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# Examining Engineering Design Cognition with Respect to Student Experience and Performance*

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This study investigated the design cognition and performance results of secondary and post-secondary engineering students while engaged in an engineering design task. Relationships between prototype performance and design cognition were highlighted to investigate potential links between cognitive processes and success on engineering design problems. Concurrent think-aloud protocols were collected from eight secondary and 12 post-secondary engineering students working individually to design, make, and evaluate a solution prototype to an engineering design task. The collected protocols were segmented and coded using a pre-established coding scheme. The results were then analyzed to compare the two participant groups and determine the relationships between students' design cognition, engineering experience level, and design performance. Significant differences between participants with secondary engineering experiences and those without were found in regards to the amount of time various cognitive processes were employed to complete a design task. For the given design scenario, students with secondary engineering experiences achieved significantly higher rubric scores than those without. Improved design performance was also found to be significantly correlated with more time employing the mental processes of *analyzing*, *communicating*, *designing*, *interpreting data*, *predicting*, and *questioning/hypothesizing*. Important links between educational experiences in engineering design, prior to college, and student success on engineering design problems may indicate necessary shifts in student preparation.

**Keywords:** engineering; design; cognition; performance

## 1. Introduction

As initiatives to integrate engineering at the P-12 level continue to increase [1–5], it has become evident there is widespread societal agreement for fostering a student's engineering design abilities as a means to promote a better educated populace with the 21st century skills necessary for future economic success [6–8]. This expanded interest in engineering can be attributed to the idea that immersing students in engineering design experiences, which naturally tie mathematics and science learning together through solving authentic problems, is an essential approach to provide new levels of relevancy to education, motivate students in learning, make STEM careers more accessible, and prepare students with the skills to address the major challenges facing the world today and in the future [1, 6, 9, 10]. Consequently, engineering design has become a central component of P-12 education with both technology education [12] and science education [4, 11] incorporating engineering design in their standards and curriculum. In this context, it becomes important to assist educators in properly enacting interventions that better enable students to employ engineering design practices that produce the most viable solutions to authentic problems. However, as Dym, Agogino, Eris, Frey and Leifer [13] explain, engineering design is challenging to understand, teach, and evaluate because many efforts to infuse engineering design are void of an empirical understanding of students' cognitive processes as they engage in the engineering design process [2].

To fill this void, researchers have begun to study the design cognition of adolescents, college students, and practitioners engaged in engineering design activities [1, 2, 5, 14–21]. However, as Grubbs [22] describes, even after decades of design cognition research there is still minimal agreement on how people design and limited examinations on effective ways to bridge design research with teaching and learning strategies. This concern may be attributed to the emphasis of design cognition research being focused time allocation to a set of predetermined design process steps [5] for only a segment of time during a student's full design activity. In doing so, researchers often lack oppor-

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tunities to compare a student's cognitive activity to the actual outcome of their problem-solving process. As Atman and Bursic [23] describe, examining both the design process and design product can enable one to explore the potential relationships between the process the student follows and the quality of their solutions. Atman and Brusic continue to explain that an understanding of this potential relationship may help identify successful, and unsuccessful, procedures in engineering design. These findings could then be used to establish interventions for the improved teaching of engineering design, help students to develop as more effective problem solvers [25], and support the evaluation of current curricular efforts in regards to engineering [1]. Consequently, it is important for researchers to examine engineering design cognition in a manner that enables the analysis of how a student's thinking can influence the outcome of their engineering design process. In addition, in light of the emphasis on engineering design at various levels of education, it is import to examine engineering design cognition in a manner that enables the analysis of students at various experience levels. As described by Wilson et al., [5], this type of research may provide "useful heuristics for secondary engineering and science teachers who seek to bridge adolescents' existing engineering practices to the formal practices of engineering by identifying gaps and commonalities between the two groups' practices [p. 3]."

Accordingly, the researchers enacted multiple exploratory case studies to describe the cognitive activities of experienced secondary engineering students and traditional first-year engineering undergraduate students as they designed, made, and evaluated a solution prototype to an authentic design task. The research was conducted intentionally to compare each student's design process to the product of their process as well as highlight potential indicators for developing more effective solutions. In addition, the research design enabled the comparison of these results with students' experience levels. In doing so, the results may assist in identifying ways in which to improve the teaching and learning of engineering design.

## 2. Background

### *2.1 Engineering design*

Design is widely considered a central element of engineering [13]. It is believed that all practicing engineers perform some form of design function and as such, engineering programs accredited by the ABET must ensure graduating students possess the abilities to apply design procedures to solve problems [25, 26]. However, as Gero [27] describes, design is not limited to engineering and has been a human function throughout history as people continuously work to improve their lives and capabilities. Therefore, as Simon [28] stated, the act of design can be viewed as a natural human process that involves identifying and understanding a problem or opportunity and devising a plan of action to resolve the problem or address the opportunity. With these explanations, one may classify design simply as a general problem-solving process that people employ to improve their situation. Consequently, design may sometimes be enacted merely as an inadvertent trial-and-error approach to solving problems in classroom environments. However, engineers do not just design, rather, they are habitually trained to follow a more explicit and intentional process toward developing solutions known as engineering design. This type of design involves developing predictions through the deliberate application of mathematical, scientific, and analytical modeling practices to determine whether the conditions for a potential solution are favorable [29]. Thus, Dym et al. [13] define engineering design as:

> a systematic, intelligent process in which designers generate, evaluate, and specify concepts for devices, systems, or processes whose form and function achieve clients' objectives or users' needs while satisfying a specified set of constraints [p. 104].

The practices of engineering design are often iterative in nature and integrate knowledge from a variety of fields within social constructs to develop and manipulate the designed world [30]. The key elements of this practice involve establishing the specifications for a successful design, conceiving innovative solution designs, narrowing potential solutions through predictive analysis, and optimizing a design through analytical modeling in order to best meet competing criteria and constraints [30–32]. These elements all draw profoundly upon complex cognitive functions [13, 17] and thus, it becomes vital to better understand engineering design thinking for the potential of developing methods for improving curriculum and instruction [33].

### *2.2 Engineering design cognition*

As the role of design in engineering curriculum at all levels of education has been established, it is fundamental to comprehend ways in which to best teach and learn the practices of engineering design [13, 34]. Because design involves the complex mental processes of inquiry, synthesis, analysis, and decision-making, research investigating how designers think and learn has been conducted across multiple disciplines and professions since the 1970's [18]. Much of this research examined the cognitive processes or design practices of engineers, architects, or post-secondary students as they worked to develop a solution design [17, 22, 35]. The intent of this track of research has primarily been to establish better methods to prepare future designers [36]. Wilson et al., [5] claim it is essential to examine engineering design cognition at all levels from adolescents to advanced practitioners as a means to identify ways in which to fully support adolescents in developing the habits of mind practiced by professional engineers.

Currently, the increased prominence of P-12 engineering education has likely led to the increase of design cognition research with primary and secondary students. Much of this research aims toward better cultivating student design thinking capabilities and integrating disciplinary content with process knowledge. The common method for examining design cognition has been the concurrent think–aloud protocol procedure employing verbal protocol analysis. The concurrent think–aloud procedure is used to collect a person's actions while solving a predetermined design task along with their own verbal interpretation of their thought processes as they preform those actions [2]. The resulting verbal interpretations are then analyzed using a verbal protocol analysis technique, which typically applies a previously derived coding scheme over a video recording or transcription of a design session [37]. The coded data are then used to describe the processes and procedures students follow to design.

However, much of this type of research paints an incomplete picture of design cognition and provides limited ways in which to synthesize findings across multiple studies. For example, the researchers have identified 14 unique design cognition studies [1, 2, 5, 14, 17–21, 38–42] between 1995 and 2016 involving participants at the P-12 level. Of these studies, only two required students to produce a physical prototype of their solution—suggesting that over 85% of the studies did not provide any means for comparing process with product performance. We assert that only studying students through the point of producing a design concept limits the understanding of the complex mental processes involved in the iterative production of a functional prototype. In addition, the majority of these design cognition studies collect student data in group-settings; which, although beneficial, does not capture an individual student's thought process(es). Additionally, the 14 identified studies employed eight different coding schemes to analyze data, which are all based upon different conceptual foundations. The variety of coding schemes limits the ability to compare findings across studies and these can be problematic as most design studies involve small samples of student populations.

## 3. Statement of the problem

While engineering students are often taught to use an idealistic engineering design process to solve problems, it is unclear exactly how people with various levels of experience cognitively navigate a complex and multifaceted engineering design problem. With greater insight into design cognition, educators may be better equipped to manage the difficulties in planning for, and assessing, student abilities in producing viable solutions to engineering design tasks. Therefore, the purpose of this study was to identify the cognitive processes employed by experienced secondary and traditional post-secondary engineering students to solve an engineering design problem in an effort to expand the understanding of how these students, with different backgrounds, cognitively navigate an engineering design process from design conception through the production of a physical prototype. In addition, this research was intentionally designed to compare student's thinking process(es) with the effectiveness of their physical prototype. This enabled the researchers to investigate potential relationships between a students' process and their designed product—allowing for the identification of potentially significant cognitive predictors of success in engineering design.

## 4. Research objectives

The research objectives that guided this study were:

$RO_1$: Identify the cognitive processes experienced secondary engineering students use to design, make, and evaluate functional prototypes to an engineering design problem.

$RO_2$: Identify the cognitive processes traditional post-secondary engineering students use to design, make, and evaluate functional prototypes to an engineering design problem.

$RO_3$: Compare the design cognition and performance of experienced secondary and traditional post-secondary engineering students.

$RO_4$: Determine potential identifiers within engineering design cognition related to student aptitude in successfully designing and making solutions.

Working hypotheses were established for the third research objective of comparing the design cognition of experienced secondary engineering students and traditional post-secondary engineering students. The researchers expected the traditional post-secondary engineering students to have completed a more rigorous study of science and mathematics for entry into a college engineering program and have also been exposed to college level engineering design models. Therefore, the post-secondary students should exhibit a more informed and analytical process of solution development while the secondary students should exhibit more of a practical and more prototype-oriented process of solution development. Specifically, the researchers hypothesized that the post-secondary students will (a) devote more time to designing a solution (i.e., cognitive processes such as *Defining Problem(s)*, *Designing*, *Analyzing*, and *Predicting*) and less time physically making a solution (i.e., the cognitive process *Modeling/Prototyping Constructing*), (b) employ the scientific and mathematical cognitive processes (*Computing, Interpreting Data, Observing, Experimenting*, and *Questioning/Hypothesizing*) for a greater amount of time than secondary students, and (c) the post-secondary students will develop more effective (i.e., better at solving the problem) solutions to the design task. Lastly, a working hypothesis for the fourth research objective was that specific cognitive processes could be identified as significant predictors of design performance.

## 5. Methodology

### *5.1 Data collection and analysis*

This study employed a multiple exploratory case study approach using a concurrent think-aloud protocol procedure to identify the cognitive processes used by both secondary and traditional post-secondary engineering students as they worked to develop physical solutions to an engineering design task. The concurrent think-aloud protocol procedure is a method used to capture a participant's behaviors and commentary on their own thought processes as they occur during a predetermined activity such as an engineering design challenge [2]. The resulting verbal commentary is then analyzed, using a verbal protocol analysis technique, which applies a previously derived coding scheme to audio/video recordings of a design session [39]. Ericsson and Simon [43] explain that concurrent think-aloud protocols represent one's directly verbalized cognitive processes and thus, they maintain that the verbal protocol analysis can be an effective research methodology to examine an individual's cognitive processes. Atman and Bursic [23] also state that using a verbal protocol analysis for assessing the cognitive processes of engineering students is an appropriate method for understanding the processes used while developing a design solution. Therefore, the participants in this study were asked to verbalize their thoughts while engaged in an engineering design task. The participants were also required to complete the task alone, instead of in a group setting; to help capture their individual thought processes while also minimizing any outside interference. To facilitate data collection, participants were equipped with point-of-view cameras that captured verbal commentary as well as the participants' non-verbal cues (i.e., hand movements and directed attention). The combination of verbal and observational protocols, in addition to the participants' design artifacts, allowed the triangulation of data—as the verbal protocol alone would be weak if used exclusively in capturing a participant's cognitive processes [35]. In addition, a demographics survey was used to identify the prior experiences of the recruited participants. Fig. 1 provides an overview of the methodology for this study.

The engineering design challenge (see Table 1) for this study was developed to support the collection of

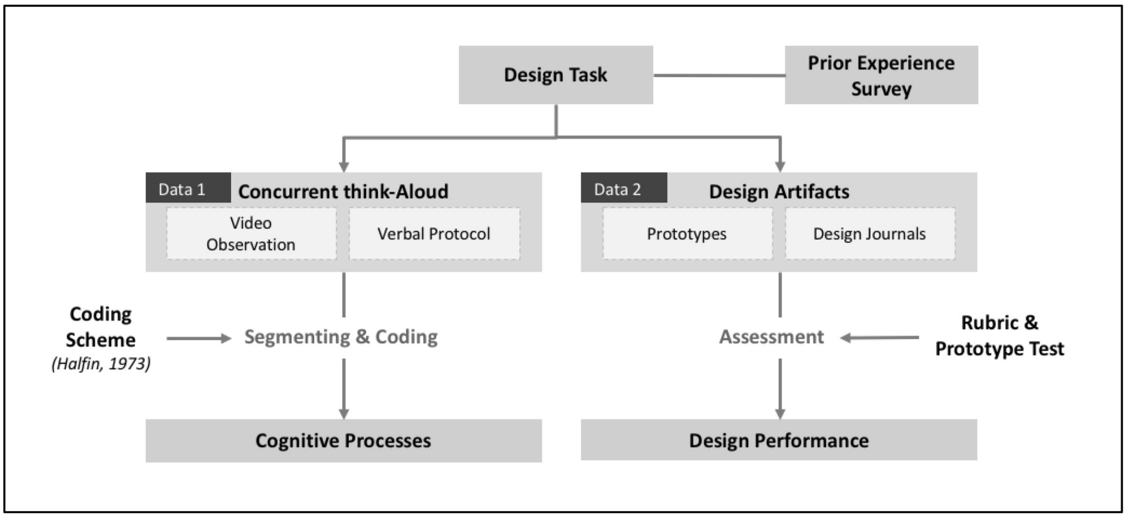


**Fig. 1.** The overview of procedures used for the study.

Table 1. Engineering design task as presented to the participants

| | |
|---|---|
| **Introduction** | In many developing countries, clean water is not readily accessible and therefore disease and illness is spread. This is especially true in the aftermath of natural disasters in these areas. While there are many challenges related to clean water, purification is an important part of many water treatment processes. |
| **Problem Statement** | People in developing countries do not have continuous access to clean water, especially after the onset of a natural disaster. Water in these situations needs significant purification. However, water purification units are expensive and not easy to obtain. Therefore, you are tasked to design an inexpensive, easy to use, easy to assemble, durable, and low maintenance water purification system using low cost, readily available materials to quickly remove contaminants from water. You will focus on reducing the turbidity of a sample of water. |
| **Testing Performance** | Turbidity is a measure of the lack of clarity (cloudiness) of water and is a key test of water quality. Turbidity is apparent when light reflects off of particles in the water. Some sources of turbidity include soil erosion, waste discharge, urban runoff, and algal growth. In addition to creating an unappealing cloudiness in drinking water, turbidity can be a health concern. It can sustain or promote the growth of pathogens in the water distribution system, which can lead to the spread of waterborne diseases. Turbidity is measured in Nephelometric Turbidity Units, NTU. Water is visibly turbid at levels above 5 NTU. However, the standard for drinking water is typically 1.0 NTU or lower. |
| **Prototype Materials** | • You are not limited to any specific materials.<br>• You can use any materials necessary to create the best solution.<br>• You should not be concerned with material availability.<br>• You should design your solution to best meet the specified criteria and constraints. |
| **Equipment/Supplies** | • Computer and Internet access, distilled water, contaminated water, water sample bottle with lid, paper towel, bucket, Vernier turbidity sensor/equipment, LabQuest Mini, Logger Pro software. |
| **Deliverables** | • Functioning Prototype of Quality Construction.<br>• Project Journal.<br>• Solution Analysis—A summary of the details of the design, its benefits, uses, and other important information that explains the design solution. |

verbal and observational protocol while participants designed, made, and evaluated their physical prototype. Data were collected as participants progressed through the full design process spectrum rather than only collecting data while they developed a solution concept. This enabled the researchers to compare a participant's cognitive strategies with the effectiveness of their final prototype. This process may be one method for bridging design cognition research with practice as it can help determine cognitive predictors for developing successful resolutions to design challenges and can identify design heuristics for enhancing design capabilities. Consequently, the design challenge for this study was developed to enable the researchers to collect quantitative data on the effectiveness of each participant's solution to better determine potential relationships between solution effectiveness and the mental strategies employed by participants. In addition, the classroom instructors used the rubric in in Table 2 to holistically evaluate the student projects.

The engineering design challenge was presented to the participants as an ill-structured, open-ended, real-world issue. The challenge required participants to define the problem, identify the criteria and constraints, determine the materials needed for their proposed solution prototype, and then make, test, and optimize their solution. The posed problem tasked the participants with designing, making, and evaluating a system or device that would help reduce the contamination of water in a developing nation after the onset of a natural disaster. Each participant was asked to work in isolation and was not limited by time. The participants were all provided the same materials and production facility as well as a computer-based turbidity sensor to evaluate how well their device removes potential contaminates from a water sample. Figs. 2 and 3 provide samples of the student design work for the challenge provided.

Following data collection, the recordings of each participant's enacted design process were divided into three distinct phases: designing, making, and evaluating. See Table 3 for a description of these phases. The concurrent think-aloud protocol for each phase were simultaneously segmented and coded using the 17 mental processes for technological problem solving defined and validated by Halfin [44]. The operational definitions of these processes and sample utterances are provided in Table 4. However, based on a review of literature, the mental process of *Modeling* was determined by the researchers to be too similar to the other codes of *Model/Prototype Constructing* and *Designing*. The inability to differentiate between these codes was stated in the original work by Halfin [44]. As a result, the use of *Modeling* as a mental processing code was avoided and the actions that could be considered *Modeling* were coded as either *Designing* or *Model/Prototype Constructing*.

To enable the coding process, the researchers used Hill's [47] *Observational Procedures for*

**Table 2.** Engineering design challenge rubric

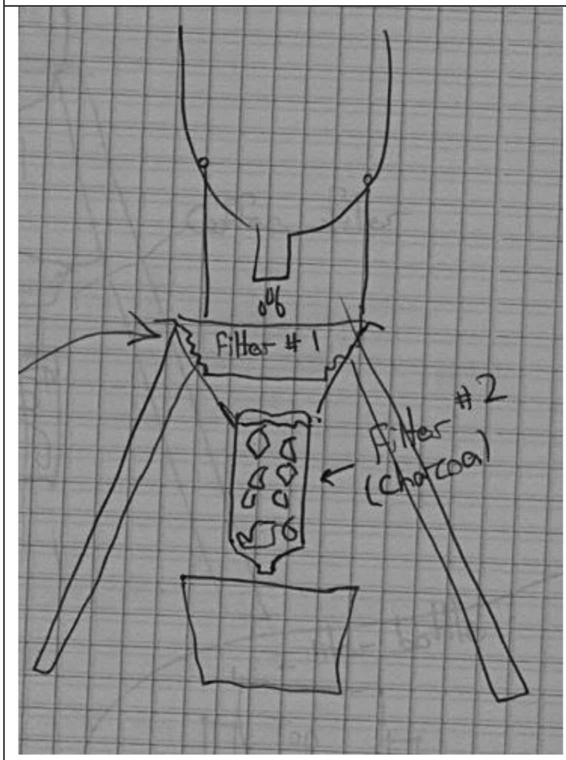
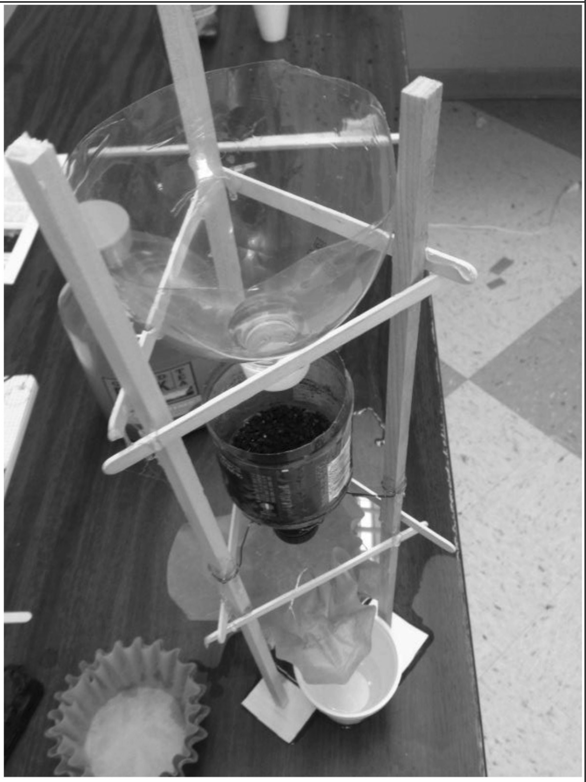
| Category | 5 – 4 Points | 3 – 2 Points | 1 – 0 Points |
|---|---|---|---|
| **Research** | Thoroughly researched and documented existing solutions and necessary concepts. | Few existing solutions and necessary concepts were researched and documented. | No evidence that research was conducted. |
| **Multiple Solutions** | Developed multiple conceptual solution ideas. | Developed only a few conceptual solution ideas. | Did not consider multiple solution ideas. |
| **Design Justification** | A robust justification for following a particular design idea is clearly stated. | A weak justification for following a particular design idea is stated. | A justification for following a particular design idea is not provided. |
| **Material Selection** | Appropriate materials were selected and properly manipulated to make a quality solution meeting the established criteria and constraints. | A few of the materials used were of quality and enabled the making of a solution that met all of the criteria and constraints. | Materials used did not aid in the creation of a quality solution. |
| **Prototype Performance** | After filtration, the clarity of the water is less than 1 NTU. | After filtration, the turbidity was reduced. | After filtration, the clarity of the water has not changed. |
| **Prototype Durability** | The final product received no damage or wears and required no adjustments or repairs during testing. | The final product received some damage or wear during testing but was easily repaired. Minor adjustments were required. | The final product received significant damage or wear during testing that was not easily repaired and interfered with testing. |
| **Prototype Use** | The final product could be easily set up and used with little or no instruction. | The final product would require careful set up with some instruction. | The final product is very difficult to set up and requires extensive or complicated instructions. |
| **Engineering Notebook** | All Best Practices for Engineering Notebook are applied | 60% of Best Practices for Engineering Notebook are applied. The quality of documented information is poor. | Less than 40% of Best Practices for Engineering Notebook are applied. Few or no Engineering notebook entries are included. |
| **Prototype Testing** | Test procedures are followed and correct data are collected. The student is knowledgeable regarding the reason for the test, each step in the procedure, and the significance of the data. | Minor deviations in test procedures and data collection occur. The student is unfamiliar with the reason for the tests performed. | Little to no evidence exists to indicate that prototype test procedures were conducted. |
| **Prototype Revision** | The test evaluation results in suggestions for improvement. Detailed description of the design modifications that were made based upon the results of prototype testing. | The test evaluation results in suggestions for improvement. Less than adequate description of the design modifications that were made based upon the results of prototype testing. | Little to no evidence exists that revisions are considered or made. |

*Technology Education Mental Processes* (OPTEMP) computer analysis tool, which permits a researcher to both segment, and code, verbal protocols simultaneously while observing video recordings. Once each video is coded, the OPTEMP tool generates a spreadsheet with the quantity of time each participant employed each cognitive process. To ensure the reliability of this procedure, two coders independently coded each participant's protocols and a Pearson's *r* correlation coefficient between the coding results was calculated. The Pearson's *r* calculation revealed a reliable level of consistency in the coding results. The mean correlation coefficient between codes, for all 20 participants, was 0.902 ($n$ = 17 [represents the number of mental processes], $p = 0.00$), demonstrating highly reliable results in the identified codes.

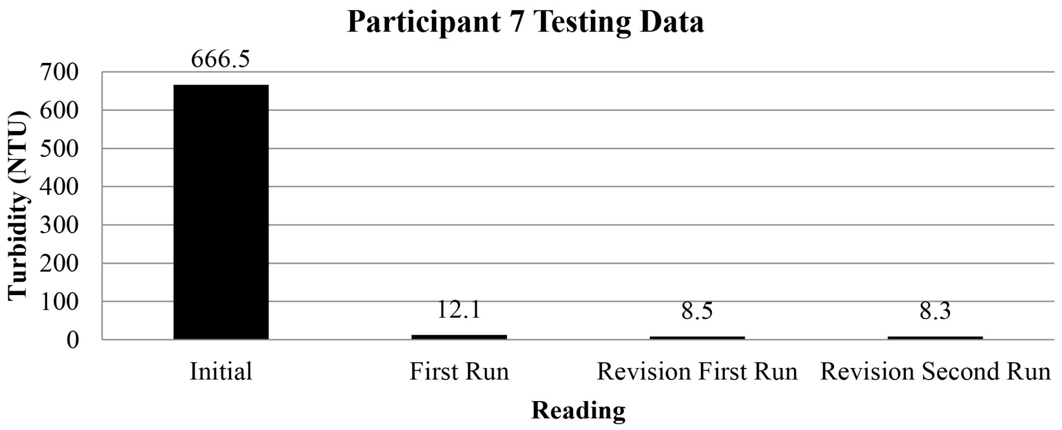
### *5.2 Participants*

This study included twenty purposefully selected participants: eight experienced secondary engineering students (age 16–18) and 12 post-secondary students (age 18+) whom were within their first-year of an engineering major at a university. The experienced secondary students were selected based on their involvement in engineering/technology coursework in high school. Each of these students were enrolled in the capstone course of the *Project Lead the Way* [48] high school engineering program at two high schools in the southeast region of the United States. The post-secondary engineering students were enrolled in the first required engineering design course at a land-grant, space-grant, and research-intensive public university in the Appalachian region of the southern United States. The

**Sample Secondary Student Project**

| Design | Prototype |
|---|---|
|  |  |

**Testing Results:**

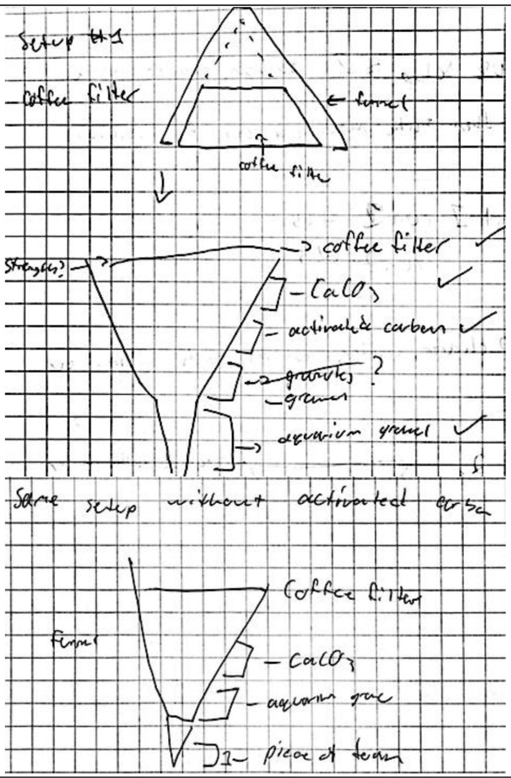


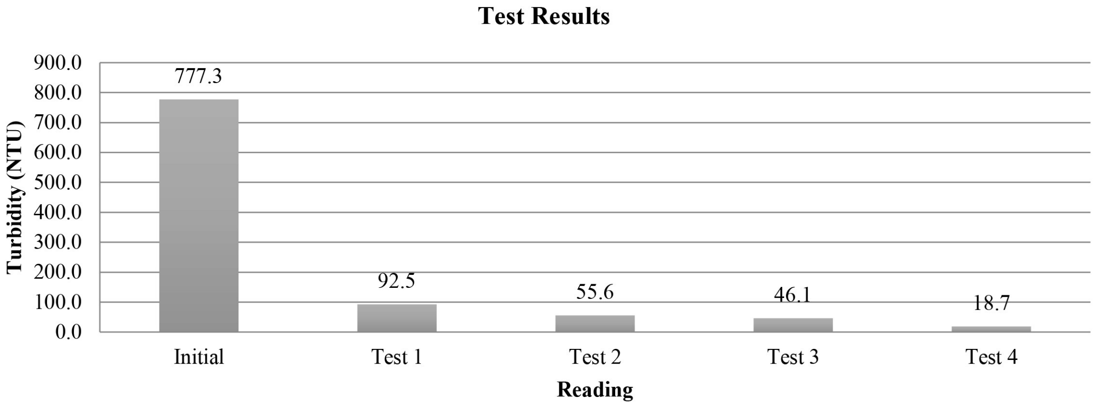
**Student Solution Analysis:**
The design involved layered filters held together in a tower. First charcoal, then sand, then stuck a cotton ball down in the bottle. Then led to two layers of coffee filters. Advantages: Structurally sound, consists of recycled materials and household items, minimum work, filters several cups of water at a time. Disadvantages: Time consuming (10 minutes to fill), turbidity at 8.5 (3 above visible; 7 above acceptable level for drinking water), nothing in filter acting, as a disinfectant; cotton balls, filters, etc. need to be constantly replaced.

**Fig. 2.** Sample secondary student project.

participants were purposefully selected from the introductory engineering course as it enabled data to be collected from a "traditional" cohort of students beginning their pursuit of an engineering major while being introduced to the concept of engineering design. The term "traditional" is used in connection with commonly practiced metrics used for admittance into an engineering major, which can be broadly viewed as requiring students to have completed a series of advanced mathematics and science courses. Important to the study, these metrics do not include completing prerequisite

**Sample Post-Secondary Student Project**

| Design | Prototype |
|---|---|
|  |  |



**Student Solution Analysis:**

1) 1st filter funnel, two pieces of foam at the bottom of funnel. Filled funnel with aquarium gravel, gravels, activated carbon, Caco3, then place coffee filter on tap. 2) Poured original sample in, that reading was 423. Water came out black, still black that had lower NTU. 3) Took original resulting water, poured it back it, but it went slower. Enough water came out that was able to be tested. Got a reading of 61.3. 4) Tested activated carbon alone and it made water black as the original resulting sample. So, I took out activated carbon and ran Setup2 with 1 piece of foam, aquarium gravel and CaCo3. Resulting NTV was higher than original NTU. 5) CaCo3 is essential to the filter but should be run several times through (Two times in Setup1). 6) What to do in the future: Make two setups, exactly the same, 1 piece of foam on the bottom, but run water through each setup twice. Take resulting water from Setup1 and run it through Setup2.

**Fig. 3.** Sample post-secondary student project.

coursework in engineering/technology such as *Project Lead the Way* during high school; therefore, most of the post-secondary participants did not have experiences in engineering/technology courses while in high school—a defining difference in the two samples included in this study. Thus, the research assumed that the comparison between the two groups would facilitate the identification of possible effects related to prior experiences in engineering/technology coursework on engineering

**Table 3.** Design Phase Descriptions

| Design Process Phases | Description |
|---|---|
| Design Phase | This phase occurred at the beginning of the problem-solving process and generally consisted of the practices of:<br>• Problem Scoping<br>• Information Gathering<br>• Ideation<br>• Solution Concept Development<br>• Concept Selection |
| Making Phase | This phase occurred during the middle portion of problem solving process and generally consisted of the practices of:<br>• Prototype Production<br>• Material Gathering<br>• Material Experimentation |
| Evaluation Phase | This phase occurred during the final portion of problem solving process and generally consisted of the practices of:<br>• Prototype Testing<br>• Data Collection/Analysis<br>• Concept/Prototype Refinement<br>• Additional Information Gathering |

design cognition and performance. Participant background data were collected through a demographics survey to provide a description of the subjects being studied and investigate comparability across groups. This information was used to determine participant similarities and differences in engineering experience.

The secondary group consisted of two female and six male participants with a cumulative high school grade point average at or above 3.6. Each participant completed the *Introduction to Engineering Design*, *Principles of Engineering*, and *Digital Electronics Project Lead the Way* high school pre-engineering courses and was enrolled in the capstone *Engineering Design and Development* course at the time of the study. Additionally, each participant completed at least Algebra I, Algebra II, Geometry, and Trigonometry/Pre-Calculus courses as well as at least one biology and physics course. Lastly, each of the participants was active in the *Skills USA* technical workforce competition program and each was interested in a future career in engineering.

The post-secondary engineering group was comprised of four female and eight male participants with an average age of 20 years who were enrolled in the first calculus-based engineering design course. All participants were either enrolled in or had completed college Calculus I at the time of the study. Additionally, six of these students reported having some experience with calculus or pre-calculus while in high school and almost all participants reported completion of high school coursework in physics (11), chemistry (12), and biology (10). However, only one of the post-secondary participants had experience in engineering/technology (*Project Lead the Way*) coursework while in high school.

The researchers do note that the number of participants is a limitation. However, design cognition research typically involves a small number of participants due to the qualitative nature of the collected data. Therefore, this study is in alignment with other recent design cognition studies at the secondary level, which on average only involve 22 participants.

## 6. Findings

### *6.1 Research Objective 1. Identify the cognitive processes experienced secondary engineering students use to design, make, and evaluate functional prototypes to an engineering design problem*

The first research objective was met by coding audio/video recordings of participants thinking aloud during a complete engineering design session. The codes used in the data analysis were a set of 17 mental processes used in technological problem solving, identified and validated by Halfin [44] and revalidated by Wicklein and Rojewski [46]. On average, the secondary participants completed the challenge in one hour, 50 minutes, and 35.8 seconds. Throughout the entire engineering design activity, the top three most employed mental processes by secondary engineering students were *Model/Prototype Constructing*, *Analyzing*, and *Managing*. *Model/Prototype Constructing* consumed 23.3 percent of the participant's time on average, which mostly consisted of physically manipulating materials. Next, *Analyzing* consumed 15.8 percent of the participant's time on average and consisted mostly of information gathering and analyzing the effectiveness of various design decisions. Lastly, *Mana-*

**Table 4.** Halfin's 17 Mental Processes for Solving Technological Problems [44–46]

| Cognitive Process | Definition & Sample Utterance |
|---|---|
| **Analyzing** | This is the process of identifying, isolating, taking apart, breaking down, or performing similar actions for the purpose of setting forth or clarifying the basic components of a phenomenon, problem, opportunity, object, system, or point of view. *"I believe I have a design flaw which is this right here."* |
| **Communicating** | This is the process of conveying information (or ideas) from one source (sender) to another (receiver) through a media using various modes (The modes may be oral or written or pictures or symbols, or any combination of these.). *"Let's write down the original sample number."* |
| **Computing** | This is the process of selecting and applying mathematical symbols, operations, and processes to describe, estimate, calculate, quantify, relate, and/or evaluate in the real or abstract numerical sense. *"At 14 inch intervals, I will need 2 of them."* |
| **Creating** | This is the process of combining the basic components or ideas of phenomena, objects, events, systems, or points of view in a unique manner that will better satisfy a need, either for the individual or for the outside world. *"I should combine both ideas."* |
| **Defining problem(s)** | This is the process of stating or defining a problem, which will then enhance the investigation leading to an optimal solution. It is transforming one state of affairs to another desired state. *"What does the device need to do?"* |
| **Designing** | This is the process of conceiving, creating, inventing, contriving, sketching, or planning by which some practical ends may be affected, or proposing a goal to meet the societal needs, desires, problems, or opportunities and do things better. Design is a cyclic or iterative process of continuous refinement or improvement. *"Let's just create a sketch here."* |
| **Experimenting** | This is the process of determining the effects of something previously untried in order to test the validity of a hypothesis, to demonstrate a known (or unknown) truth, or to try out various factors relating to a particular phenomenon problem, opportunity element, object, event, system, or point of view. *"Let us see what works better for the base then the foam I have."* |
| **Interpreting data** | This is the process of clarifying, evaluating, explaining, and translating to provide (or communicate) the meaning of particular data. *"I can deduct that this way of sampling is not working."* |
| **Managing** | The process of planning, organizing, directing, coordinating, and controlling the inputs and outputs of the system. *"I will move all of our stuff back to the table."* |
| **Measuring** | This is the process of describing characteristics (by the use of numbers) of a phenomenon, problem, opportunity, element, object, event, system, or point of view in terms that are transferable. Measurements are made by direct or indirect means, are on relative or absolute scales, and are continuous or discontinuous. *"I know it needs to be at least this big."* |
| **Modeling*** | This is the process of producing or reducing an act or condition to a generalized construct that may then be presented graphically in the form of a sketch, diagram, or equation; physically in the form of a scale model or prototype; or in the form of a written generalization. |
| **Model/Prototype Constructing** | This is the process of forming, making, building, fabricating, creating, or combining parts to produce a scale model or prototype. *"I need a pair of scissors to cut a hole in the bottom."* |
| **Observing** | This is the process of interacting with the environment through one or more of the senses (seeing, hearing, touching, smelling, or tasting). The senses are utilized to determine the characteristics of a phenomenon, problem, opportunity, element, object, event, system, or point of view. The observer's experiences, values, and associations may influence the results. *"Visually, I can tell I'm not doing any better."* |
| **Predicting** | This is the process of prophesying or foretelling something in advance, anticipating the future based on special knowledge. *"That's not going to work."* |
| **Questioning/ Hypothesizing** | Questioning is the process of asking, interrogating, challenging, or seeking answers related to a phenomenon, problem, opportunity, element, object, event, system, or point of view. *"What materials will work best?"* |
| **Testing** | This is the process of determining the workability of a model, component, system, product, or point of view in a real or simulated environment to obtain information for clarifying or modifying design specifications. *"Okay let's do this!"* |
| **Visualizing** | This is the process of perceiving a phenomenon, problem, opportunity, element, object, event, or system in the form of a mental image based on the experience of the perceiver. It includes an exercise of all the senses in establishing a valid mental analogy for the phenomena involved in a problem or opportunity. *"If I poke holes in the cup here, the water will run into there."* |

* *Modeling* was not used as a code in this study as a review of literature indicated difficulty in differentiating this process from others, such as *Model/Prototype Constructing* and *Designing.*

*ging* consumed 13.9 percent of participant time and consisted mostly of the participants planning their actions and gathering necessary resources. The least used mental processes were *Experimenting* (0.7%), *Computing* (0.08%), *Questioning/Hypothesizing* (1.9%), *Defining Problems* (2.0%), *Interpreting Data* (2.1%), *Predicting* (2.3%), and *Measuring* (2.6%). Each participant's cognitive processes data for the entire engineering design session is reported in Table 5. The average time for each mental process employed by the secondary-level participants can be found in Table 6.

**Table 5.** Secondary Cognitive Processes During Engineering Design Activity

| | **Time (Hours:Minutes:Seconds)** | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| **Code** | **Participant 1** | **Participant 2** | **Participant 3** | **Participant 4** | **Participant 5** | **Participant 6** | **Participant 7** | **Participant 8** |
| Analyzing | 0:09:41 | 0:23:54 | 0:23:10 | 0:18:33 | 0:21:23 | 0:20:04 | 0:13:22 | 0:09:34 |
| Communicating | 0:07:44 | 0:15:51 | 0:07:31 | 0:04:19 | 0:07:07 | 0:03:30 | 0:03:39 | 0:02:23 |
| Computing | 0:01:28 | 0:03:13 | 0:00:28 | 0:00:20 | 0:00:28 | 0:00:25 | 0:00:29 | 0:00:10 |
| Creating | 0:01:01 | 0:01:59 | 0:04:01 | 0:04:20 | 0:03:01 | 0:00:53 | 0:04:29 | 0:03:36 |
| Designing | 0:06:52 | 0:10:20 | 0:08:23 | 0:10:35 | 0:07:58 | 0:08:18 | 0:09:23 | 0:02:17 |
| Defining Problems | 0:03:38 | 0:01:11 | 0:01:44 | 0:01:30 | 0:01:38 | 0:04:37 | 0:01:29 | 0:01:52 |
| Experimenting | 0:00:40 | 0:01:25 | 0:01:11 | 0:00:06 | 0:01:00 | 0:01:26 | 0:00:11 | 0:00:34 |
| Interpreting Data | 0:04:56 | 0:05:23 | 0:01:14 | 0:01:36 | 0:02:56 | 0:01:35 | 0:00:20 | 0:00:53 |
| Managing | 0:13:06 | 0:21:49 | 0:14:24 | 0:17:09 | 0:12:58 | 0:14:44 | 0:12:00 | 0:17:08 |
| Measuring | 0:02:24 | 0:04:16 | 0:01:08 | 0:02:32 | 0:02:56 | 0:00:48 | 0:07:34 | 0:01:12 |
| Modeling | 0:00:00 | 0:00:56 | 0:00:00 | 0:00:23 | 0:00:00 | 0:00:00 | 0:00:00 | 0:00:00 |
| Model/Prototype Constructing | 0:20:34 | 0:06:48 | 0:39:19 | 0:35:16 | 0:15:01 | 0:24:20 | 0:38:33 | 0:26:47 |
| Observing | 0:05:07 | 0:09:09 | 0:02:08 | 0:05:22 | 0:04:58 | 0:04:46 | 0:02:57 | 0:04:00 |
| Predicting | 0:02:23 | 0:05:21 | 0:02:46 | 0:02:09 | 0:02:19 | 0:01:36 | 0:01:49 | 0:01:38 |
| Questioning/Hypothesizing | 0:01:55 | 0:02:07 | 0:02:07 | 0:01:46 | 0:01:59 | 0:01:59 | 0:02:30 | 0:02:24 |
| Testing | 0:13:31 | 0:25:07 | 0:13:08 | 0:10:08 | 0:16:14 | 0:07:37 | 0:04:55 | 0:07:58 |
| Visualizing | 0:03:11 | 0:01:20 | 0:01:36 | 0:06:44 | 0:01:45 | 0:03:59 | 0:06:34 | 0:03:11 |
| **TOTAL** | **1:38:09** | **2:20:11** | **2:04:20** | **2:02:48** | **1:43:41** | **1:40:39** | **1:50:13** | **1:25:39** |

**Table 6.** Mean Cognitive Process Times for all Secondary Students (N = 8)

| **Code** | **$\bar{x}$ Time (Hours:Minutes:Seconds)** | **Code** | **$\bar{x}$ Time (Hours:Minutes:Seconds)** |
|---|---|---|---|
| Analyzing | 17:27.5 | Measuring | 02:51.1 |
| Communicating | 06:30.5 | Modeling | 00:09.8 |
| Computing | 00:52.5 | Model/Prototype Constructing | 25:49.8 |
| Creating | 02:54.9 | Observing | 04:48.5 |
| Designing | 08:00.8 | Predicting | 02:30.2 |
| Defining Problems | 02:12.6 | Questioning/Hypothesizing | 02:05.9 |
| Experimenting | 00:49.3 | Testing | 12:20.0 |
| Interpreting Data | 02:21.8 | Visualizing | 03:32.5 |
| Managing | 15:24.8 | **Total Design Time** | 1:50:35.8 |

*Note.* $\bar{x}$ represents the sample mean for all secondary students.

### *6.2 Research Objective 2. Identify the cognitive processes traditional post-secondary engineering students use to design, make, and evaluate functional prototypes to an engineering design problem*

As before, this objective was also met by coding audio/video recordings of participants thinking aloud during a complete engineering design session. On average, the post-secondary participants completed the challenge within one hour, 21 minutes, and 16 seconds. Throughout the entire engineering design activity, the three most employed mental processes were *Model/Prototype Constructing*, *Managing*, and *Testing*. *Model/Prototype Constructing* consumed 28.9 percent of the participant's time on average, which consisted mostly of physically manipulating materials. Next, *Managing* consumed 23.8 percent of their time on average and consisted mostly of the participants planning their actions and gathering necessary resources. Lastly, *Testing* consumed 10.5 percent of their time on average and consisted mostly of operating their devices with the purpose of collecting data to determine how well it performed. The least used mental processes were *Computing* (0.3%), *Measuring* (1.2%), *Predicting* (1.4%), *Interpreting Data* (1.4%), *Visualizing* (2.2), and *Questioning/Hypothesizing* (2.2%). Each participant's cognitive process data for the entire engineering design session is reported in Tables 7. The secondary participant group average of each process can be seen in Table 8.

### *6.3 Research Objective 3. Compare the design cognition and performance of experienced secondary and traditional post-secondary engineering students*

To achieve this objective, the researchers performed a comparison between secondary and post-secondary participants' design cognition using the Mann-Whitney statistical test. This approach was intentionally pursued, as the Mann-Whitney test is less sensitive to the concern of the cognitive process data

**Table 7.** Post-Secondary Cognitive Processes During Engineering Design Activity

| | **Time (Hours:Minutes:Seconds)** | | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| **Code** | **Participant 1** | **Participant 2** | **Participant 3** | **Participant 4** | **Participant 5** | **Participant 6** | **Participant 7** | **Participant 8** | **Participant 9** | **Participant 10** | **Participant 11** | **Participant 12** |
| Analyzing | 0:04:02 | 0:02:02 | 0:02:19 | 0:03:54 | 0:03:14 | 0:08:22 | 0:06:55 | 0:01:50 | 0:05:41 | 0:05:44 | 0:05:57 | 0:01:58 |
| Communicating | 0:02:48 | 0:00:00 | 0:01:19 | 0:01:02 | 0:00:54 | 0:02:09 | 0:04:05 | 0:01:16 | 0:03:35 | 0:01:27 | 0:03:24 | 0:06:23 |
| Computing | 0:00:00 | 0:00:00 | 0:00:21 | 0:00:03 | 0:00:00 | 0:00:08 | 0:00:15 | 0:01:33 | 0:00:08 | 0:00:29 | 0:00:13 | 0:00:00 |
| Creating | 0:02:02 | 0:06:21 | 0:02:02 | 0:04:40 | 0:03:09 | 0:01:27 | 0:02:00 | 0:01:35 | 0:10:18 | 0:03:32 | 0:05:16 | 0:03:31 |
| Designing | 0:02:53 | 0:00:00 | 0:01:59 | 0:01:04 | 0:00:43 | 0:03:09 | 0:00:18 | 0:01:02 | 0:03:30 | 0:03:23 | 0:02:55 | 0:05:05 |
| Defining Problems | 0:03:24 | 0:01:17 | 0:01:17 | 0:00:53 | 0:00:24 | 0:00:58 | 0:04:03 | 0:03:37 | 0:04:16 | 0:01:39 | 0:00:39 | 0:03:26 |
| Experimenting | 0:02:18 | 0:05:09 | 0:02:44 | 0:00:05 | 0:03:27 | 0:08:11 | 0:02:14 | 0:03:34 | 0:01:38 | 0:01:53 | 0:09:43 | 0:01:43 |
| Interpreting Data | 0:01:05 | 0:01:05 | 0:01:44 | 0:00:28 | 0:01:42 | 0:01:09 | 0:01:07 | 0:00:25 | 0:01:24 | 0:00:11 | 0:02:52 | 0:00:38 |
| Managing | 0:20:09 | 0:16:26 | 0:23:23 | 0:16:16 | 0:15:17 | 0:17:46 | 0:23:26 | 0:20:46 | 0:18:47 | 0:19:44 | 0:21:41 | 0:18:47 |
| Measuring | 0:00:00 | 0:00:00 | 0:00:43 | 0:00:20 | 0:00:22 | 0:00:13 | 0:00:47 | 0:00:31 | 0:00:30 | 0:05:16 | 0:02:28 | 0:01:01 |
| Modeling | 0:00:00 | 0:00:00 | 0:00:00 | 0:00:00 | 0:00:00 | 0:00:00 | 0:00:00 | 0:00:00 | 0:00:00 | 0:00:00 | 0:00:00 | 0:00:00 |
| Model/Prototype Constructing | 0:23:15 | 0:24:03 | 0:21:34 | 0:32:35 | 0:21:26 | 0:14:09 | 0:12:39 | 0:16:57 | 0:26:48 | 0:37:53 | 0:21:07 | 0:29:40 |
| Observing | 0:05:01 | 0:04:21 | 0:07:46 | 0:01:47 | 0:06:49 | 0:03:36 | 0:03:20 | 0:06:03 | 0:02:47 | 0:02:36 | 0:05:21 | 0:02:12 |
| Predicting | 0:01:54 | 0:01:22 | 0:01:16 | 0:01:41 | 0:01:10 | 0:00:20 | 0:00:05 | 0:00:00 | 0:02:34 | 0:01:09 | 0:01:35 | 0:00:22 |
| Questioning/Hypothesizing | 0:00:46 | 0:02:31 | 0:00:57 | 0:01:49 | 0:03:00 | 0:02:12 | 0:01:39 | 0:00:19 | 0:02:45 | 0:01:34 | 0:03:25 | 0:00:43 |
| Testing | 0:04:24 | 0:04:45 | 0:08:43 | 0:04:25 | 0:19:19 | 0:07:42 | 0:10:41 | 0:12:36 | 0:08:14 | 0:03:54 | 0:08:00 | 0:09:50 |
| Visualizing | 0:02:44 | 0:01:36 | 0:01:01 | 0:03:55 | 0:01:35 | 0:01:18 | 0:00:21 | 0:00:32 | 0:03:35 | 0:03:00 | 0:00:53 | 0:00:51 |
| **TOTAL** | **1:16:45** | **1:10:58** | **1:19:08** | **1:14:56** | **1:22:33** | **1:12:48** | **1:13:56** | **1:12:36** | **1:36:29** | **1:33:23** | **1:35:30** | **1:26:11** |

**Table 8.** Mean Cognitive Process Times for all Post-Secondary Students (N = 12)

| **Code** | **$\bar{x}$ Time (Hours:Minutes:Seconds)** | **Code** | **$\bar{x}$ Time (Hours:Minutes:Seconds)** |
|---|---|---|---|
| Analyzing | 04:19.8 | Measuring | 01:00.9 |
| Communicating | 02:21.8 | Modeling | 00:00.0 |
| Computing | 00:15.9 | Model/Prototype Constructing | 23:30.4 |
| Creating | 03:49.5 | Observing | 04:18.3 |
| Designing | 02:10.0 | Predicting | 01:07.4 |
| Defining Problems | 02:09.4 | Questioning/Hypothesizing | 01:48.3 |
| Experimenting | 03:33.2 | Testing | 08:32.8 |
| Interpreting Data | 01:09.2 | Visualizing | 01:46.7 |
| Managing | 19:22.5 | **Total Design Time** | 1:21:16.0 |

*Note.* $\bar{x}$ represents the sample mean for all post-secondary students.

**Table 9.** Mann-Whitney Analysis between Secondary and Post-Secondary Participants

| | **Mean Time Dedicated to Each Cognitive Process (sec.)** | | | |
|---|---|---|---|---|
| | **Secondary ($N = 8$)** | **Post-Secondary ($N = 11$)** | **Mann-Whitney $U$** | **Asymp. Sig. (2-tailed)** |
| **Analyzing** | 1047.63 | 261.45 | 0.000** | 0.000 |
| **Communicating** | 390.50 | 139.45 | 10.000** | 0.005 |
| **Computing** | 52.63 | 17.27 | 16.500* | 0.023 |
| Creating | 175.00 | 239.18 | 34.000 | 0.409 |
| **Designing** | 480.75 | 126.18 | 5.000** | 0.001 |
| Defining Problems | 132.38 | 122.64 | 32.000 | 0.322 |
| **Experimenting** | 49.13 | 220.09 | 8.000** | 0.003 |
| Interpreting Data | 141.63 | 69.55 | 27.000 | 0.160 |
| **Managing** | 924.75 | 1158.09 | 15.000* | 0.017 |
| **Measuring** | 171.25 | 66.45 | 12.000** | 0.008 |
| Modeling | 9.88 | 0.00 | 33.000 | 0.088 |
| Model/Prototype Constructing | 1549.75 | 1411.91 | 37.000 | 0.563 |
| Observing | 288.38 | 254.36 | 37.000 | 0.563 |
| **Predicting** | 150.13 | 63.09 | 8.000** | 0.003 |
| Questioning/Hypothesizing | 125.88 | 114.00 | 39.000 | 0.679 |
| Testing | 739.75 | 535.36 | 29.000 | 0.215 |
| **Visualizing** | 212.50 | 101.55 | 15.500* | 0.019 |
| **Total Design Time** | 6642.39 | 4900.73 | 4.000** | 0.001 |
| **Design Phase Time** | 1776.40 | 915.30 | 10.000** | 0.005 |
| Making Phase Time | 2385.18 | 1637.55 | 24.000 | 0.099 |
| Evaluation Phase Time | 2480.86 | 2347.71 | 40.000 | 0.741 |
| | **Mean** | | | |
| | **Secondary ($N = 8$)** | **Post-Secondary ($N = 11$)** | **Mann-Whitney $U$** | **Asymp. Sig. (2-tailed)** |
| Number of Prototypes Trials | 3.13 | 3.64 | 34.500 | 0.418 |
| **Rubric Score** | 37.75 | 29.18 | 16.000* | 0.021 |
| Final Turbidity | 20.60 | 47.17 | 25.000 | 0.117 |

Note: Post-secondary student 1 was excluded in this test, as they did not produce a testable prototype. It is important to note that *Prototype Trials* refers to the number of times students tested their solutions and that *Final Turbidity* refers to the lowest turbidity level achieved.
* Significant at the 0.05 level (2-tailed). ** Significant at the 0.01 level (2-tailed).

displaying evidence of non-normality. The Mann-Whitney test results indicated that secondary participants dedicated significantly more time employing the mental processes of *analyzing* ($U < 0.000$, $p < 0.000$), *communicating* ($U = 10.000$, $p = 0.005$), *computing* ($U = 16.500$, $p = 0.023$), *designing* ($U = 5.000$, $p = 0.001$), *measuring* ($U = 12.000$, $p = 0.008$), *predicting* ($U = 8.000$, $p = 0.003$), and *visualizing* ($U = 15.500$, $p = 0.019$) than the post-secondary participants. Conversely, the secondary participants dedicated significantly less time employing the cognitive processes of *experimenting* ($U = 8.000$, $p = 0.003$) and *managing* ($U = 15.000$, $p = 0.017$) than the post-secondary participants. Moreover, the Mann-Whitney test indicated that secondary participants devoted significantly more time to completing the entire engineering design session ($U = 4.000$, $p = 0.001$) and specifically the design phase of the process ($U = 10.000$, $p = 0.005$). These results are summarized in Table 9. In terms of design performance, the secondary participants achieved significantly higher rubric scores ($U = 16.000$, $p = 0.021$) than the post-secondary participants. Additional analysis revealed that secondary participant prototypes had better results (e.g., lower turbidity levels) than post-secondary participants, although the difference between the two groups was not statistically significant (see Table 9).

In this study's sample, secondary participants all had educational experiences in engineering design through the *Project Lead the Way* high school engineering program. However, only one post-secondary participant (PS4) reported secondary experience in engineering through the *Project Lead the Way* curriculum. Therefore, to explore significant differences in design cognition between secondary participants having previous educational experiences in engineering design and post-secondary having no experience, another Mann-Whitney test was conducted. To do so, the researchers first prepared the data by removing the post-secondary participant with secondary experiences in engineering design (PS4) and the post-secondary participant who failed to produce a testable prototype (PS1). Following data conditioning the Mann-Whitney test was conducted and the results indicated that the secondary participants having engineering design experiences in high school were significantly different than the post-secondary participants with no previous educational experiences in engineering/technology. Specifically, the secondary participants who completed high school engineering/technology coursework dedicated significantly more time to *analyzing* ($U < 0.000$, $p < 0.000$), *communicating* ($U = 10.000$, $p = 0.008$), *computing* ($U = 16.500$, $p = 0.036$), *designing* ($U = 5.000$, $p = 0.002$), *measuring* ($U = 12.000$, $p = 0.013$), *predicting* ($U = 6.000$, $p = 0.003$), and *visualizing* ($U = 10.500$, $p = 0.009$) than the post-secondary participants having no previous educational experience in engineering design.

**Table 10.** Mann-Whitney Analysis between Secondary Engineering Participants and Post-Secondary Participants without prior Engineering Coursework During High School

| | **Mean Time Dedicated to Each Cognitive Process (sec.)** | | | |
|---|---|---|---|---|
| | **Secondary Engineering Participants ($N = 8$)** | **Post-secondary Participants Without Secondary Engineering Experience ($N = 10$)** | **Mann-Whitney $U$** | **Asymp. Sig. (2-tailed)** |
| **Analyzing** | 1047.63 | 264.20 | 0.000** | 0.000 |
| **Communicating** | 390.50 | 147.20 | 10.000** | 0.008 |
| **Computing** | 52.63 | 18.70 | 16.500* | 0.036 |
| Creating | 175.00 | 235.10 | 34.000 | 0.594 |
| **Designing** | 480.75 | 132.40 | 5.000** | 0.002 |
| Defining Problems | 132.38 | 129.60 | 32.000 | 0.477 |
| **Experimenting** | 49.13 | 241.60 | 0.000** | 0.000 |
| Interpreting Data | 141.63 | 73.70 | 26.000 | 0.214 |
| **Managing** | 924.75 | 1176.30 | 12.000* | 0.013 |
| **Measuring** | 171.25 | 71.10 | 12.000* | 0.013 |
| Modeling | 9.88 | 0.00 | 30.000 | 0.104 |
| Model/Prototype Constructing | 1549.75 | 1357.60 | 32.000 | 0.477 |
| Observing | 288.38 | 269.10 | 37.000 | 0.790 |
| **Predicting** | 150.13 | 59.30 | 6.000** | 0.003 |
| Questioning/ Hypothesizing | 125.88 | 114.50 | 38.000 | 0.859 |
| Testing | 739.75 | 562.40 | 29.000 | 0.328 |
| **Visualizing** | 212.50 | 88.20 | 10.500** | 0.009 |
| **Total Design Time** | 6642.39 | 4941.20 | 4.000** | 0.001 |
| **Design Phase Time** | 1776.40 | 942.75 | 10.000** | 0.008 |
| Making Phase Time | 2385.18 | 1582.77 | 21.000 | 0.091 |
| Evaluation Phase Time | 2480.86 | 2415.47 | 37.000 | 0.790 |
| | **Mean** | | | |
| | **Secondary ($N = 8$)** | **Post-Secondary ($N = 11$)** | **Mann-Whitney $U$** | **Asymp. Sig. (2-tailed)** |
| Number of Prototypes Trials | 3.13 | 3.40 | 34.500 | 0.612 |
| **Rubric Score** | 37.75 | 27.80 | 9.000** | 0.006 |
| Final Turbidity | 20.60 | 51.88 | 18.000 | 0.051 |

Note: Post-secondary student 1 and 4 were excluded in this test. It is important to note that *Prototype Trials* refers to the number of times students tested their solutions and that *Final Turbidity* refers to the lowest turbidity level achieved.
* Significant at the 0.05 level (2-tailed). ** Significant at the 0.01 level (2-tailed).

Further, the data revealed that the secondary participants having engineering design experiences in high school devoted less time to *experimenting* ($U < 0.000$, $p < 0.000$) and *managing* ($U = 12.000$, $p = 0.013$) than the post-secondary participants. Also, the results demonstrated that secondary participants with high school engineering experiences dedicated significantly more time to the design phase of the process ($U = 10.000$, $p = 0.008$). In terms of student performance, the secondary participants achieved significantly higher rubric scores ($U = 9.000$, $p = 0.006$) than the post-secondary students without engineering experiences during high school. In the final turbidity, the secondary participants yielded better test results than post-secondary participants, but was not significant. Table 10 presents the Mann-Whitney analysis results.

For Research Objective 3, this study sought to test three working hypotheses in regards to the comparison of design cognition between secondary and post-secondary participants. First, the researchers hypothesized that post-secondary participants would devote more time to *Defining Problems*, *Designing*, *Analyzing*, and *Predicting* and less time to *Modeling/Prototyping Constructing*. However, the Mann-Whitney tests determined that secondary participants devoted significantly more time to *designing, analyzing*, and *predicting* than post-secondary participants. Additionally, there was no significant difference in the amount of time dedicated to *defining problems* and *model/prototype constructing* between the two groups.

The second hypothesis was that post-secondary participants would employ more scientific and mathematical cognitive processes, such as *Computing, Interpreting Data, Observing, Experimenting*, and *Questioning/Hypothesizing* than secondary participants. The analysis results confirmed that post-secondary participants did devote significantly more time to *experimenting*, however, they spent significantly less time on *computing* than secondary participants. Other cognitive processes demonstrated no significant differences between the two participant groups.

Lastly, the researchers hypothesized that post-secondary participants would develop more effective solutions to the design challenge. The results showed that post-secondary students scored significantly less on the rubric scores than their secondary counterparts. However, the prototype test results (turbidity achieved) were not significantly different between the two groups. Taken together these findings may highlight differences in engineering design cognition between first-year traditional engineering majors and high school students with multiple years of experience in engineering/technology. This may also indicate that traditional cognitive metrics for admittance into engineering programs do not align with actions of designing and making. Lastly, these findings may suggest the importance of expanding engineering education at the secondary level. Table 11 presents the statistical analysis results related to the working hypotheses.

### *6.4 Research Objective 4. Determine potential identifiers within engineering design cognition, related to student aptitude in successfully designing and making solutions*

To achieve Research Objective 4, the researchers examined the performance variables (i.e., rubric score and final turbidity) and the cognitive processes that the participants employed during the design session. Based on the results of the study, participants' rubric scores were significantly correlated to the amount of time they employed the mental processes of *analyzing* ($r = 0.635$, p = 0.003), *communicating* ($r = 0.528$, $p = 0.020$), *designing*

**Table 11.** Statistical Results on Working Hypotheses

| | **Working Hypotheses** | | **Result** |
|---|---|---|---|
| (a) Designing and Making Solutions | Defining Problems (DP) | S < PS | S = PS |
| | Designing (DE) | S < PS | S > PS ** |
| | Analyzing (AN) | S < PS | S > PS ** |
| | Predicting (PR) | S < PS | S > PS ** |
| | Model/Prototype Constructing (MP) | S > PS | S = PS |
| (b) Scientific and Mathematical Cognitive Process | Computing (CP) | S < PS | S > PS * |
| | Interpreting Data (ID) | S < PS | S = PS |
| | Observing (OB) | S < PS | S = PS |
| | Experimenting (EX) | S < PS | S < PS ** |
| | Questioning/Hypothesizing (QH) | S < PS | S = PS |
| (c) Solution Effectiveness | Rubric Score | S < PS | S > PS * |
| | Prototype Test Result | S < PS | S = PS |

*Note.* The working hypotheses where generated to determine which group of students would devote greater cognitive effort (time) to a specific cognitive process. For example, S > PS signifies that for that specific cognitive process, secondary students devoted more time to the process than the post-secondary students (S: Secondary Students / PS: Post-Secondary Students).
* Significant at the 0.05 level (2-tailed). ** Significant at the 0.01 level (2-tailed).

**Table 12.** Correlation between Participant Cognitive Processes and Engineering Design Performance

| | | **Rubric Score** | | **Final Turbidity** | |
|---|---|---|---|---|---|
| | *M* | **Pearson Correlation** ***r*** | **Sig. (2-tailed)** ***p*** | **Pearson Correlation** ***r*** | **Sig. (2-tailed)** ***p*** |
| **Analyzing** (s) | 592.47 | 0.635** | 0.003 | –0.146 | 0.551 |
| **Communicating** (s) | 245.16 | 0.528* | 0.020 | –0.374 | 0.114 |
| Computing (s) | 32.16 | 0.300 | 0.212 | –0.295 | 0.22 |
| Creating (s) | 212.16 | 0.052 | 0.831 | –0.246 | 0.31 |
| **Designing** (s) | 275.47 | 0.619** | 0.005 | –0.201 | 0.409 |
| Defining Problems (s) | 126.74 | –0.187 | 0.442 | –0.302 | 0.209 |
| Experimenting (s) | 148.11 | –0.318 | 0.184 | 0.221 | 0.363 |
| **Interpreting Data** (s) | 99.89 | 0.477* | 0.039 | 0.138 | 0.573 |
| Managing (s) | 1059.84 | –0.286 | 0.235 | –0.317 | 0.186 |
| Measuring (s) | 110.58 | 0.319 | 0.183 | 0.251 | 0.300 |
| Modeling (s) | 4.16 | 0.358 | 0.132 | –0.002 | 0.992 |
| Model/Prototype Constructing (s) | 1469.95 | 0.189 | 0.439 | –0.312 | 0.193 |
| Observing (s) | 268.68 | 0.008 | 0.975 | –0.061 | 0.805 |
| **Predicting** (s) | 99.74 | 0.749** | 0.000 | 0.038 | 0.877 |
| Questioning/Hypothesizing (s) | 119.00 | 0.185 | 0.450 | –0.547* | 0.015 |
| Testing (s) | 621.42 | 0.097 | 0.694 | –0.106 | 0.666 |
| Visualizing (s) | 148.26 | 0.325 | 0.175 | –0.003 | 0.992 |
| **Total Design Time** (s) | 5634.06 | 0.561* | 0.013 | –0.209 | 0.390 |
| **Design Phase Time** (s) | 1277.87 | 0.550* | 0.015 | –0.239 | 0.325 |
| Making Phase Time (s) | 1952.34 | 0.197 | 0.420 | –0.223 | 0.358 |
| Evaluation Phase Time (s) | 2403.77 | –0.032 | 0.897 | –0.178 | 0.466 |
| Number of Prototype Trials*** | 3.42*** | 0.220 | 0.365 | –0.450 | 0.053 |

*Note:* Post-secondary student 1 was excluded in this test. It is important to note that *Prototype Trials* refers to the number of times students tested their solutions and that *Final Turbidity* refers to the lowest turbidity level achieved.
* Significant at the 0.05 level (2-tailed). ** Significant at the 0.01 level (2-tailed).

($r = 0.619, p = 0.005$), *interpreting data* ($r = 0.477, p = 0.039$), and *predicting* ($r = 0.749$, $p < 0.000$). Also, the rubric scores were significantly related to the total time participants dedicated for the design phase time ($r = 0.550$, $p = 0.015$). Therefore, the results indicate that higher rubric scores are significantly correlated with more time employing the mental processes of *analyzing, communicating, designing, interpreting data*, and *predicting* as well as more time dedicated for the entire design session and specifically the design phase of the process. Additionally, the final turbidity results of each participant's prototype were significantly correlated with more time in the cognitive process of *questioning/hypothesizing* ($r = –0.547, p = 0.015$). Hence, the results indicate that more time dedicated to *questioning/ hypothesizing* may be a predictor of better prototype performance. Table 12 illustrates the correlational analysis results between mental processes and student performance.

Furthermore, to identify significant cognitive predictors of performance success in terms of design process (participant rubric scores) and product (turbidity score attained), multiple linear regression analyses of the design cognition data were attempted between the cognitive processes, the rubric score, and the turbidity levels. Prior to pursuing the multiple linear regression analyses, regression diagnostics were conducted to test statistical assumptions of linearity, homoscedasticity, normality of residuals, mean independence, and non-linear relationships. While these assumptions proved to be justifiable, an issue with multicollinearity was uncovered as the analysis revealed that several of the predictors (cognitive processes) were highly correlated with one another. To account for this issue, the numbers of collinear predictors were reduced by combining highly correlated cognitive processes into an aggregate process. Based on the results of these statistical diagnostics, the cognitive processes of *Computing* and *Interpreting Data* were combined to form *Quantitative Reasoning* (QR); *Experimenting*, *Testing*, *Questioning/Hypothesizing*, and *Observing* were combined to form *Scientific Inquiring* (SI); and *Designing*, *Creating, and Modeling* were combined to form *Designing/Ideating* (DI). While the collinearity of the cognitive processes presented an issue for conducting a multiple linear regression analysis, the diagnostic procedures provided statistical evidence for refining the design cognition-coding scheme established through the work of Halfin in 1973.

Following the creation of the new cognitive process codes, the data were again examined. While the issues of multicollinearity were mitigated by the aggregation of the cognitive processes, it was determined that the sample size in this study was too small to produce a significant equation to predict student design success based on cognitive processing. Despite the issues preventing the regression, the creation of aggregated codes may prove beneficial to future research.

## 7. Discussion

It is important to note that this study was limited to a purposive sample of 20 participants; therefore, the results of the study are not generalizable to all engineering programs. However, design cognition research typically involves a small number of participants due to the qualitative nature of the collected data and thus, this study is in alignment with recent design cognition studies at the secondary level. Although limitations exist, stakeholders within the engineering education community should consider the findings from this research in future curriculum efforts and researchers should consider this research methodology with larger sample sizes. While the findings in this paper help to highlight elements of design cognition with respect to design performance, further investigations are necessary. For example, one might design a study using this methodology that includes a larger sample of high school students with no engineering experiences, high school students with engineering experiences, post-secondary students with no engineering experience, and post-secondary students with high school engineering experiences. Then identifying the cognitive processes employed, or the lack thereof, may serve as better indicators of potential voids in curricula, instruction, and student learning. In addition, design cognition research results may be used to reveal latent disconnects between secondary and post-secondary engineering education programs. Furthermore, studies such as this can highlight potential cognitive indicators for enhancing a student's engineering design performance. For example, Strimel's [49] qualitative analysis suggested better performing students devoted more time to *communicating, managing, testing, observing, interpreting data*, and *experimenting* and the results of this study implies that better performance is significantly correlated with more cognitive effort in *predicting, analyzing, designing, communicating, interpreting data*, and *questioning/hypothesizing*. Therefore, design heuristics around these areas maybe important to integrate within secondary engineering curriculum.

In addition, a multiple regression analysis of the data was attempted to identify influential predictors of success in terms of design performance and prototype effectiveness. While the sample size in this study proved to be too small for generating a significant equation for using cognitive process time to predict design success, we recommend future efforts following this approach should be attempted. It is also important to note that the effort to conduct a multiple regression analysis uncovered cognitive processes that were highly correlated with one another. This discovery provides support for revising the Halfin [44] coding scheme by combining highly correlated cognitive processes into aggregate processes. Therefore, it is recommended that for future research the cognitive processes of *Computing* and *Interpreting* be combined to form *Quantitative Reasoning* (QR); *Experimenting*, *Testing*, *Questioning/Hypothesizing*, and *Observing* be combined to form *Scientific Inquiring* (SI); and *Designing*, *Creating, and Modeling* be combined to form *Designing/Ideating* (DI).

The results of this study also highlight the potential that P-12 engineering/technology experiences hold for cultivating a student's cognitive and physical abilities for solving problems using engineering design practices. Other studies have attempted to demonstrate this potential as well [14, 38, 40, 20]. For example, Mentzer et al. [40] evidenced that the more experiences in engineering design students have, the more cognitive efforts they engage in for idea generation, feasibility analysis, and decision-making. Similarly, Grubbs [14] identified that secondary students having engineering design experiences spent considerably more cognitive effort when proposing solutions to engineering problem than those without these experiences. Moreover, Grubbs [14] findings suggest that students immersed in secondary engineering/technology curriculum may have the opportunity to experience or develop background knowledge of viable solutions and thus, further their ability to generate a series of solution ideas than non-engineering high school students. However, Kannengiesser et al. [38] and Wells et al. [20] found no statistically significant differences in design thinking between students with secondary engineering experience and those without.

The results of this study, support the idea that secondary engineering/technology education can influence a students' engineering design cognition by demonstrating significant differences in *analyzing, designing, predicting, communicating, measuring, visualizing*, and *computing* between students with and without the previous engineering design experiences. However, the coding schemes used in design cognition research are based on a variety of different conceptual foundations and thus, may elicit different study results and these contradictions may be a result of the coding schemes employed. The coding scheme used in this study was founded on the actions of practicing designers and engineers while the Kannengiesser et al. [38] and Wells et al. [20] studies employed a scheme founded in cognitive science. Therefore, the coding scheme employed in this study emphasized performance rather than cognitive processing of information. Consequently, the results of this study may suggest an influence of secondary engineering experiences on design performance but not necessarily on the cognitive processing of information in design decision-making.

As mentioned, the findings suggest the importance of educational experiences in engineering design before entering college engineering programs. In Strimel's [49] study of secondary-level engineering students he suggested that secondary students are heavily focused on making their solutions and devote a minimal amount of time to thoroughly planning and making predictions about their designs before prototyping their proposed solution. Strimel noted that most of the participants did not experiment with materials to determine what would be the best choice for their solution; instead, they relied on repair materials such as tape and hot glue. He further explained that these findings might indicate that authentic engineering practices of predictive analysis, modeling, and optimization are not accurately practiced throughout P-12 engineering/technology curricula and instruction. However, upon analysis of the post-secondary level design cognition data in this study, the researchers identified that the secondary engineering/technology students, as well as the one post-secondary participant with prior high school experience, were more successful in creating effective solutions to the proposed design challenge. The results showed students with experience in engineering/technology devoted significantly more time to the *Design Phase* of the problem-solving process and dedicated significantly more time to employing the mental processes of *Analyzing*, *Designing*, *Communicating, Computing*, and *Predicting* than the post-secondary engineering students.

Moreover, secondary engineering experiences seemed to have an influence on student practices when developing a design and producing a physical prototype. The researchers observed the post-secondary level participants, with no prior engineering coursework, experienced what may be described as a "failure to launch," meaning the students found it difficult to even start developing a solution to the problem. These students had extensive experience in science and mathematics but no identified experience with designing or making. Therefore, when tasked to solve an ill-structured problem without a sequence of steps, they struggled to determine what they needed to do to complete the challenge. Furthermore, these students were observed experimenting solely with the resources or solutions available and often avoiding the design of a novel device to solve the problem. On the other hand, the secondary-level participants, with High School engineering/technology experiences, sketched ideas and used gathered information to create an informed design concept prior to doing any type of making or experimentation. Also, the secondary-level participants devoted significantly more time to the mental processes of *Visualizing* and *Measuring*. The secondary students were observed dedicating more time to mentally conceiving how components of their device would be assembled and making measurements before manipulating materials. Conversely, the post-secondary participants without prior engineering experience were seen struggling with the assembly of their prototypes and did not use tools and materials properly (e.g., these participants were observed failing to put a drill bit in the chuck of a hand-held power drill and performing inappropriate tasks such as hammering a screw into a piece of wood). While these experiences in designing and making may not be aligned with the work performed by a professional engineer, a lack of these proficiencies and an understanding of these practices may limit the abilities of future engineers in making informed design decisions. Therefore, early engineering experiences seem to be crucial to afford students the opportunities to better practice designing and making as well as performing more informed design decisions based on the properties of materials and abilities to manipulate them. However, the opportunities for students to participant in engineering coursework at the P-12 are limited across the United States as it is not often a requirement for students. Secondary student experiences with informed engineering design and physically making prototypes are left to chance [50] as indicated by the National Assessment of Educational Progress for the United States which showed that more than half of the nation's eighth graders were not proficient in engineering and technology literacy.

## 8. Conclusions

As the teaching of engineering design continues to increase at the P-12 level, it becomes essential to understand the ways in which students mentally process engineering design tasks to provide effective teaching, establish suitable scaffolding of engineering design experiences, and integrate interventions that enhance student design abilities. This study investigates the design cognition and performance results of secondary and post-secondary engineering students while engaged in engineering design problems. Relationships between prototype performance and design cognition were highlighted to investigate potential links between cognitive processes and success on engineering design problems. Concurrent think-aloud protocols were collected from eight secondary and 12 post-secondary engineering students working individually to design, make, and evaluate a solution prototype to an engineering design challenge. The resulting protocol were then coded using a pre-established coding scheme and analyzed to compare the two participant groups as well as determine the relationship between students' design cognition, experience level, and design performance. Significant differences between participants with secondary engineering experiences and those without were found in regards to the amount of time various cognitive processes were employed to complete a design task. For the given design scenario, students with secondary engineering experiences achieved significantly higher rubric scores than those without. Improved design performance was also found to be significantly correlated with more time employing the mental processes of *analyzing, communicating, designing, interpreting data*, *predicting*, and *questioning/ hypothesizing*. These results may highlight important links between educational experiences in engineering design, prior to college, and student success on engineering design problems. Thus, this study may indicate necessary shifts in student preparation in and for engineering while in primary and secondary schools.

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