideas for a particular subassembly. A negative CF was thought of as non-optimal persistence. This was typically seen as repeated stability or other issues that the student would keep repairing but never address the underlying issue. Boy 7, for example, continually tried to make his ride spin with a solid axle to cross connection so he had to hand start his ride.

Figure 98 shows the relationship between CF and the final ride rating for the students in this study. Two students - Boy 7 and Boy 8- had low CF but were able to compensate for it with strengths in other key process skills or structural knowledge.

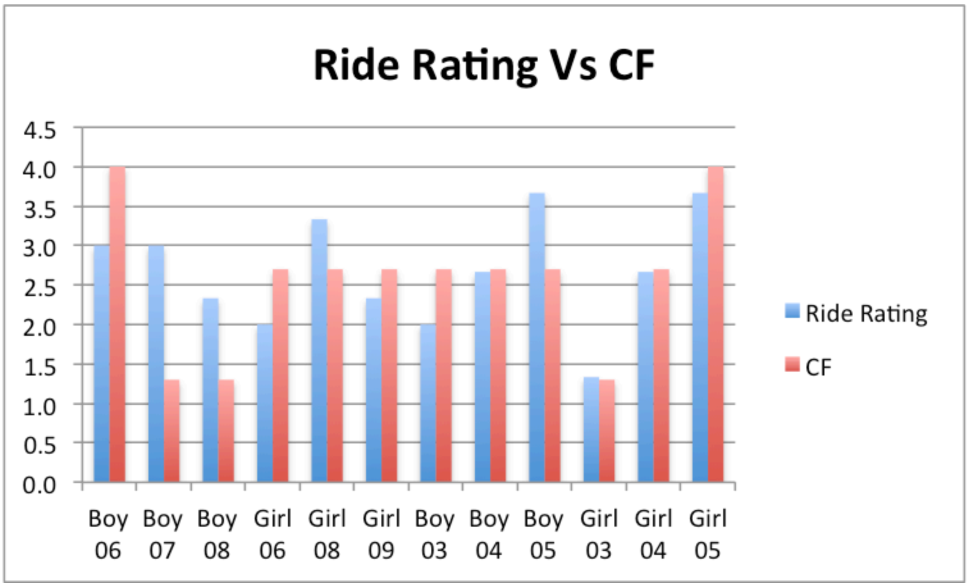


Figure 98. Ride rating versus cognitive flexibility (CF).

The implications for teaching in terms of CF are as follows. First, students showing non-optimal persistence need either encouragement to rethink what they are doing and start over or may be lacking a specific piece of domain knowledge. In the example of Boy 7 above, he needed to know that an axle needs to be inserted into a cross piece to make a stable connection. Of course, positive persistence or positive CF should be encouraged. Now that all the key factors have been explained, how do they all fit together?

Model of build complexity, structural knowledge, and process skills. Leaving out build complexity for a moment, we can envision the continuum of process skills and structural knowledge for each student as shown in Figure 99.

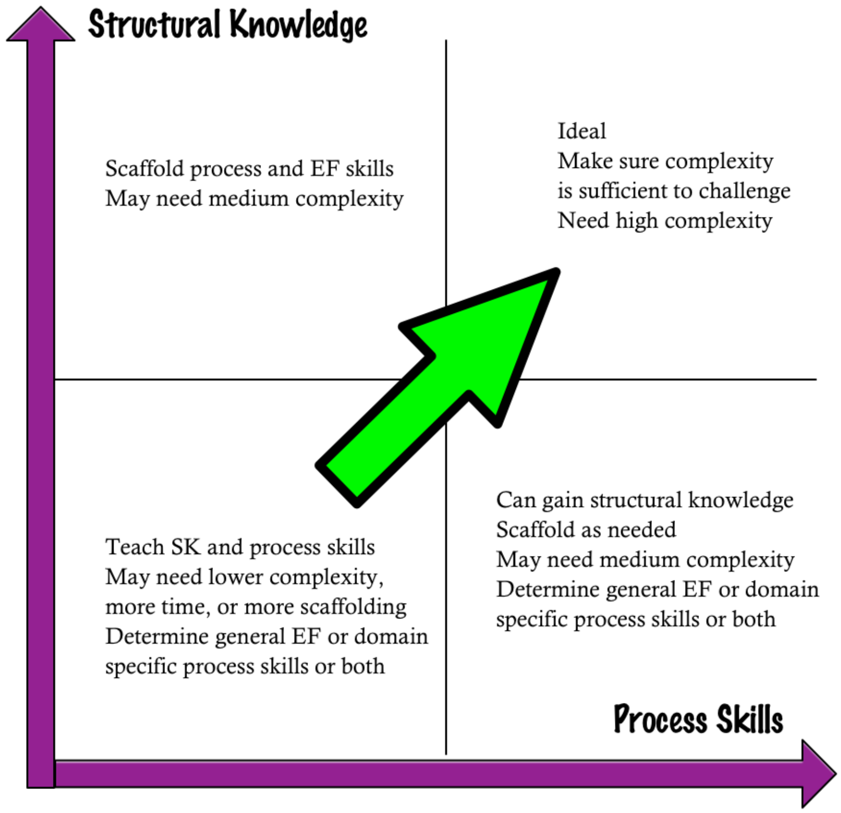


Figure 99. Structural knowledge and process skills.

Students can be thought of as being in one of four quadrants. Each one is explained below. The green arrow shows where we want students to go.

- High SK, High Process Skills - students in this group are in an excellent position to tackle complex engineering problems. We did see that complexity should be high or the problem will be too easy as we saw with Girl 8 in this study who completed her ride without much failure or iteration.
- High SK, Low Process Skills - while there were no clear examples of this in this study, some students with high SK did have gaps in various domain specific or executive function skills. Students in this group need instruction or scaffolding in

domain specific skills such as applying mathematics or science, the EDP, or design principles such as stability and symmetry. Teachers might also identify and help students with low EF such as planning, causal reasoning, or cognitive flexibility. Students in this quadrant may do best with medium complexity tasks. They may also do well with high complexity tasks with sufficient scaffolding.

- Low SK, High Process Skills - students in this group need scaffolding in LEGO connection and other domain specific skills. SK will be improved just by doing LEGO engineering activities. Many students compensated (Girl 9, Boy 8, and Girl 4, for example) for low SK with other strengths such as high EDP or strong CR or CF. Teachers or LEGO itself can create building activities that help teach structural knowledge of LEGO connection techniques. Teachers should try to identify the specific process strengths and lacks and provide the appropriate help. For example, if it is clear that the student's knowledge of the EDP is weak, that can be emphasized. Students in this quadrant may do best with medium complexity tasks. They may also do well with high complexity tasks with sufficient scaffolding
- Low SK, Low Process Skills - students in this group need scaffolding in multiple domain specific process skills and/or executive function skills and also need help with structural knowledge of LEGO connection techniques. Students may need to lower complexity tasks or significant time or scaffolding with medium or high complexity builds.

Now, let's examine the model of build complexity, process skills, and structural knowledge in three dimensions as shown in Figure 100.

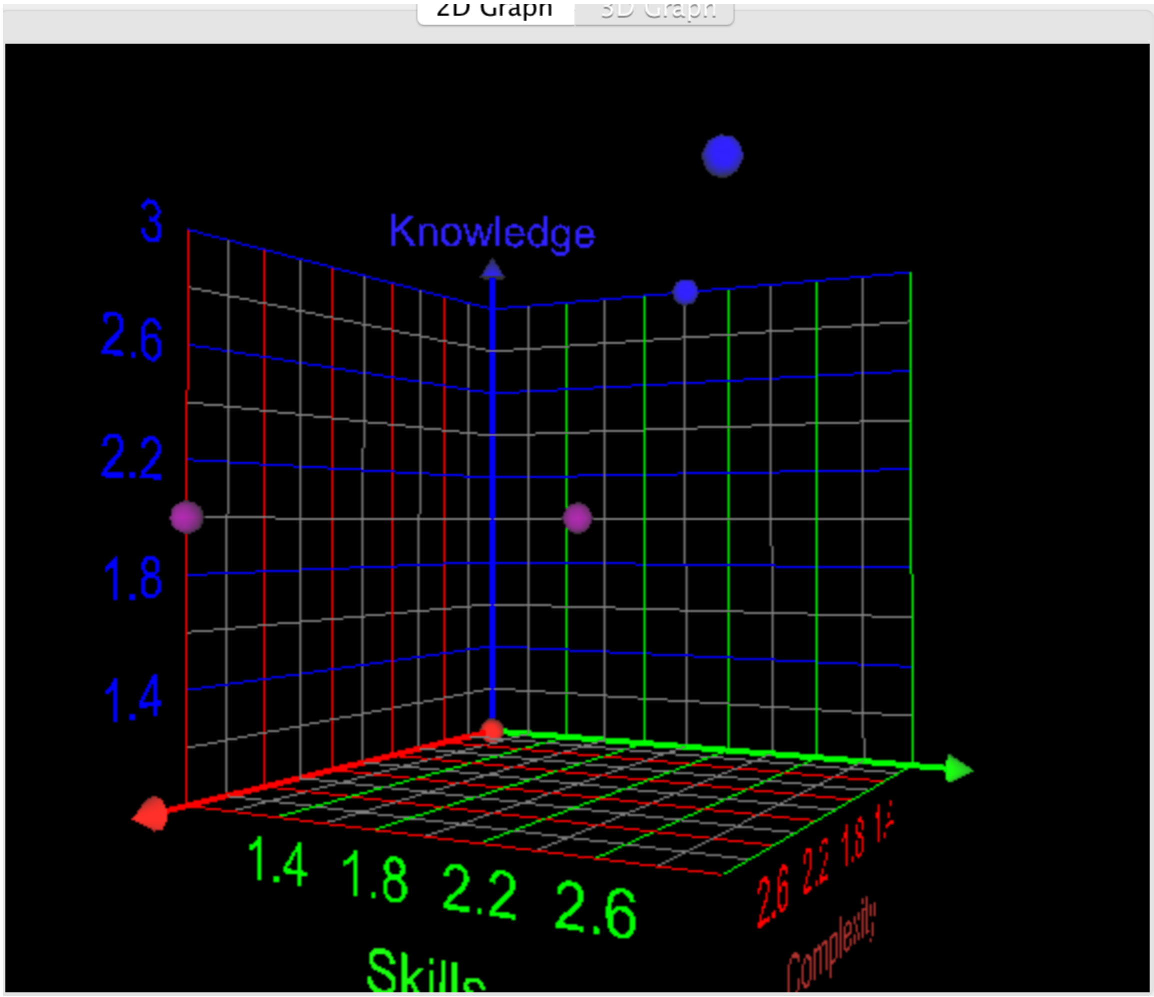


Figure 100. 3D model of build complexity, structural knowledge, and process skills.

Point (1,1,1) indicates a low complexity, low skills, and low SK student. The goal is to move this student to medium complexity, medium skills, and medium SK point (2.2,2) shown in the graph. Likewise, those students would ideally move to the high complexity, high skills, and high SK point at (3,3,3). The line connecting (1,1,1) to (2,2,2) to (3,3,3) represents an ideal case where students move to higher complexity with a balance of SK and process skills.

The point at Complexity = 2, Knowledge =2, and Process Skills = 1 indicates a student with a medium complexity, medium SK, and low tools. In this case, teachers can help move this student more to the centerline by scaffolding their EF or domain specific process skills. The blue point at Complexity = 1, skills= 2, and SK =3 indicates a student with a low complexity build, medium skills, and high SK. This student may need a higher complexity build and also some scaffolding in one or more process skills. Now that a model that explains the EDP timelines for all students in this study as function of build complexity, structural knowledge, and key executive function and domain specific process skills has been presented, other specific results will be presented.

Specific Conclusions

Engineering Design Process (EDP), Causal Reasoning (CR), and time. I found it helpful to think about time and how it relates to EDP and CR when coding the video of elementary students doing open-ended engineering challenges using LEGO robotics materials. The following diagram (see Figure 101) summarizes these relationships.

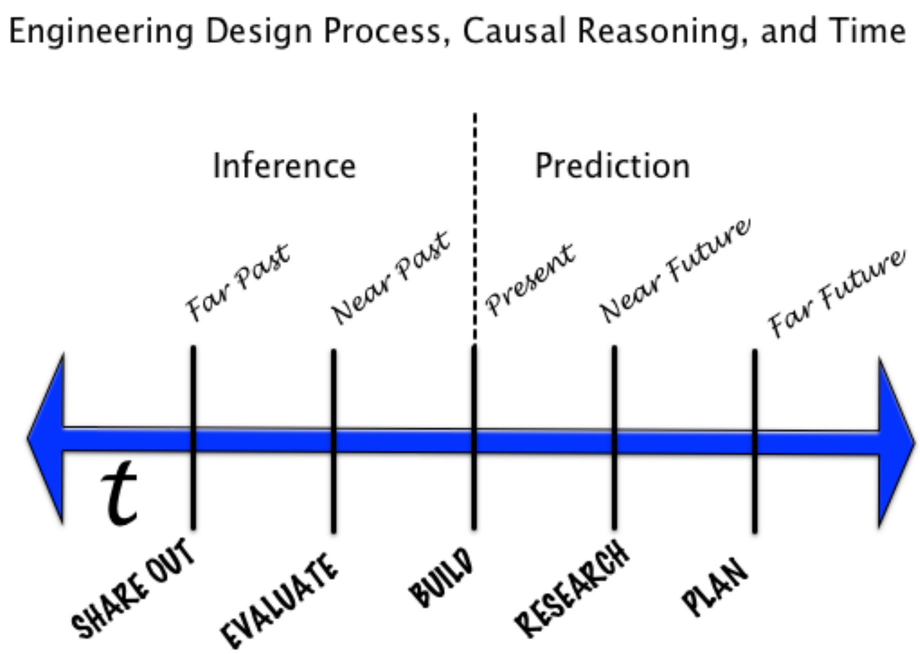


Figure 101. EDP, causal reasoning, and time.

Predictions are defined as anticipating an outcome based on the initial state of a system and plausible causal relationships. Inference is defined as the opposite process as prediction, that is, positing events and initial conditions based on a final set of conditions and plausible causal relationships. (Jonassen & Ionas, 2008) Time can also be seen as a way to separate prediction from inference. That is, prediction is based on future causal relationships while inference is based on teasing out causal relationship in the past. Building takes in the present moment. Sharing out can be seen as involving the far past. Engineers share out their result when finished. Planning can be seen as involving the far future while research takes place in the near future and is focused on more immediate results. I found this model helpful when coding in cases where determination of the EDP phase was ambiguous: 1) looking at verb tenses, 2) classifying the time aspect of the utterance, or 3) determining from the video what the verbal output referred in terms of the past, present, or future activity.

Here is an example of the PLAN code. Note that the subject is talking about the (relatively far) future. While not making a specific scientific, causal prediction in this case, he is predicting what he will do in the future. I noted that the physical segment descriptor {gesturing} was found frequently when planning. This is likely to be for two reasons. First, the model is not built yet so it is not possible to demonstrate by moving the model. Second, subjects acting out the idea physically as a way to make the abstract more concrete (Sullivan & Lin, 2012; Sullivan & Heffernan, 2016).

[00:02:21] [PLAN] Boy 05: I think I'm going to make swings that swing around.

Predictions (coded as PROJECTION in this study) typically occur when the subject is planning as shown below. Predictions always involve the future. While not all planning (and research) involves explicit cause and effect predictions, all predictions seem to occur in the context of planning. (They might also be seen in RESEARCH but have not been seen there to date.)

[00:29:26] {moving} [2:PLAN] Boy 05: Now I'm thinking that if I have a longer piece, I can just add that and there's no need to add this. [PROJECTION+]

In the example of RESEARCH below, the subject is describing a more immediate move where he is physically trying out something to see if it will work. Planning, since it is farther out in time, does not involve physically trying these out but is typically done verbally (or with drawings in a few cases). The {moving} segment descriptor is typically seen with RESEARCH (or EVALUATE). However, the subject is not actually connecting anything (which is usually building).

> [00:20:29] {moving} [RESEARCH] Boy 05: I'm thinking of a way to connect it on it. (Tries out motor in place.)

Next is an example of building. (She also evaluates when she comments that it is balanced.) The subject is describing what she is currently doing in the present and uses the present tense. The {connecting} segment descriptor is always seen with building. (Connecting can also happen when the subject is making a separate side research build to try out an idea.)

> [00:27:52] {connecting} Girl 05: Okay, now I'm putting the other motor on, so now it's balanced.

Evaluation involves the near past. The subject builds and then evaluates what they have just built. (In rare cases, this could be delayed for a while if the subject notices something that needs testing "after the fact".) Like RESEARCH (which is the analogous operation in the near future) the subject is typically moving parts to test out some aspect of it (EVALUATE) or try out a part without actually connecting it (RESEARCH).

> [00:09:55] {moving} [EVALUATE-PHYSICAL] [EVALUATE-VERBAL] Boy 05: I'm now trying to see if they're lined up properly. (Referring to something he just built.)

Explicit inferences involve the past and most often occur in the context of a verbal evaluation where the subject verbalizes the cause of a problem found. (It may also be found in SHARE-OUT but has not been seen there to date.) Note that past tense in this example.

> [00:35:10] [2:EVALUATE-VERBAL] Boy 05: The problem was it has a gap in it, so I can't attach this to line up like this. [INFERENCE]

SHARE-OUT typically occurred in the post interview prompted by the researcher (and therefore was not coded). However, it is the analog of planning in that it involves a description of what happened in a more distant time. Sharing out frequently involves gesturing just like the analogous planning EDP phase.

> [01:18:41] {gesturing} Girl 05: The description is the upside-down ... The name of the ride is the Upside-down Cake Ride because it looks like an upside-down layer cake. On one side it shows a kiddie ride for younger kids, and this is for people who just like to throw up. The gears on one side make this side go really fast, and this goes not as fast, and there are two motors and a lot of LEGOs.

How did the notion of time help in the coding of students' EDP? To give one example, the verbal output of the subject in the snippet below seemed to indicate planning. However, the video clearly showed that she was describing what she was building in the present moment so that helped determine the code as BUILD and not PLAN.

> [00:10:18] [BUILD-NORMAL] Girl 06: I think if I put them together, and then if I put this on, and then if I would put this on, and then if I would put that on ... (Sounds like planning but from the video we see that she is really just describing what she is doing.)

In summary, the theoretical notions of prediction and inference are related to the engineering design process. Coupled with the observations of temporality in the verbal output of elementary aged subjects doing open-ended engineering challenges, a model was created that links time, EDP phases, inference, and prediction in a way that helps determine EDP phases in research videotape sessions.

EDP phase frequency, time, and average duration graphs. There was no discernable pattern to the EDP frequency and average duration graphs of students in this student. However, eight of nine students %EDP Phase Time graphs showed one of two typical patterns (see Figure 102 and Figure 103) if the student's EDP and build complexity were medium or higher. Both patterns show significant time spent in each EDP phase (with the exception of programing) with the most time spent building.

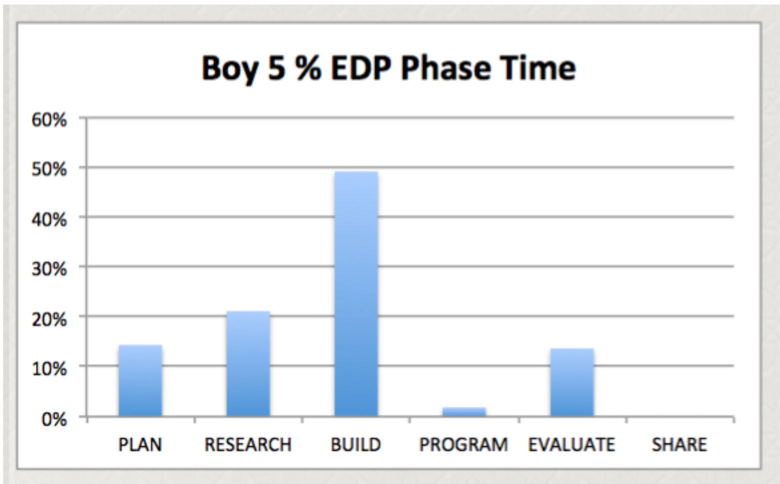


Figure 102. Typical staircase %EDP phase time graph.

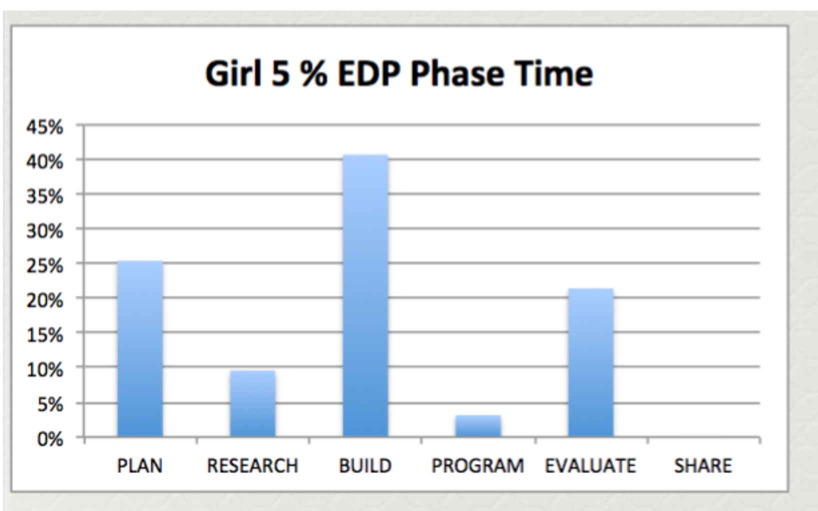


Figure 103. Second type of typical %EDP phase time graph.

On the other hand, a different pattern than the ones above generally indicated a problem. For example, shows that a student did not chose a build complexity that matched her tools so no research and little evaluation was needed.

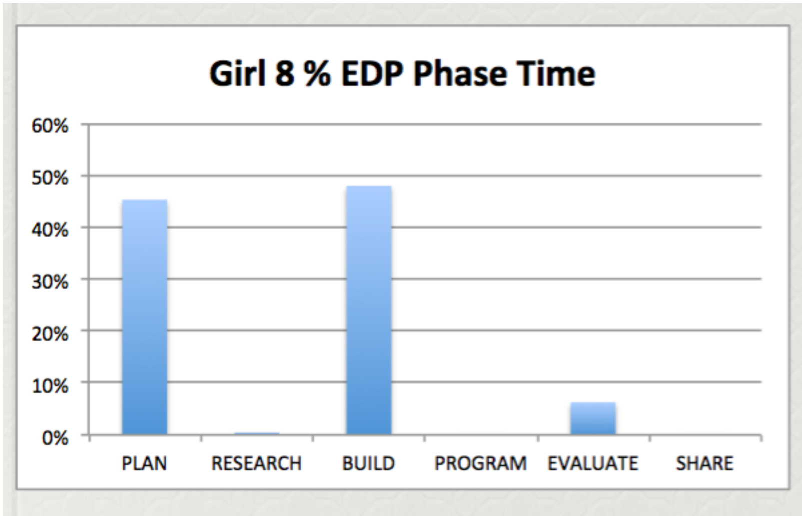


Figure 104. Atypical %EDP phase time graph.

While formal measurement of EDP phase time would be difficult in the classroom setting, teachers could informally monitor for unbalanced engineering design processes. For example, teachers might suggest more research, planning, or evaluation if none of those is detected. The EEC (Heffernan, 2013) requires some planning to be done (though lower grade students typically veer away from their original plans).

Role of development. The initial thesis of this study was that developmental factors, such as reported by Piaget (Piaget & Inhelder, 1969) in the realm of mathematics, would also be found in students in this study, which compared second and sixth grade students. However, significant differences by age were not found. The exception was in the area of executive function, casual reasoning in particular, which was somewhat more developed in grade 6 students. Also, as predicted by theory (Baynes, 1994; Vygotsky,

1986) designerly (also called creative or fantasy) play was seen more explicitly in grade 2 students (n=61) but was also seen (albeit more subtlety) in grade 6 students (n=23). Students used age appropriate materials so greater differences might be seen if students had used the same materials. As predicted by neo-Piagetian constructivism, universal Piagetian stages were not found but a web structure of different stages for different skills was verified. Additionally, both domain specific and general cognitive skills were found. Finally, the mental inflexibility sometimes found in tool innovation research was found in similar way here, that is, with some students and more at younger ages.

While I had an original hope that this research might form the basis of defining a learning progression (Krajcik, 2011) for students, significant developmental differences were not found. I ***can*** conclude that good structural knowledge of LEGO connection, building, and programming techniques form a perquisite base for many of the other factors such as casual reasoning, the application of mathematics and science, and planning. Good knowledge of design principles and the EDP are also helpful for students to have before undertaking open-ended design tasks.

Applicability of the Informed Design Teaching and Learning Matrix. Recall that Crismond & Adams (2012) defined a Informed Design Teaching and Learning Matrix meant to help define novice and expert levels for each part of the EDP along with teaching strategies and learning goals for each EDP phase. For example, in the General Ideas phase, they say that novices: "work with few or just one idea, which they can get fixated or stuck on, and may not want to change or discard" while experts "Practice idea fluency in order to work with lots of ideas by doing divergent thinking, brainstorming, etc." (p. 748). This particular row of the matrix fits well with the cognitive flexibility factor identified in this study. However, many other rows had expert columns that were too advanced for the elementary level. They were not seen or rarely seen. An example of this is: "Use words and graphics to display and weigh both benefits and tradeoffs of all ideas before picking a design" (p. 748). So, while the matrix is quite useful, it may need to be adapted for elementary students.

Role of programming. An examination of the EDP timelines show very little time spent programming. Some students (n=3) choose to not even use the computer for their ride. Some of this could be that the time limit and less adult direction in the research setting. Programs were very simple typically with a few exceptions. I do see more developed programs when the same assignment is done in classrooms with partners. However, the animation of the rides was very important to those students who use a motor. So programming played a small but important role for students in this study. With the current focus on early programming, we can say that teachers should teach and encourage programming in young students and that robotics is a rich way to introduce coding to students.

Parts first versus idea first. I saw two styles of LEGO building in this study. One was looking at parts first to generate ideas and the second was to find parts to implement ideas, which I call idea first.

Boy 07, for example, showed evidence of the parts first style.

> He actually articulated this in the post-interview as follows: 'Because I never know what I'm going to build until I find a piece, and I'm like, "Oh, that piece could be used for this, and I can make that out of it," and that's what I usually do at home.'

Boy 4 also articulated the parts first style.

> [00:26:51] Boy 04: I'm just looking for parts to see if they give me any inspiration for something new. [IMPORTANT]

Other students such as Girl 5 and Boy 5, who used more planning, used an idea first style in general. Some students used both styles in the same build. Both styles can work but we did see that in the case of more complex builds, that planning or an idea first style could be an advantage to students.

Sharing out side effect. Some students modified their ride during the post interview sharing out. This should be expected as they found things they wanted to improve during the demonstration. Here is an example from Girl 6.

> Researcher: You all done? All right, I'm going to ask you a few more questions about your ride. Can you describe your ride and demonstrate how it works?
>
> [00:21:22] {moving} [SHARE-OUT] Girl 06: There's a person holding it, and it's turning, and it's going in circles. [CREATIVE-PLAY]
>
> [00:21:31] {searching} [BUILD-NORMAL] [2:PLAN] Then I'm going to try to make steps, so he can get out. [IMPORTANT]

Prevalence of simultaneous EDP phases. It was very natural for children of all ages to do concurrent EDP phases when building with LEGO. That is, students easily talked about one EDP phase while performing another one with their hands. This was a widespread phenomenon. There did seem to be a range of responses in terms of the ability of students to talk aloud and build at the same time. Some students like Boy 4 struggled to talk aloud and build at the same time while others, Girl 5, for example, could build, talk aloud, and plan (or otherwise engage in separate talk and build EDP phases) easily at the same time. Girl 5 was even seen searching for parts with two different hands simultaneously. The methodology used in this study (or another like it) that accounted for separate EDP phases would be required for any similar research if an accurate picture of students' EDP processed is desired.

Transition rates. Transition rate is defined as the average number of EDP phases changes per unit time. Some researchers (Atman et al., 2008, 2005) have found that higher transition rates are a positive factor in engineering processes of undergraduate students. This result was not found in either grade 2 or grade 6 elementary students. See Figure 105. No relationship was discerned between transition rates and other factors for the students in this study.

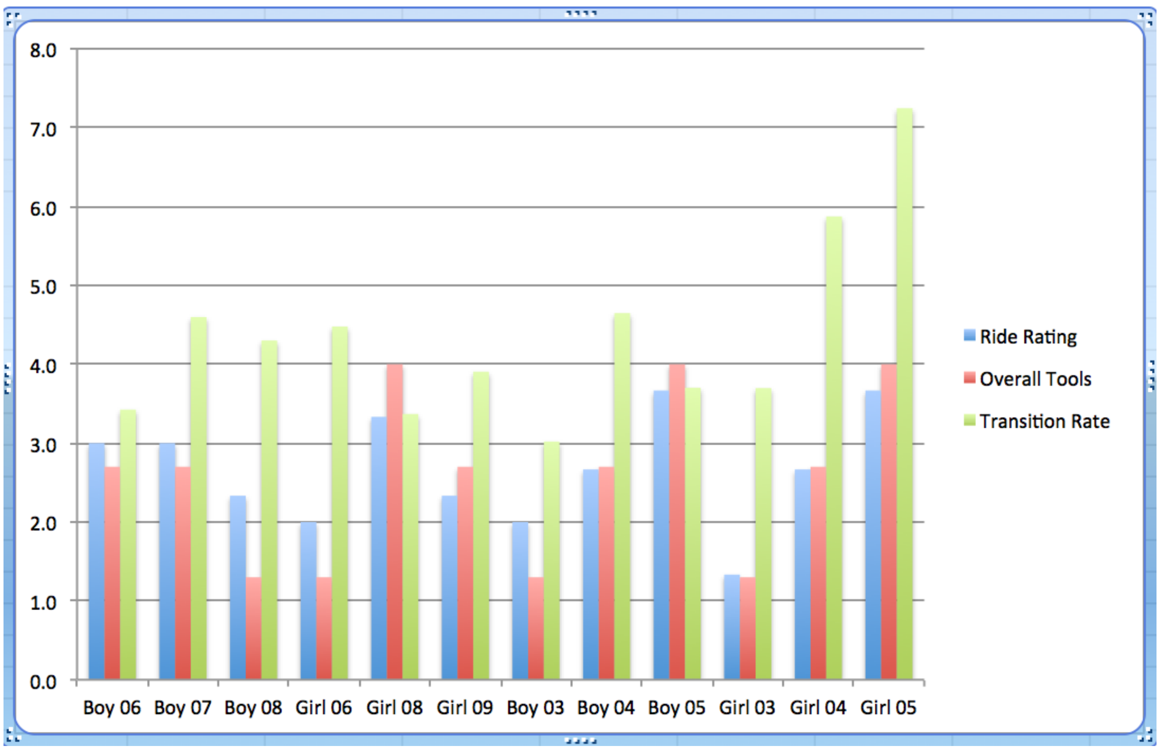


Figure 105. Transition rates versus overall tools and ride rating.

Role of imagination. Students' choices in this study in some cases met their needs perfectly but would not have met the expectations of teachers or expert LEGO builders. For example, the roller coaster of Boy 3 had LEGO pieces laid down freely on the table without even being connected. Three students did not use a motor in their designs. Students were also fine with the filling in of important details with their imaginations. For example, Boy 04 uses an impromptu wheel as a cart when asked to demonstrate ride at the end. Girl 9's ride was not really functional but she felt that is was close enough and could be imagined. Here is how she explains this.

> [00:20:30] [2:PLAN] Girl 09: Uh-huh. I think it's going to move. I don't know how to make it move this. It's probably just going to make it so the handle spins. [IMPORTANT] [PROJECTION=]

Perhaps on their own, students recreated as well as they could their own internal representations of ride, rather than trying to represent the adult, "accurate", actual ride. This is also another example of kids being fine with not having things work in a way that would be important for adults. As our final example, Girl 6 explains that a detail she could not build will be put in her post make drawing and that will meet her needs.

> [00:22:31] Girl 06: I can do it when I'm drawing it.   [IMPORTANT]

Teachers should be aware of this difference in how the models are viewed and be tolerant, to the extent possible, of student imagination in filling in important details in their work.

Role of teacher prompts. As in the pilot study, teacher scaffolding in the form of a neutral suggestion or question triggered learning. Girl 5 does not understand why her geared up ride had fifty rotations when she programmed ten rotations, at least initially. I suggested she count the other seat instead, which was directly coupled and which I knew would rotate ten times. This caused an important learning moment where she figured out the relationship between number of rotations and gearing up. At another point in her build, I restated a science concept about gearing up that she has articulated previously. This also caused her to solve her design issue. This shows that teachers should be aware that simply restating information or asking questions can trigger significant and deeper learning than might be obtained from giving the answer to the student.

Limitations of Study

Methodology limitations. The coding of the engineering design process of students is an approximation and it is not possible to be 100% accurate because some building and verbal moves could be interpreted in different ways. However, the IRR showed consistent interpretation across multiple students. Also, students did not always verbalize their thinking perfectly. But the use of the dual physical track helped to ameliorate this limitation.

Mixing VPA and clinical interview techniques is also limitation of this study since there were cases where the clinical interview questions could influence the process. For example, my scaffolding questions that triggered learning in Girl 5 would not be considered a pure VPA where the researcher only asks what the subject is thinking. However, the additional information gained from the clinical interview question was worth any possible distortion in the students' processes. The varying ability of students to verbalize their thinking is also a possible source of some error.

Small sample size. The small sample size of twelve was also a limitation of this study. However, the time involved to segment, code, and process the video was already substantial and is a limitation of this kind of research (Atman & Bursic, 1998). It was also a challenge to find qualifying, typical students at the small rural school and the makeup of the students was in this small, rural public school not typical of many public schools.

Session Time. The fact that I had to videotape twelve students "in my spare time" given the other demands of my position created some pressure for students to finish their builds. Ideally, there would have been less pressure and more time for students to work on their designs. Some creativity such as complex programs and sounds may have been limited by the single session time limit. Students typically do more finishing touches in the classroom setting when they have more time.

Future Research

Further analysis of subcodes and secondary codes. Time constraints precluded a full analysis of subcodes and secondary codes. However, the rich data set offers potential for further analysis of subcodes such how much students built versus rebuilt, for example. The secondary coding, which was partially completed also could offer additional insights into the causal reasoning, creative play, and other aspects of EDP of the different students.

Relative importance of different factors. The relative importance of the different factors identified in this study is unknown and could be a topic for future research. For example, structural knowledge seems more important than both design principles and application of mathematics and science but the exact relationships are not known. Furthermore, future research could untangle some of these dependencies between some of the factors. For example, there seems be a dependency between structural knowledge and causal reasoning.

Segmenting data. The segmenting data could provide additional insights into LEGO building. For example, even the simple aggregating of time spent in different physical activities looked at by different independent variables such as gender grade level, ride rating, and overall tools could provide insights into the efficacy of different physical move profiles.

Planning types. Additional codes for different types of planning could be useful in future research to differentiate long and short term planning. This could be added to the EDP timeline to further differentiate short (serial) and long term (system) planning and EDP styles in general.

CHAPTER 7

CONCLUSION

Development and gender were not significant factors in determining the EDP or the success of designs in this study with the exception of executive functions such as causal reasoning, which, in particular, showed some evidence of an age related component. Elementary students' engineering design processes (EDP) were defined instead by build complexity and the overall tools that students brought to the task. These tools were found to be structural knowledge of LEGO and a combination of executive function (casual reasoning, planning ability, and cognitive flexibility) and domain specific process skills (EDP process knowledge, application of design principles of stability, symmetry, and scale, and application of mathematics and science). Note that three of these - structural knowledge, EDP process knowledge, and design principles - were found in the literature review as being utilized by experts. Since these particular factors did not appear to be developmental, this suggests that they could be taught to students explicitly. Additional research is needed to determine more accurately the relative importance of the different factors. See Figure 106 for a diagram of these key factors.

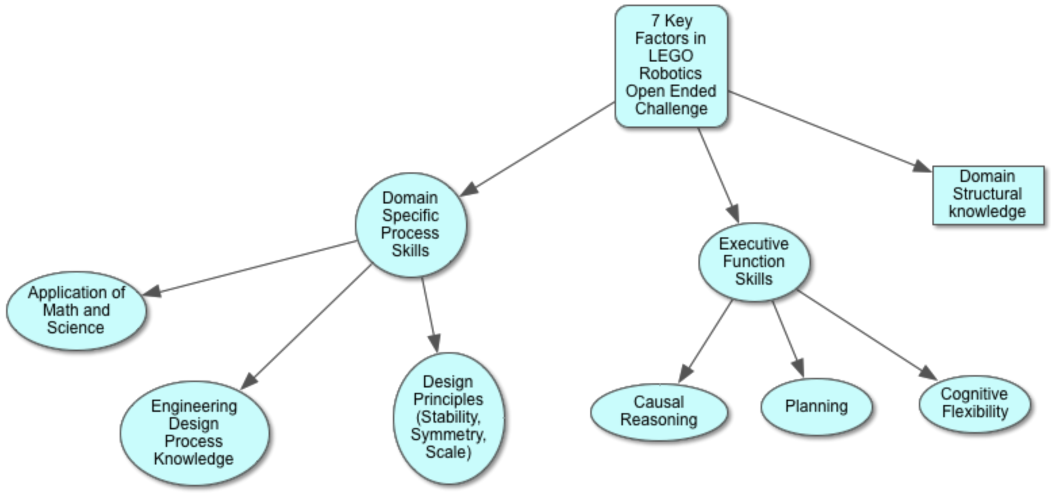


Figure 106. Key factors found in study.

What are the primary implications of these findings? Students with high tools that choose a low complexity build had an idealized EDP without much need to research or evaluation. These students need a more challenging assignment. Students with low tools and a high complexity build may get stuck in research and may need scaffolding in planning, structural knowledge or other process skills. Other educational implications were found primarily on how to effectively scaffold the various process skills. For example, neutral questions or restating knowledge can trigger deep student learning.

Elementary engineering based on LEGO robotics in a K-6 yearly program showed rich affordances to develop student engineering and executive function skills. While not a part of this study, students also develop 21st century skills of collaboration, communication, and creativity. Additionally, students have shown high interest and enthusiasm for these open-ended engineering challenges based on LEGO and programming. My hope is that this study has provided significant characterization, insight, and implications for teaching elementary engineering to help sustain the natural interest and ability of young children to design, build, and program to help overcome the complex problems of today.

APPENDIX A

CODE BOOK

DESIGN ATTRIBUTES

These codes describe the prototype at the end of the session.

DESIGN ATTRIBUTES - specific attributes of the design that can indicate the complexity or other aspects of the prototype.

- NUMBER-PARTS - number of parts used in final prototype.
- NUMBER-STEPS - number of steps/blocks in final program.
- CREATIVITY - subjective rating of whether design did (or did not) shown originality (4 highest to 1 lowest)
- FUNCTIONALITY - rating of how well the ride meets the design criteria.
- PROCESS - rating of the subject's engineering design process specifically with respect to causal reasoning and planning (4 highest to 1 lowest)
- RATING - overall rating using a rubric; mean of above 3 aspects - creativity, functionality, and process (4 highest to 1 lowest)
- STABLE - final design is stable (1/0)
- SYMMETRICAL - final design is symmetrical (1/0)
- SCALE - final design is to scale (1/0)
- USE-COMPUTER - subject used the computer to animate the prototype. (1/0)
- USE-CRAFTS - the subject used craft materials (includes blocks) in the prototype. (1/0)
- USE-DIRECT-COUPLING - the ride uses direct coupling of motor to axle to move. (1/0)
- USE-GEARS - the ride uses gears to move. (1/0)
- USE-MOTOR - the rides uses a motor. (1/0)
- USE-PULLEYS - the ride uses pulleys between to move. (1/0)
- USE-SENSOR - the ride uses a sensor. (1/0)
- USE-PLANNING - the student produced planning artifacts on paper before building. Post-make builds are not counted. (1/0)
- TIME - elapsed time of build. Not judged in any way but captured as a possible item of interest.

ENGINEERING DESIGN PROCESS PHASES

These codes describe the engineering design process. In the case of clear, overlapping design phases, code the verbal with [2:*name*] and then indicate the end with [2:END] Code the end of the session as [END], which is normally the start of the post-interview. If the subject starts building again during the post-interview, delay the end until building is complete and code that building.

BUILD-NORMAL - normal building, which includes looking for parts unless the looking for parts was researching the feasibility of a potential design or subsystem. If the subject is describing what they are doing now, count as building and not planning. The use of present tense verbs help indicate building. Count cleaning up and organizing as BUILD-NORMAL. Measuring a part by comparing it in place is part of building and not RESEARCH. Referring to a plan (drawing) to build is BUILD-NORMAL.
BUILD-REBUILD - rebuilding (fixing) something that built previously. This includes building it in a different way as well as reattaching a subsystem that fell off for example.
EVALUATE-PHYSICAL - evaluate model by testing physically. Trying out pieces in place (without connecting them) to see if they will work is counted as RESEARCH.
EVALUATE-VERBAL - evaluate model without any physical test by talking. Include comments about the process.
EVALUATE-VISUAL - evaluate model by looking without touching or talking.
EVALUATE-SYSTEM - evaluate the whole system including the program by running the program.
PLAN - subject was planning some aspect of their design, typically verbally. Do not count describing what the subject is currently building. That should be coded as building. If the subject is verbalizing what they are planning to build in the future, even if it is the immediate future, count as planning. The use of future tense verbs help indicate planning (for example, "I will …", "I am going to", etc.). Plan can include giving rationale for their plan, demonstrating their plan, or evaluating the plan itself (such as drawings). Sometimes planning can be inferred depending on the surrounding activity when the physical activity segment is coded as no_activity and the subject is not talking. If subject verbalizes the need for the next, identified, single part, count that as BUILD (for example, "I need another one of these"). If they verbalize the possible use of a single part ("I could use this one at the end" for example), count as PLAN. If they verbalize the need for more than one part, count as PLAN.
PROBLEM-SCOPING - subject tries to clarify the problem as defined by the researcher, typically by asking a question and/or gathering more information about the problem (not about a possible solution, which is research). Include questions about the process.
PROGRAM-NORMAL - Programming the robot. Connecting the USB cable and downloading programs (for NXT) are counted as PROGRAM-NORMAL.
PROGRAM-REPROGRAM - Fixing a previous program.
RESEARCH - researching a problem or possible solution. Looking for parts can be considering research if it is affecting major design decisions before building starts or during the build. Otherwise, consider it part of building. If there is a small, separate builds to test out a possible solution, code that as research. When the small, separate build is evaluated, consider that research as well. Trying out pieces in place (without actually connecting them) with the intent of evaluating for suitability is considered research. However, do not count measuring a part by comparing it in place, which is part of building.
SHARE-OUT - the student is sharing out without being prompted. Normally not used since sharing out is part of the post interview. However, this should be used if the student is sharing out unprompted or is prompted but later starts building again. Specifically, use this code if the subject is making post-make drawings.

DESIGN PROCESS - Strengths and Challenges

These categories and codes describe behaviors seen during the design process that relate to strengths and challenges during the task. Codes *in italics* were added from theoretical frameworks or existing research.

CAUSAL REASONING - subject exhibiting aspects of causal reasoning. Some codes have values of + (successful), - (unsuccessful), or = (neither successful or unsuccessful).

- *CONTROL-VARIABLES* - subject attempted to control variables to isolate a cause. (+/-/=)
- *INFERENCE* - subject made a inference as to why something occurred, typically while troubleshooting. (+/-/=)
- *MAGICAL-THINKING* - subject attributed an effect to a magical cause.
- *MULTIVARIATE-REASONING* - subject attempted to deal with multiple variables at the same time. (+/-/=)
- PROJECTION - A simple cause and effect projection. X will happen because of Y. In the pilot study, there was a separate code for significant incorrect projections. These will be noted as -- here. (+/-/=)
- *SYSTEMS-THINKING* - the subject showed an understanding of the complete system he or she designed and how the different subsystems interrelate. (+/-/=)

DESIGNERLY PLAY - exhibiting explicit signs of designerly play

- CREATIVE-PLAY - subject shows creative play by using mini-figures, verbalizing story lines, etc.
- TALK-TO-ROBOT - the subject talked to the robot as if it were a living being. This is also known as anthromorphisation.
- PLAYFUL-TALK - elements of "humor, puns, teasing, music making, and other word play"

DESIGN PRINCIPLES- codes indicating aspects of design noted. Some codes have values of + (successful), - (unsuccessful), or = (neither successful or unsuccessful).

- SCALE - student was concerned about the proper scale of his/her design.
- STABILITY - the subject was concerned with stability issues or the design had stable or unstable attributes.
- SYMMETRY - Subject built symmetrically or is concerned about symmetry or balance. Negative sign indicates that asymmetrical qualities of the design were noted.

DESIGN PROCESS - codes indicating aspects of the design process noted.

- CONNECTOR-META - subject showed structural or meta knowledge of LEGO connectors either verbally or clearly demonstrated in their building process. (+/-/=)

- IDEA-FIRST - subject indicated verbally that they were looking for specific parts to instantiate a design idea.
- PARTS-FIRST - subject indicated verbally that they were looking at parts to help them come up with a design idea.
- PLAN-AHEAD - subject is (or is not planning ahead). Serial builders do not plan ahead. Other builders look ahead and identify subsystems that will be needed ahead of time. = indicates some evidence of near term planning ahead. (+/-/=)

PHYSICAL - codes indicating challenges with the physical aspect of building

- FINE-MOTOR - subject exhibits difficulty with fine motor operations such as attaching LEGO pieces.

PROBLEM-SOLVING - codes indicating some secondary aspect of problem solving as seen in the context of a robotics open-ended challenge. Most codes have values of + (successful), - (unsuccessful). If unsuccessful, they used the strategy but it did not help or actually hurt their efforts.

- *ATTEND-CONSTRAINTS* - subjects attending (or not) to the constraints of the problem (ride is specified to be safe and interesting). (+/-)
- MATH - student used math to help solve a problem. (+/-)
- PERSISTENCE - the subject was persistent in solving a problem. Note that, as seen in the pilot study, this can be non-optimal if the subject needs to do a significant redesign and is reluctant to do so. + also indicates flexibility in terms of "starting from scratch" if an idea is not working. (+/-)
- PROBLEM-SOLVED - subject solved or did not solve a significant problem that was encountered and a solution attempted (+/-)
- SCIENCE - the student used science to help solve a problem. (+/-)
- SEQUENCING - the subject was concerned with building or programming in a certain order required to solve the problem. (+/-)
- TROUBLESHOOTING-TACTIC - the subject used a general purpose tactic for troubleshooting, such as stepping back to examine their design, looking at a design from different angles, or using the WeDo or NXT connection information for troubleshooting. The exact tactic used is noted. (+/-)
- *SYSTEMIC-TESTING* - subject used a through and systemic plan for testing the system. (+/-)

SUBJECT ATTRIBUTES - attributes of the subject determined by interview or by classroom and technology teacher

- GRADE- second or sixth (2 or 6)
- GENDER- male or female (M or F)
- LEGO experience at home - (1 or 0)
- SELF-EFFICACY - self-reported confidence in building and programming LEGO robots (1 low to 5 high)

RESEARCH PROCESS

These codes indicate something about the research process itself.

- HELP - The researcher gave help to student. This is noted as a code so it will not be counted as an action of the subject.
- IMPORTANT - an important and significant event occurred that might benefit from further analysis.
- WAIT - student had to wait for researcher or was temporarily interrupted in some way for at least 2 seconds. This can also include side talk with the researcher that is not related to the experiment. For example, use this code when the researcher paused the student to take a photograph. This is used so that this time is not counted in any analysis.

UNUSED

- SEMI-CONCRETE - A semi-concrete projection or test, where the subject, for example, brings a part up to another part to evaluate whether it will fit but does not end up needing to put the part wholly next to the other part. (+/-)

APPENDIX B

RESEARCH PROMPT

Research Prompt

[Student's name], I asked you to join me to help me with some of my homework for my own schoolwork. My homework is to better understand how kids design and build robots at different ages. [For returning students only: You may remember working with me last year on an amusement park ride.]

To better understand what you are thinking, I am going to ask you to talk out load as you work so I understand what you are doing and thinking. I may also ask you other questions if I am not sure what you are doing or thinking.

Have you ever been to a fair or amusement park? What rides do you like? [Make sure student understands what an amusement park ride is.]

You will now build a model amusement park ride. It can be like a ride you have been on before or it can be one you make up using your own imagination. You may want to use paper to draw pictures or write words that help to plan what you are going to build. You can also tell me in your own words what you are planning to build, if you know that ahead of time.

You can use any of the materials you see. [Show student LEGOs, craft materials, wooden blocks.] You may also use a computer laptop to program your ride with motors, sounds, or sensors.

You will have about 1 hour to build your model amusement park ride.

Are there any questions before you start?

APPENDIX C

PERMISSION LETTER

ELEMENTARY ROBOTICS CASE STUDY
University of Massachusetts, Amherst

CONSENT FOR VOLUNTARY PARTICIPATION

My child ____ may participate in this study. I understand that:

1. My child will be asked to build a robotics project for approximately one hour. The researcher will be present with my child and will ask questions while he or she builds.
2. The questions your child will be answering will attempt to determine my child's goals, processes, and thinking related to my child's building and programming. The purpose of the research is to characterize students' robotics engineering skills as they go progress in age.
3. My child will be videotaped for subsequent analysis.
4. My child's name will not be used nor will he/she be identified personally, in any way or at any time.
5. I may withdraw my child from all or part of the study at any time.
6. I have a right to review the material prior to any publication of the results.
7. I understand that the results from the study my be included in John Heffernan's comprehensive examination papers, doctoral dissertation, and may also be included in manuscripts submitted to professional journals for publication.
8. My child is free to participate or not to participate without prejudice.
9. Because of the small number of participants, approximately two, I understand that there is some small risk that my child may be identified as a participant in this study.

If you have questions or comments regarding this study, please feel free to contact John Heffernan. John Heffernan's phone number is 413-320-5816 and email address is jheffernan@hr-k12.org. You may also contact John Heffernan's chairperson, Dr. Florence Sullivan, at (413) 577-1950, fsullivan@educ.umass.edu, or Dr. Linda Griffin, Associate Dean for Academic Affairs and Graduate Program Director at 413-545-6985 or lgriffin@educ.umass.edu.

____
Participant's Signature   Date

____
Researcher's Signature   Date

APPENDIX D

WARM UP TASK RUBRIC

	Below Grade 2	**Typical Grade 2**	**Typical Grade 6**	**Above Grade 6**
	1	**2**	**3**	**4**
Time to Complete	More than 15 minutes	10-15 minutes	5-10 minutes	Less than 5 minutes
Functionality	Roof does not hold the load.	Roof holds the load but is not sturdy. Roof is not flat.	Roof holds the load and is sturdy. Roof is fairly flat.	Roof is completely flat; roof holds the load and is very sturdy. Roof is aesthetically pleasing.
Engineering Process	All trial and error. No evidence of planning or causal reasoning. Cognitive inflexibility evident.	Mostly trial and error with some evidence of planning and causal reasoning. Some evidence of cognitive inflexibility.	Evidence of planning and causal reasoning. Cognitive flexibility evident.	Clear evidence of planning and causal reasoning. Clear evidence of cognitive flexibility. Applies math or science to problem.

APPENDIX E

FINISHED MODEL DESIGN QUALITY RUBRIC

	1	**2**	**3**	**4**
Originality	Design clearly derivative or a copy of a design already used. Design is not animated with computer and robotic elements. No decorative elements or mini-figure use.	Design is animated with computer and robotic elements with one-step simple program. One decorative elements or mini-figure use. [If not animated, has some detailed build work.]	Design is animated with computer and robotic elements and multi-step program. Some decorative elements or mini-figure use. [If not animated, has detailed build work.]	Recorded own sound(s). Decorated with craft materials. Very inventive design. Creative use of mini-figures and additional ride elements. Design is animated with computer and robotic elements and complex program.
Functionality	Design neither safe nor interesting. Very unstable design. Not to scale. No concern for symmetry. Could not finish.	Design is safe or interesting. Design somewhat unstable. A few elements of appropriate scale or symmetry. Met some elements of challenge and works to some extent.	Design is safe and interesting. Design is basically stable. Design has some appropriate elements of symmetry and scale. Met basic requirements and is functional.	Design is safe and interesting. Design is very stable. Design symmetrical (if appropriate) and to scale. Use of gears and/or pulleys. Goes beyond basic requirements and works very well.
Engineering Process	All trial and error. No evidence of planning or causal reasoning. Cognitive inflexibility evident.	Mostly trial and error with some evidence of planning and causal reasoning. Some evidence of cognitive inflexibility.	Evidence of planning and causal reasoning. Cognitive flexibility evident.	Clear evidence of planning and causal reasoning. Clear evidence of cognitive flexibility. Applies math or science to problem.

APPENDIX F

CODE SCANNER PROGRAM

```
import string
import re # regular expressions
from datetime import datetime

## This program takes a text file exported from Word and checks all the codes and
timestamps for proper format.
##
## 1) Maincodes:  EDP codes such as PLAN, BUILD, RESEARCH along with
timestamps and durations.
## 2) Subcodes:  EDP codes such as PLAN, BUILD-NORMAL, BUILD-REBUILD, abd
RESEARCH along with timestamps and durations.
## 3) Secondary (or non-EDP)  codes:  related phenomonon such causal reasoning,
designerly play, and problem solving codes such as PROJECTION, INFERENCE,
CREATIVE-PLAY.  Some
## of these have values such as +, -, and =.
##
## This program was created as part of a dissertation research project that seeks to
understand elementary
## engineering processes.
##
## Author:  John Heffernan
## Date:  May 21, 2016
##

## Function to get secondary code value, if any.  Returns None is none present.
Secondary codes can have another hyphen so just extract the last one.
## Example:  [SYSTEMS-THINKING-]


## Function to output an error of the transcript coding and the line.
def printError (error, line):
	print (error + ' in line ' + line + '\n' )
	fouterror.write (error + ' in line ' + line + '\n' )


# Open the transcript file with read only permissions.  File should be plain text, MAC
OS, Western, Boy LF but
# 'End Lines With Line Feeds" box not checked.  Export from Word.  Open all the error
file.

showLine = False
print ('CODE SCANNER')
```

```
genderNumber = input ("Gender space Number?")
inputfilename = genderNumber  + ' Ride Transcript CD.txt'
errorfilename = genderNumber + 'Errors.txt'
fin = open(inputfilename, 'r', encoding='latin-1', errors='backslashreplace')
fouterror= open (errorfilename, 'w')


## Construct a regular expression for the timestamps.

timestampRE = r"""\[0[0-1]:[0-5][0-9]:[0-5][0-9]\]"""

## Construct a regular expression for the EDP codes and concurrent EDP codes.

codesEDP = r"""\[BUILD-NORMAL\]|\[BUILD-REBUILD\]|\[EVALUATE-
PHYSICAL\]|\[EVALUATE-VERBAL\]|\[EVALUATE-VISUAL\]|\[EVALUATE-
SYSTEM\]|\[PLAN\]|\[PROBLEM-SCOPING\]|\[PROGRAM-
NORMAL\]|\[PROGRAM-REPROGRAM\]|\[RESEARCH\]|\[SHARE-
OUT\]|\[WAIT\]|\[END\]|"""
codesEDP2 = r"""\[2:EVALUATE-VERBAL\]|\[2:PLAN\]|\[2:PROBLEM-
SCOPING\]|\[2:SHARE-OUT\]|\[2:END\]|"""

## Construct a regular expression for transcription notes.
transcription = r"""\[inaudible.*?\]|\[crosstalk.*?\]|"""

##  Construct a regular expression string for the secondary codes.
codesCR = r"""\[CONTROL-VARIABLES[+-=?]\]|\[INFERENCE[+-=?]\]|\[MAGICAL-
THINKING\]|\[MULTIVARIATE-REASONING[+-=?]\]|\[PROJECTION[+-
=?]\]|\[SYSTEMS-THINKING[+-=?]\]|"""
codesPlay = r"""\[CREATIVE-PLAY\]|\[TALK-TO-ROBOT\]|\[PLAYFUL-TALK\]|"""
codesDesign = r"""\[SCALE[+-=?]\]|\[STABILITY[+-=?]\]|\[SYMMETRY[+-=?]\]|"""
codesProcess = r"""\[CONNECTOR-META[+-=?]\]|\[PARTS-FIRST\]|\[IDEA-
FIRST\]|\[PLAN-AHEAD[+-=]\]|"""
codesPhysical = r"""\[FINE-MOTOR\]|\[IMPORTANT\]|\[HELP\]|"""
codesProblem = r"""\[ATTEND-CONSTRAINTS[+-=?]\]|\[MATH[+-
=?]\]|\[PERSISTENCE[+-=?]\]|\[PROBLEM-SOLVED[+-=?]\]|\[SCIENCE[+-
=?]\]|\[SEQUENCING[+-=?]\]|\[TROUBLESHOOTING-TACTIC[+-
=?]\]|\[SYSTEMIC-TESTING[+-=?]\]|"""
codes = codesCR + codesPlay + codesDesign + codesProcess + codesPhysical +
codesProblem + codesEDP + codesEDP2 + transcription + timestampRE

## Construct more general RE for [anyText]

possibleRE = r"""\[.*?\]"""

## print (codes)
```

```
pattern = re.compile(codes)
possiblePattern = re.compile (possibleRE)

## print (pattern)
## If the file is not empty keep reading line one at a time
## until the file is empty

## Read the first line
line = fin.readline()
FMT = '%H:%M:%S'

while line:
	if showLine :
		print ('------------------')
	if showLine:
		print (line)
	if showLine:
		print ('------------------')
	if len (line) > 1 :
	## Get array of [anyText] for each line and see if each one is syntactically correct.
If not, issue and error.
		possibleCodes  = re.findall (possiblePattern, line)
		if possibleCodes :
			for currentCode in possibleCodes :
				## print ('Current code: ' + currentCode)
				## Get any value if present
				match = re.findall (pattern, currentCode)
				if not match :
					printError ("Bad code: " + currentCode, line)

		##print nonedplist
	line = fin.readline()
fin.close()

fouterror.close ()
print ('Processing ' + inputfilename + ' complete')
```

APPENDIX G

CODE EXTRACTION PROGRAM

```
import string
import re # regular expressions
from datetime import datetime

## This program takes a text file exported from Word and extracts all the research codes
and timestamps into a format that can be imported into
## EXCEL for further analysis.  3 files are produced along with an error log.
##
## 1) Maincodes:  EDP codes such as PLAN, BUILD, RESEARCH along with
timestamps and durations.
## 2) Subcodes:  EDP codes such as PLAN, BUILD-NORMAL, BUILD-REBUILD, abd
RESEARCH along with timestamps and durations.
## 3) Secondary (or non-EDP)  codes:  related phenomonon such causal reasoning,
designerly play, and problem solving codes such as PROJECTION, INFERENCE,
CREATIVE-PLAY.  Some
## of these have values such as +, -, and =.
##
##This program was created as part of a dissertation research project that seeks to
understand elementary
## engineering processes.
##
## Author:  John Heffernan
## Date:  May 7, 2016
##

## Function to get secondary code value, if any.  Returns None is none present.
Secondary codes can have another hyphen so just extract the last one.
## Example:  [SYSTEMS-THINKING-]

def getSecondaryCodeValue (currentCode, line):
    ## print (currentCode + "  " + line )
    if '+]' in currentCode :
        return '+'
    if '-]' in currentCode :
        return '-'
    if '=]' in currentCode :
        return '='
    if '?]' in currentCode :
        printError ("Warning:  secondary code needs value: " + currentCode, line)
        return '?'
    return None
```

```
## Function to output an error of the transcript coding and the line.
def printError (error, line):
	print (error + ' in line ' + line + '\n' )
	fouterror.write (error + ' in line ' + line + '\n' )

## Function to check for and return an full code and subcode.
def getEDPCode (line ) :
	if '[BUILD-NORMAL]' in line :
		return 'BUILD-NORMAL'
	if '[BUILD-REBUILD' in line:
		return 'BUILD-REBUILD'
	if  '[EVALUATE-PHYSICAL]' in line :
		return 'EVALUATE-PHYSICAL'
	if '[EVALUATE-VERBAL]' in line  :
		return 'EVALUATE-VERBAL'
	if '[EVALUATE-VISUAL]' in line  :
		return 'EVALUATE-VISUAL'
	if '[EVALUATE-SYSTEM]' in line :
		return 'EVALUATE-SYSTEM'
	if '[PLAN]' in line :
		return 'PLAN'
	if '[PROGRAM-NORMAL]' in line :
		return 'PROGRAM-NORMAL'
	if '[PROGRAM-REPROGRAM]' in line  :
		return 'PROGRAM-REPROGRAM'
	if '[RESEARCH]' in line  :
		return 'RESEARCH'
	if '[SHARE-OUT]' in line :
		return 'SHARE-OUT'
	if '[WAIT]' in line  :
		return 'WAIT'
	return None

## Function to translate main string code to a number code used by Excel to graph the
EDP.
def getExcelCode (stringCode, line) :
	if 'PLAN' in stringCode :
		return '6'
	if 'RESEARCH' in stringCode :
		return '5'
	if 'BUILD' in stringCode :
		return '4'
	if 'PROGRAM' in stringCode :
		return '3'
	if 'EVALUATE' in stringCode :
		return '2'
```

```
        if 'SHARE' in stringCode :
                return '1'
        if 'WAIT' in stringCode :
                return '0'
        printError ('Unknown string code', line )
        return None

## Function to look for and return  a secondary (or concurrent) EDP phase.  This should only happen with verbal
## output but the code checks all EDP phases even BUILD and the like and issues a error message in that case.
def getEDPSCode (line ) :
        if '[2:BUILD-NORMAL]' in line :
                printError (error, line)
                return 'BUILD-NORMAL'
        if '[2:BUILD-REBUILD' in line:
                printError (error, line)
                return 'BUILD-REBUILD]'
        if  '[2:EVALUATE-PHYSICAL]' in line :
                printError (error, line)
                return 'EVALUATE-PHYSICAL'
        if '[2:EVALUATE-VERBAL]' in line  :
                return 'EVALUATE-VERBAL'
        if '[2:EVALUATE-VISUAL]' in line  :
                return 'EVALUATE-VISUAL'
        if '[2:EVALUATE-SYSTEM]' in line :
                printError (error, line)
                return 'EVALUATE-SYSTEM'
        if '[2:PLAN]' in line :
                return 'PLAN'
        if '[2:PROGRAM-NORMAL]' in line :
                printError (error, line)
                return 'PROGRAM-NORMAL'
        if '[2:PROGRAM-REPROGRAM]' in line  :
                printError (error, line)
                return 'PROGRAM-REPROGRAM'
        if '[2:RESEARCH]' in line  :
                printError (error, line)
                return 'RESEARCH'
        if '[2:SHARE-OUT]' in line :
                return 'SHARE-OUT'
        if '[2:WAIT]' in line  :
                printError (error, line)
                return 'WAIT'
        if '[2:END]' in line  :
                return 'END'
```

```
        return None

def extractMainCode (code) :
## Gets main code from full code with subcodes.  For example, EVALUATE-
PHYSICAL becomes EVALUATE.
## Subcodes are separated from main code by a hyphen.  Some codes do not have
subcodes.  PLAN is an
## example.

        if '-' in code :
                maincode = code.split('-')
                return maincode[0]
        return code

def strip (text) :
## Strip out square brackets from a string
        code = text.strip ('[]')
        return code

def stripS (text) :
## Strip out square brackets from a secondary code string, which can have a value at the
end.
        code = text.strip ('[+-=?]')
        return code

def strip2 (text) :
## Strip out square brackets and secondary code indicater from a string
        code = text.strip ('[2:]')
        return code

# Open the transcript file with read only permissions.  File should be plain text, MAC
OS, Western, Boy LF but
# 'End Lines With Line Feeds" box not checked.  Export from Word.  Name and open all
the output files.

showLine = False
genderNumber = input ("Gender space Number?")
## genderNumber ='Boy 05'
## genderNumber ='Girl 06'
## genderNumber = 'Girl 08'
inputfilename = genderNumber  + ' Ride Transcript CD.txt'
outsubfilename = genderNumber  + 'Subcodes.txt'
outmainfilename = genderNumber  + 'Maincodes.txt'
outnonedpfilename = genderNumber  + 'NonEDPCodes.txt'
errorfilename = genderNumber + 'Errors.txt'
fin = open(inputfilename, 'r', encoding='latin-1', errors='backslashreplace')
```

```
foutsub = open (outsubfilename, 'w')
foutmain = open (outmainfilename, 'w')
foutnonedp = open (outnonedpfilename, 'w')
fouterror= open (errorfilename, 'w')


## Read the first line
line = fin.readline()

##  Construct a regular expression string for the secondary codes.
codesCR = r"""\[CONTROL-VARIABLES[+-=?]\]|\[INFERENCE[+-=?]\]|\[MAGICAL-
THINKING\]|\[MULTIVARIATE-REASONING[+-=?]\]|\[PROJECTION[+-
=?]\]|\[SYSTEMS-THINKING[+-=?]\]|"""
codesPlay = r"""\[CREATIVE-PLAY\]|\[TALK-TO-ROBOT\]|\[PLAYFUL-TALK\]|"""
codesDesign = r"""\[SCALE[+-=?]\]|\[STABILITY[+-=?]\]|\[SYMMETRY[+-=?]\]|"""
codesProcess = r"""\[CONNECTOR-META[+-=]\]|\[PARTS-FIRST\]|\[IDEA-
FIRST\]|\[PLAN-AHEAD[+-=]\]|"""
codesPhysical = r"""\[FINE-MOTOR\]|"""
codesProblem = r"""\[ATTEND-CONSTRAINTS[+-=?]\]|\[MATH[+-
=?]\]|\[PERSISTENCE[+-=?]\]|\[PROBLEM-SOLVED[+-=?]\]|\[SCIENCE[+-
=?]\]|\[SEQUENCING[+-=?]\]|\[TROUBLESHOOTING-TACTIC[+-
=?]\]|\[SYSTEMIC-TESTING[+-=?]\]"""
codes = codesCR + codesPlay + codesDesign + codesProcess + codesPhysical +
codesProblem
## print (codes)

pattern = re.compile(codes)
##print (pattern)
## If the file is not empty keep reading line one at a time
## until the file is empty
prevcode = ""
prevmaincode = ""
firstCode = True
prevtime = ''
FMT = '%H:%M:%S'
##  Keep expected EDP concurrent or secondary EDP phase state so coding errors can be
detected (2 ENDs in a row or 2 codes in a row (missing END))
store = 1
end = 2
expectedSPhase = store
## Write header row to EDP files.
foutsub.write ('Time,Elapsed,Code \n')
foutmain.write ('Time,Elapsed,Code,Code \n')
while line:
```

```
        ## Is this a timestamp?  11 below should be 10 but Python seems to count LR/CR
but not indexable
        if showLine :
            print ('------------------')
        if showLine:
            print (line)
        if showLine:
            print ('------------------')
        if len (line) > 1 :
            ## print (len (line) )
            if line[1] == '[' :
                printError ('timeStamp Error', line)

        ##  If we have a timestamped line
        if len(line) >= 11 and line[0] == '[' and line[1].isdigit() :
            ## print len (line)
            ## print line
            ##  See if any of our EDP codes are here.  First, check for a main EDP phase.
Then for a concurrent or secondary EDP phase.
            ##  Note that you could have one of each in the same line.
            time = line[1:9]
            code = getEDPCode (line)
            if code :
                time = line[1:9]
                ## Primary EDP phase.  Since we need the elapsed time, we need to write
out the previous code when the next EDP phase is detected.
                ## the current code and time becomes the previous time.
                ## print ("TIME: " + time, "PREVTIME: " , prevtime)
                ## print ("got EDP code")
                ## print m[0]
                ##print timestamp
                ##  Write out full EDP code such as BUILD-NORMAL
                ## print ('FC: ' ,  firstCode)
                maincode = extractMainCode (code)
                if not firstCode :
                    delta = datetime.strptime(time, FMT) - datetime.strptime(prevtime,
FMT)
                    if delta.days < 0 :
                        printError ('Negative elapsed time', line)
                    deltaStr = str(delta)
                    timestamp = prevtime + ',' + deltaStr + ',' + prevcode + '\n'
                    foutsub.write (timestamp)
                    ## print ('------')
                    ## print ('PREVIOUS: ', prevcode)
                    ## print ('CURRENT: ' , maincode)
                    ## print ('------')
```

```
                    ##print out main codes only if not the same as previous code such as
BUILD because 2 full codes could have the same main code.
                    if maincode != prevcode :
                        timestamp = prevtime  + ','  + deltaStr + ',' + prevmaincode + ','
+ getExcelCode(prevmaincode,line) + '\n'
                        foutmain.write (timestamp)
                firstCode = False
                prevtime = time
                prevcode = code
                prevmaincode = maincode

            ##  Now see if there is a concurrent (secondary) EDP phase occuring.
            sCode = getEDPSCode (line)
            if sCode :
                ##  print ('Line: ', line, ' mainSCode: ', mainSCode)
                ##  Secondaary EDP Phase.  Save the code until END is detected, when it
is written out.
                if sCode :
                    ## print ('SCode:  ', mainSCode + '/n')
                    if 'END' in sCode:
                        ##print ('---------', '\n')
                        ##print ('Detected END - writing stored secondary EDP Code ' +
prevMainSCode + '\n')
                        if expectedSPhase == store :
                            printError ('Unexpected S Phase expecting store ', line)
                        ## print ('---------', '\n')
                        delta = datetime.strptime(time, FMT) -
datetime.strptime(prevStime, FMT)
                        if delta.days < 0 :
                            printError ('Negative elapsed S time', line)
                        deltaStr = str(delta)
                        ## Write out full EDP code
                        timestamp = prevStime + ','  + deltaStr + ',' + prevSCode  + '\n'
                        foutsub.write (timestamp)
                        ## Write out main EDP code (no subcodes)
                        mainSCode = extractMainCode (prevSCode)
                        timestamp = prevStime + ',' + deltaStr + ',' + mainSCode + ','+
getExcelCode (mainSCode, line) +'\n'
                        foutmain.write (timestamp)
                        expectedSPhase = store
                    else :
                        ##print ('---------', '\n')
                        ##print ('Detected and storing S Code: ', mainSCode, time)
                        if expectedSPhase == end :
                            printError ('Unexpected S Phase - expecting write/END ' ,
line )
```

```
                    ## print ('---------', '\n')
                    prevSCode = sCode
                    prevStime = time
                    expectedSPhase = end
                firstCode = False


            ## Now check for non-EDP codes (and their value, if any).  Note that there
may be more than one.
            nonedplist = re.findall (pattern, line)
            ##print line
            if nonedplist:
                for currentCode in nonedplist:
                    outputCode = strip (currentCode)
                    ## Get any value if present
                    value = getSecondaryCodeValue (currentCode, line)
                    outputCode = stripS (currentCode)
                    if value:
                        timestamp1 = time + ',' + outputCode + ',' + value + '\n'
                    else :
                        timestamp1 = time + ',' + outputCode + '\n'

                    foutnonedp.write (timestamp1)
            ##print nonedplist
        line = fin.readline()
fin.close()
foutsub.close ()
foutmain.close ()
foutnonedp.close ()
fouterror.close ()
print ('Processing ' + inputfilename + ' complete')
```

APPENDIX H

LEGO EXPERIENCE QUESTIONAIRE

Goal: determine if the student has had significant LEGO and/or LEGO robotics experience outside of school. This will be judged at an age appropriate level. Sixth grade students will fill out the questionnaire themselves. Parents of second grade students will fill out the questionnaire. The scale will be adjusted if it does not differentiate enough.

SCORING:

Q1: 3 points
Q2: 3 points for grade 2, 1 point for grade 6
Q3: 2 points for every instance.
Q4: 2 points for every instance.
Q5: 2 points for now, 1 point for in the past.

3 or more points results in a + for LEGO Experience

ELEMENTARY ROBOTICS CASE STUDY
University of Massachusetts, Amherst

Dear Parent(s),

Thanks so much for your child's participation in this study!   I hope it was a fun and enjoyable experience for your child.

One possibility already emerging from the study is that students' out of school LEGO experience could be a significant factor in how they approach in-school LEGO challenges. Please take a moment to fill out this short questionnaire that helps me understand how much out of school LEGO experience each student has.

If you have any questions, you can call me at 413-320-5816 or email me at jheffernan@hr-k12.org. You can return the questionnaire with your student or scan and email it to jheffernan@hr-k12.org by Wednesday, December 9, 2015.

Thanks,

John Heffernan

Grade 2 LEGO Experience Questionnaire

Student's Name ___________________________________

_____ My child uses LEGO Mindstorms NXT or EV3 at home.

_____ My child uses LEGO WeDo at home.

_____ My child has taken LEGO **robotics** enrichment classes after school or in the summer. If true, about how many times? ____________

_____ My child has taken LEGO enrichment classes after school or in the summer. If true, about how many times? ____________

_____ My child builds with LEGOs at home more than once a week either now or in the past. If true, circle NOW or IN THE PAST.

Grade 6 LEGO Experience Questionnaire

Name: ___________________________________

Check if true.

_____ I use LEGO Mindstorms NXT or EV3 at home.

_____ I use LEGO WeDo at home.

_____ I have taken LEGO **robotics** enrichment classes after school or in the summer. If true, about how many times? ____________

_____ I have taken LEGO enrichment classes after school or in the summer. If true, about how many times? ____________

_____ I build with LEGOs at home more than once a week either now or in the past. If true, circle NOW or IN THE PAST.

REFERENCES

Adamchuk, V., Barker, B. S., Nugent, G., Grandgenett, N., Patent-Nygren, M., Lutz, C., & Morgan, K. (2012). Learning Geospatial Concepts as Part of a Non-Formal Education Robotics Experience. In *Robots in K-12 Education: A New Technology for Learning* (p. 284). Hershey, PA: IGI Global.

Adi-Japha, E., Berberich-Artzi, J., & Libnawi, A. (2010). Cognitive flexibility in drawings of bilingual children. *Child Development*, *81*(5), 1356–1366.

Alimisis, D. (2012). Robotics in Education & Education in Robotics: Shifting Focus from Technology to Pedagogy. Presented at the 3rd International Conference on Robotics in Education, Prague. Retrieved from http://www.etlab.eu/files/alimisis_RIE2012_paper.pdf

Anning, A. (1994). Dilemmas and opportunities of a new curriculum: Design and technology with young children. *International Journal of Technology and Design Education*, *4*(2), 155–177.

Apedoe, X. S., Reynolds, B., Ellefson, M. R., & Schunn, C. D. (2008). Bringing engineering design into high school science classrooms: the heating/cooling unit. *Journal of Science Education and Technology*, *17*(5), 454–465.

Arter, J., & McTighe, J. (2001). *Scoring rubrics in the classroom: Using performance criteria for assessing and improving student performance*. Corwin Press.

Atman, C. J., Adams, R. S., Cardella, M. E., Turns, J., Mosborg, S., & Saleem, J. (2007). Engineering design processes: A comparison of students and expert practitioners. *Journal of Engineering Education*, *96*(4), 359–379.

Atman, C. J., & Bursic, K. M. (1998). Verbal protocol analysis as a method to document engineering student design processes. *Journal of Engineering Education*, *87*(2), 121–132.

Atman, C. J., Cardella, M. E., Turns, J., & Adams, R. (2005). Comparing freshman and senior engineering design processes: an in-depth follow-up study. *Design Studies*, *26*(4), 325–357. https://doi.org/10.1016/j.destud.2004.09.005

Atman, C. J., McDonnell, J., Campbell, R. C., Borgford-Parnell, J. L., & Turns, J. A. (2015). Using Design Process Timelines to Teach Design: Implementing Research Results. ASEE Conferences. https://doi.org/10.18260/p.24998

Atman, C. J., Yasuhara, K., Adams, R. S., Barker, T. J., Turns, J., & Rhone, E. (2008). Breadth in problem scoping: A comparison of freshman and senior engineering students. *International Journal of Engineering Education*, *24*(2), 234–245.

Banta, M. A. (1980). Unit Blocks: A Curriculum for Early Learning.

Barak, M., & Zadok, Y. (2009). Robotics projects and learning concepts in science, technology and problem solving. *International Journal of Technology and Design Education*, *19*(3), 289–307.

Barker, B. S., & Ansorge, J. (2007). Robotics as means to increase achievement scores in an informal learning environment. *Journal of Research on Technology in Education*, *39*(3), 229.

Barrett, T. M., Davis, E. F., & Needham, A. (2007). Learning about tools in infancy. *Developmental Psychology*, *43*(2), 352–368. https://doi.org/10.1037/0012-1649.43.2.352

Barron, B., & Engle, R. (2007). Analyzing data derived from video records. *Guidelines for Video Research in Education: Recommendations from an Expert Panel*, 24–43.

Baynes, K. (1994). *Designerly play*. Loughborough: Loughborough University of Technology, Department of Design and Technology.

Benitti, F. B. V. (2012). Exploring the educational potential of robotics in schools: A systematic review. *Computers & Education*, *58*(3), 978–988. https://doi.org/10.1016/j.compedu.2011.10.006

Bers, M. (2008). *Blocks to robots: learning with technology in the early childhood classroom*. Teachers College Press.

Bers, M., Flannery, L., Kazakoff, E., & Sullivan, A. (2014). Computational thinking and tinkering: Exploration of an early childhood robotics curriculum. *Computers & Education*, *72*, 145–157. https://doi.org/10.1016/j.compedu.2013.10.020

Bidell, T. R., & Fischer, K. W. (1992). Cognitive development in educational contexts. In A. Demetriou, A. Efklides, & M. Shayer (Eds.), *Neo-Piagetian theories of cognitive development: Implications and applications for education* (pp. 11–30). New York, New York: Routledge.

Brenner, M. E. (2006). Interviewing in educational research. In *Handbook of complementary methods in education research* (pp. 357–370).

Brophy, S., Portsmore, M., Klein, S., & Rogers, C. (2008). Advancing Engineering Education in P-12 Classrooms. *Journal of Engineering Education*, *97*(3).

Brunton, G., Stansfield, C., & Thomas, J. (2012). Finding relevant studies. In *An introduction to systematic reviews* (pp. 107–134). Los Angeles, CA: Sage Publications.

Buchanan, D. W., & Sobel, D. M. (2011). Mechanism-Based Causal Reasoning in Young Children: Knowledge of Causal Mechanisms. *Child Development*, *82*(6), 2053–2066. https://doi.org/10.1111/j.1467-8624.2011.01646.x

Buckner, R. L., & Carroll, D. C. (2007). Self-projection and the brain. *Trends in Cognitive Sciences*, *11*(2), 49–57. https://doi.org/10.1016/j.tics.2006.11.004

Butler, J. (2011). *Gender trouble: Feminism and the subversion of identity*. routledge.

Byun, H., Lee, J., & Cerreto, F. A. (2014). Relative effects of three questioning strategies in ill-structured, small group problem solving. *Instructional Science*, *42*(2), 229–250. https://doi.org/10.1007/s11251-013-9278-1

Carberry, A., Klassner, F., Schafer, B., & Varnado, T. E. (2014). LEGO® Product Research: A Literature Review.

Cardella, M. E., Atman, C. J., Turns, J., & Adams, R. S. (2008). Students with differing design processes as freshmen: Case studies on change. *International Journal of Engineering Education*, *24*(2), 246.

Cartwright, K. B. (2012). Insights From Cognitive Neuroscience: The Importance of Executive Function for Early Reading Development and Education. *Early Education & Development*, *23*(1), 24–36. https://doi.org/10.1080/10409289.2011.615025

Case, R. (1991). *The mind's staircase: Exploring the conceptual underpinnings of children's thought and knowledge*. Psychology Press.

Case, R. (1992). The role of central conceptual structures in the development of children's scientific and mathematical thought. In *Neo-Piagetian theories of cognitive development: Implications and applications for education* (pp. 52–64). New York, New York: Routledge.

CEEO: Home. (n.d.). Retrieved March 12, 2014, from http://ceeo.tufts.edu/

Charmaz, K. (2014). *Constructing grounded theory*. Thousand Oaks, CA: Sage.

Chen, C.-H., & Bradshaw, A. C. (2007). The effect of web-based question prompts on scaffolding knowledge integration and ill-structured problem solving. *Journal of Research on Technology in Education*, *39*(4), 359–375.

Cohen, J. (1971). *Thinking*. Chicago, IL: Rand McNally.

Committee on Maximizing the Potential of Women in Academic Science and Engineering (U.S.), Committee on Science, E. and Public Policy (U.S.), National Academy of Sciences (U.S.), National Academy of Engineering, & Institute of Medicine (U.S.). (2007). *Beyond bias and barriers: fulfilling the potential of women in academic science and engineering*.

Crismond, D. (2001). Learning and using science ideas when doing investigate-and-redesign tasks: A study of naive, novice, and expert designers doing constrained and scaffolded design work. *Journal of Research in Science Teaching*, *38*(7), 791–820.

Crismond, D., & Adams, R. S. (2012). The informed design teaching and learning matrix. *Journal of Engineering Education*, *101*(4), 738–797.

Cross, N. (2008). *Engineering design methods: strategies for product design* (4th ed.). West Sussex, England: John Wiley and Sons.

Cunningham, C. M., & Hester, K. (2007). Engineering is elementary: An engineering and technology curriculum for children. In *American Society for Engineering Education Annual Conference & Exposition, Honolulu, HI*.

Cutting, N., Apperly, I. A., & Beck, S. R. (2011). Why do children lack the flexibility to innovate tools? *Journal of Experimental Child Psychology*, *109*(4), 497–511. https://doi.org/10.1016/j.jecp.2011.02.012

Cutting, N., Apperly, I. A., Chappell, J., & Beck, S. R. (2014). The puzzling difficulty of tool innovation: Why can't children piece their knowledge together? *Journal of Experimental Child Psychology*, *125*, 110–117. https://doi.org/10.1016/j.jecp.2013.11.010

Davidson, M. C., Amso, D., Anderson, L. C., & Diamond, A. (2006). Development of cognitive control and executive functions from 4 to 13 years: Evidence from manipulations of memory, inhibition, and task switching. *Neuropsychologia*, *44*(11), 2037–2078. https://doi.org/10.1016/j.neuropsychologia.2006.02.006

Demetriou, A., Gustafsson, J.-E., Efklides, A., & Platsidou, M. (1992). Structural systems in developing cognition, science, and education. In A. Demetriou, A. Efklides, & M. Shayer (Eds.), *Neo-Piagetian theories of cognitive development: Implications and applications for education* (pp. 79–103). New York, New York: Routledge.

Eguchi, A. (2012). Educational Robotics Theories and Practice: Tips for how to do it Right. In *Robots in K-12 Education: A New Technology for Learning, B. Barker, G. Nugent, N. Grandgenett, & V. Adamchuk, Eds. Hershey, PA, IGI Global* (pp. 1–30). Hershey, PA: IGI Global.

Engineering - Definition and More from the Free Merriam-Webster Dictionary. (n.d.). Retrieved April 5, 2015, from http://www.merriam-webster.com/dictionary/engineering

English, L. D., Hudson, P., & Dawes, L. (2013). Engineering-Based Problem Solving in the Middle School: Design and Construction with Simple Machines. *Journal of Pre-College Engineering Education*, *3*(2). Retrieved from http://search.ebscohost.com/login.aspx?direct=true&profile=ehost&scope=site&authtype=crawler&jrnl=21579288&AN=92609426&h=ht05k9am%2Ftl2QOU10jBAcagHyYxbrbL5QLpZyclHMmSLkzUB%2FYLBo6kmakVxYabX12tvjZ1iZfSRTKmxqBdJxg%3D%3D&crl=c

Erickson, F. (2006). Definition and analysis of data from videotape: Some research procedures and their rationales. In *Handbook of complementary methods in education research* (pp. 177–192).

Ericsson, K. A., & Simon, H. A. (1993). *Protocol Analysis: Verbal Reports as Data*. Cambridge, MA: MIT Press.

Ernst, J. V., & Bottomley, L. (2011). AC 2011-227: ELEMENTARY ENGINEERING IMPLEMENTATION AND STUDENT LEARNING OUTCOMES. Retrieved from http://www.asee.org/file_server/papers/attachment/file/0001/0688/NIH_Paper_3_10_11.pdf

Fleer, M. (1999). The science of technology: Young children working technologically. *International Journal of Technology and Design Education*, *9*(3), 269–291.

Fortus, D., Krajcik, J., Dershimer, R. C., Marx, R. W., & Mamlok-Naaman, R. (2005). Design-based science and real-world problem-solving. *International Journal of Science Education*, *27*(7), 855–879. https://doi.org/10.1080/09500690500038165

Freelon, D. G. (2010). ReCal: Intercoder reliability calculation as a web service. *International Journal of Internet Science*, *5*(1), 20–33.

Funke, J. (1991). Solving complex problems: Exploration and control of complex systems. *Complex Problem Solving: Principles and Mechanisms*, 185–222.

Fuson, K. (1976). Piagetian Stages in Causality: Children's Answers to" Why?" *The Elementary School Journal*, 150–158.

Galman, S. C. (2007). *Shane, the lone ethnographer: a beginner's guide to ethnography*. Rowman Altamira.

Galman, S. C. (2013). *The good, the bad, and the data: Shane the lone ethnographer's basic guide to qualitative data analysis*. Walnut Creek, CA: Left Coast Press.

Gardner, W., & Rogoff, B. (1990). Children's deliberateness of planning according to task circumstances. *Developmental Psychology*, *26*(3), 480.

Ginsburg, H. (1997). *Entering the child's mind: The clinical interview in psychological research and practice*. Cambridge University Press.

Glaser, B. G., & Strauss, A. L. (2009). *The discovery of grounded theory: Strategies for qualitative research*. Transaction Publishers.

Goldman, R., Erickson, F., Lemke, J., & Derry, S. J. (2007). Selection in video. *Guidelines for Video Research in Education: Recommendations from an Expert Panel*, 15–22.

Gura, M. (2011). *Getting Started with LEGO Robotics: A Guide for K-12 Educators [Paperback]*. Eugene, OR: ISTE.

Gustafson, B. J., & Rowell, P. M. (1998). Elementary Children's Technological Problem Solving: selecting an initial course of action. *Research in Science & Technological Education*, *16*(2), 151–163.

Heffernan, J. (2013). *Elementary Engineering: Sustaining the Natural Engineering Instincts of Children*. Charlestown, SC: Printed by CreateSpace.

Hynes, M. (2007). AC 2007-1684: IMPACT OF TEACHING ENGINEERING CONCEPTS THROUGH CREATING LEGO-BASED ASSISTIVE DEVICES. Presented at the American Society for Engineering Education Annual Conference & Exposition, Honolulu,HI: American Society for Engineering Education. Retrieved from http://icee.usm.edu/ICEE/conferences/asee2007/papers/1684_IMPACT_OF_TEACHING_ENGINEERING_CONCEPTS_.pdf

Johnsey, R. (1993). Observing the way primary children design and make in the classroom: an analysis of the behaviours exhibited. Retrieved from https://dspace.lboro.ac.uk/dspace/handle/2134/1566

Jonassen, D. H. (2000). Toward a design theory of problem solving. *Educational Technology Research and Development*, *48*(4), 63–85.

Jonassen, D. H., & Ionas, I. G. (2008). Designing effective supports for causal reasoning. *Educational Technology Research and Development*, *56*(3), 287–308.

Karmiloff-Smith, A. (1990). Constraints on representational change: Evidence from children's drawing. *Cognition*, *34*(1), 57–83. https://doi.org/10.1016/0010-0277(90)90031-E

Karmiloff-Smith, A. (1995). *Beyond modularity: A developmental perspective on cognitive science*. MIT press.

Kazakoff, E., & Bers, M. (2012). Programming in a robotics context in the kindergarten classroom: The impact on sequencing skills. *Journal of Educational Multimedia and Hypermedia*, *21*(4), 371–391.

Kolodner, J. L., Camp, P. J., Crismond, D., Fasse, B., Gray, J., & Holbrook, J. (2003). Problem-based learning meets case-based reasoning in the middle-school science classroom: Putting Learning by Design (TM) into practice. *Journal of the Learning Sciences*, *12*(4), 495–547.

Krajcik, J. (2011). Learning Progressions Provide Road Maps for the Development and Validity of Assessments and Curriculum Materials. *Measurement: Interdisciplinary Research & Perspective*, *9*(2-3), 155–158. https://doi.org/10.1080/15366367.2011.603617

Krippendorff, K. (2007). Computing Krippendorff's alpha reliability. *Departmental Papers (ASC)*, 43.

Kuhn, D. (2007). Reasoning about multiple variables: Control of variables is not the only challenge. *Science Education*, *91*(5), 710–726. https://doi.org/10.1002/sce.20214

Kuhn, D., & Dean, D., Jr. (2004). Connecting Scientific Reasoning and Causal Reasoning. *Journal of Cognition and Development*, *5*(2), 261–288.

Kuhn, D., Schauble, L., & Garcia-Mlia, M. (1992). Cross Domain Development of Scientific Reasoning. *Cognition And Instruction*, *9*(4), 285–327.

Legare, C. H., Gelman, S. A., & Wellman, H. M. (2010). Inconsistency with prior knowledge triggers children's causal explanatory reasoning. *Child Development*, *81*(3), 929–944.

Leonard, M. J., & Derry, S. J. (2011). "What's the Science Behind It?" The Interaction of Engineering and Science Goals, Knowledge, and Practices in a Design-Based Science Activity. Retrieved from http://widaredesign.wceruw.org/publications/workingPapers/Working_Paper_No_2011_05.pdf

Levy, S. T., & Mioduser, D. (2008). Does it "want" or "was it programmed to..."? Kindergarten children's explanations of an autonomous robot's adaptive functioning. *International Journal of Technology and Design Education*, *18*(4), 337–359. https://doi.org/10.1007/s10798-007-9032-6

Levy, S. T., & Mioduser, D. (2010). Approaching Complexity Through Planful Play: Kindergarten Children's Strategies in Constructing an Autonomous Robot's Behavior. *International Journal of Computers for Mathematical Learning*, *15*(1), 21–43. https://doi.org/10.1007/s10758-010-9159-5

Lindh, J., & Holgersson, T. (2007). Does lego training stimulate pupils' ability to solve logical problems? *Computers & Education*, *49*(4), 1097–1111. https://doi.org/10.1016/j.compedu.2005.12.008

Margolis, J., & Fisher, A. (2003). *Unlocking the clubhouse: Women in computing*. MIT press.

Martinez, S. L., & Stager, G. (2013). *Invent To Learn: Making, Tinkering, and Engineering in the Classroom*. Constructing Modern Knowledge Press.

Massachasetts Department of Education School and District Profiles. (n.d.). Retrieved March 11, 2015, from http://profiles.doe.mass.edu/

McCarthy, N. (2012). *Engineering: a beginner's guide*. Oneworld Publications.

McCormack, T., & Atance, C. M. (2011). Planning in young children: A review and synthesis. *Developmental Review*, *31*(1), 1–31. https://doi.org/10.1016/j.dr.2011.02.002

McFarland, M. E., & Bailey, R. (2015). Investigating Pattern in Design Performance of Interdisciplinary Undergraduate Engineering Student Teams. ASEE Conferences. https://doi.org/10.18260/p.24375

McGrath, E., Lowes, S., McKay, M., Sayres, J., & Lin, P. (2012). Robots Underwater! Learning Science, Engineering and 21st Century Skills: The Evolution of Curricula, Professional Development and Research in Formal and Informal Contexts. In V. Adamchuk, N. Grandgenett, B. S. Barker, & G. Nugent (Eds.), *Robots in K-12 Education: A New Technology for Learning* (pp. 141–167). Hershey, PA: IGI Global.

McRobbie, C. J., Stein, S. J., & Ginns, I. (2001). Exploring designerly thinking of students as novice designers. *Research in Science Education*, *31*(1), 91–116.

Mead, R. A., Thomas, S. L., & Weinberg, J. B. (2012). From Grade School to Grad School: An Integrated STEM Pipeline Model through Robotics. In *Robots in K-12 Education: A New Technology for Learning* (pp. 302–325). Hershey, PA: IGI Global. Retrieved from http://services.igi-global.com/resolvedoi/resolve.aspx?doi=10.4018/978-1-4666-0182-6.ch015

Mehalik, M. M., Doplet, Y., & Schunn, C. D. (2008). Middle-school science through design-based learning versus scripted inquiry: Better overall science concept learning and equity gap reduction. *Journal of Engineering Education*, *97*(1), 75=81.

Melchior, A., Cutter, T., & Cohen, F. (2004). *Evaluation of FIRST LEGO League*. Waltham, MA: Heller School for Social Policy and Management, Brandeis University.

Milto, E., Rogers, C., & Portsmore, M. (2002). Gender differences in confidence levels, group interactions, and feelings about competition in an introductory robotics course. In *Frontiers in Education, 2002. FIE 2002. 32nd Annual* (Vol. 2, p. F4C–7). IEEE. Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=1158224

Mioduser, D., Levy, S. T., & Talis, V. (2007). Episodes to scripts to rules: concrete-abstractions in kindergarten children's explanations of a robot's behavior. *International Journal of Technology and Design Education*, *19*(1), 15–36. https://doi.org/10.1007/s10798-007-9040-6

Mitnik, R., Recabarren, M., Nussbaum, M., & Soto, A. (2009). Collaborative robotic instruction: A graph teaching experience. *Computers & Education*, *53*(2), 330–342. https://doi.org/10.1016/j.compedu.2009.02.010

National Academy of Engineering, Committee on Technological Literacy, & National Research Council (U.S.). (2002). *Technically speaking why all Americans need to know more about technology*. (G. Pearson & A. T. Young, Eds.). Washington, D.C.: National Academy Press. Retrieved from http://site.ebrary.com/id/10032442

National Science Foundation, National Center for Science and Engineering Statistics. (2013). *Women, Minorities, and Persons with Disabilities in Science and Engineering: 2013* (No. Special Report NSF 13-304.). Retrieved from http://www.nsf.gov/statistics/wmpd/.

Next Generation Science Standards. (2012). Retrieved November 2, 2012, from http://www.nextgenscience.org/

Norton, S. J., McRobbie, C. J., & Ginns, I. S. (2007). Problem Solving in a Middle School Robotics Design Classroom. *Research in Science Education*, *37*(3), 261–277. https://doi.org/10.1007/s11165-006-9025-6

Nourbakhsh, I. R., Crowley, K., Bhave, A., Hamner, E., Hsiu, T., Perez-Bergquist, A., … Wilkinson, K. (2005). The robotic autonomy mobile robotics course: Robot design, curriculum design and educational assessment. *Autonomous Robots*, *18*(1), 103–127.

Nugent, G., Barker, B., Grandgenett, N., & Adamchuk, V. (2009). The use of digital manipulatives in K-12: robotics, gps/gis and programming. In *Frontiers in Education Conference, 2009. FIE'09. 39th IEEE* (pp. 1–6). Retrieved from http://ieeexplore.ieee.org/xpls/abs_all.jsp?arnumber=5350828

Nugent, G., Barker, B., Grandgenett, N., & Adamchuk, V. I. (2010). Impact of robotics and geospatial technology interventions on youth STEM learning and attitudes. *Journal of Research on Technology in Education*, *42*(4), 391–408.

Outterside, Y. (1993). The emergence of design ability: The early years. Retrieved from https://dspace.lboro.ac.uk/dspace/handle/2134/1574

Papert, S. (1993). *Mindstorms: Children, Computers, And Powerful Ideas* (2nd ed.). Basic Books.

Papert, S. (2000). What's the big idea? Toward a pedagogy of idea power. *IBM Systems Journal*, *39*(3.4), 720–729.

Papert, S., & Harel, I. (1991). Situating constructionism. *Constructionism*, *36*, 1–11.

Penner, D. E., Giles, N. D., Lehrer, R., & Schauble, L. (1997). Building functional models: Designing an elbow. *Journal of Research in Science Teaching*, *34*(2), 125–143.

Petroski, H. (2003). Engineering: Early Education. *American Scientist*, 206–209.

Piaget, J., & Inhelder, B. (1969). *The psychology of the child*. Basic Books.

Portsmore, M. (2009). *Exploring How Experience With Planning Impacts First Grade Students' Planning And Solutions To Engineering Design Problems (Doctoral Dissertation)*. Retrieved from https://www.researchgate.net/publication/252861164_Exploring_how_experience_with_planning_impacts_first_grade_students'_planning_and_solutions_to_engineering_design_problems

Portsmore, M. (2011). *Scaffolding the Engineering Design Process for Elementary Students (PowerPoint Slides)*.

Portsmore, M. D., & Brizuela, B. M. (2011). AC 2011-1780: FIRST GRADE STUDENTS PLANNING AND ARTIFACT CONSTRUCTION WHILE WORKING ON AN ENGINEERING DESIGN PROBLEM. Presented at the ASEE Annual Conference, Vancouver, BC, Canada. Retrieved from http://jee.asee.org/file_server/papers/attachment/file/0001/1710/Draft_Portsmore_ASEE2011v2.pdf

Puntambekar, S., & Kolodner, J. L. (2005). Distributed Scaffolding: Helping Students Learn Science from Design. *Journal of Research in Science Teaching`*, *42*(2), 185–217.

Resnick, M. (2007). All I really need to know (about creative thinking) I learned (by studying how children learn) in kindergarten. In *Proceedings of the 6th ACM SIGCHI conference on Creativity & cognition* (pp. 1–6). ACM. Retrieved from http://dl.acm.org/citation.cfm?id=1254961

Resnick, M., & Rosenbaum, E. (2013). Designing for Tinkerability. In M. Honey & D. Kantor (Eds.), *Design, Make, Play: Growing the Next Generation of STEM Innovators* (pp. 163–181). Routledge. Retrieved from http://llk.media.mit.edu/courses/readings/DesignMakePlay-Ch10.pdf

Roden, C. (1997). Young children's problem-solving in design and technology: towards a taxonomy of strategies. *Journal of Design & Technology Education*, *2*(1). Retrieved from https://jil.lboro.ac.uk/ojs/index.php/JDTE/article/view/375

Roden, C. (1999). How children's problem solving strategies develop at Key Stage 1. *Journal of Design & Technology Education*, *4*(1). Retrieved from http://ojs.lboro.ac.uk/ojs/index.php/JDTE/article/view/404

Rogoff, B. (2003). *The cultural nature of human development*. Oxford University Press.

Rosen, J., Stillwell, F., & Usselman, M. (2012). Promoting Diversity and Public School Success in Robotics Competitions. In *Robots in K-12 Education: A New Technology for Learning* (p. 326). Hershey, PA: IGI Global.

Roth, W.-M. (1996). Art and Artifact of Children's Designing: A Situated Cognition Perspective. *Journal of the Learning Sciences*, *5*(2), 129–166.

Schunn, C. D. (2009). How Kids Learn Engineering: The Cognitive Science Perspective. *National Academy of Engineering, The Bridge*, *39*(3). Retrieved from http://www.nae.edu/Publications/Bridge/16145/16214.aspx?layoutChange=Normal&PS=10&PI=0&TC=8&BBM=0

Skorinko, J. L., Doyle, J. K., & Tryggvason, G. (2012). Do Goals Matter in Engineering Education? An Exploration of How Goals Influence Outcomes for FIRST Robotics Participants. *Journal of Pre-College Engineering Education Research (J-PEER)*, *2*(2), 3.

Slangen, L., Keulen, H., & Gravemeijer, K. (2010). What pupils can learn from working with robotic direct manipulation environments. *International Journal of Technology and Design Education*, *21*(4), 449–469. https://doi.org/10.1007/s10798-010-9130-8

Stein, C., Nickerson, K., & Schools, N. P. (2004). Botball robotics and gender differences in middle school teams. In *Proceedings of the 2004 American Society for Engineering Education Annual Conference*. Retrieved from http://dpm.kipr.org/papers/asee04-gender.pdf

Sternberg, R. J. (2003). Creative thinking in the classroom. *Scandinavian Journal of Educational Research*, *47*(3), 325–338.

Stiles, J., & Stern, C. (2001). Developmental change in spatial cognitive processing: Complexity effects and block construction performance in preschool children. *Journal of Cognition and Development*, *2*(2), 157–187.

Stone-Macdonald, A. K., Wendell, K. B., Douglass, A., Love, M. L., & Hyson, M. L. (2015). *Engaging Young Engineers: Teaching Problem Solving Skills Through STEM*. Baltimore, MD: Brookes Publishing.

Sullivan, A., & Bers, M. U. (2013). Gender differences in kindergarteners' robotics and programming achievement. *International Journal of Technology and Design Education*, *23*(3), 691–702. https://doi.org/10.1007/s10798-012-9210-z

Sullivan, F., & Lin, X. (2012). The ideal science student: Exploring the relationship of students' perceptions to their problem solving activity in a robotics context. *Journal of Interactive Learning Research*, *23*(3), 273–308.

Sullivan, F. R. (2008). Robotics and science literacy: Thinking skills, science process skills and systems understanding. *Journal of Research in Science Teaching*, *45*(3), 373–394. https://doi.org/10.1002/tea.20238

Sullivan, F. R. (2011). Serious and playful inquiry: Epistemological aspects of collaborative creativity. *Educational Technology & Society*, *14*(1), 55–65.

Sullivan, F. R., & Heffernan, J. (2016). Robotic Construction Kits as Computational Manipulatives for Learning in the STEM Disciplines. *Journal of Research on Technology in Education*, *48*(2), 1–24. https://doi.org/10.1080/15391523.2016.1146563

Sullivan, F. R., & Wilson, N. C. (2015). Playful Talk: Negotiating Opportunities to Learn in Collaborative Groups. *Journal of the Learning Sciences*, *24*(1), 5–52. https://doi.org/10.1080/10508406.2013.839945

Summerfield, M. (2010). *Programming in Python 3: a complete introduction to the Python language*. Addison-Wesley Professional.

Suomala, J., & Alajaaski, J. (2002). Pupils' Problem-Solving Processes In A Complex Computerized Learning Environment. *Journal of Educational Computing Research*, *26*(2), 155–176. https://doi.org/10.2190/58XD-NMFK-DL5V-0B6N

Theory of Mind | Internet Encyclopedia of Philosophy. (n.d.). Retrieved September 13, 2015, from http://www.iep.utm.edu/theomind/

The Partnership for 21st Century Skills. (2002). Framework for 21st Century Learning. Retrieved November 3, 2012, from http://www.p21.org/index.php

Torok, R. (2012). Robotics Education Literature Review.

Turkle, S., & Papert, S. (1991). Epistemological pluralism and the revaluation of the concrete. In I. Harel & S. Papert (Eds.), *Constructionism* (pp. 161–192). Ablex Publishing Corporation. Retrieved from http://kvantti.kapsi.fi/Documents/Turkle%20Papert%20-%20Epistemological%20Pluralism%20and%20the%20Revaluation%20of%20the%20Concrete%20-%201992.pdf

Varnado, T. E. (2005). *The Effects of a Technological Problem Solving Activity on FIRST™ LEGO™ League Participants' Problem Solving Style and Performance*. Virginia Polytechnic Institute and State University. Retrieved from http://scholar.lib.vt.edu/theses/available/etd-04282005-101527/

Voyles, M. M., Fossum, T., & Haller, S. (2008). Teachers respond functionally to student gender differences in a technology course. *Journal of Research in Science Teaching*, *45*(3), 322–345.

Vygotsky, L. S. (1986). Thought and Language. In *Thought and Language*. Cambridge, MA: MIT.

Wagner, S. P. (1999). Robotics and Children Science Achievement and Problem Solving. *Journal of Computing in Childhood Education*, *9*(2), 149–192.

Weinberg, J. B., Pettibone, J. C., Thomas, S. L., Stephen, M. L., & Stein, C. (2007). The impact of robot projects on girls' attitudes toward science and engineering. In *Workshop on Research in Robots for Education*. Citeseer.

Welch, M. (1999). Analyzing the Tacit Strategies of Novice Designers. *Research in Science & Technological Education*, *17*(1), 19–33.

Wendell, K. B., & Lee, H. S. (2010). Elementary students' learning of materials science practices through instruction based on engineering design tasks. *Journal of Science Education and Technology*, *19*(6), 580–601.

Williams, D., Ma, Y., Lai, G., Prejean, L., & Ford, M. J. (2007). Acquisition of Physics Content Knowledge and Scientific Inquiry Skills in a Robotics Summer Camp. In *Society for Information Technology & Teacher Education International Conference* (Vol. 2007, pp. 3437–3444). Retrieved from http://www.editlib.org/p/25146/

Young, G. (2011). *Development and causality: Neo-Piagetian perspectives*. New York, New York: Springer.

Zhao, Y. (2012). *World class learners: Educating creative and entrepreneurial students*. SAGE.