DIGITIZING DISSECTION: A CASE STUDY ON AUGMENTED REALITY AND
ANIMATION IN ENGINEERING EDUCATION

A Thesis in
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by
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ABSTRACT

The global pandemic of 2020 has caused a paradigm shift in engineering education. In a matter of weeks, and sometimes days, faculty members across the world were forced to move their hands-on engineering courses into a remote environment to stop the spread of COVID-19. This drastic shift to online learning has also resulted in an increased need to empirically understand the impact of technology on students learning, particularly when it replaces hands-on in-person instruction. In an effort to help educators identify how these technologies can be leveraged in engineering education, this thesis research was conducted to evaluate the impact of Augmented Reality (AR) and animation on engineering student learning, cognitive load, and recall during a virtual product dissection educational activity. AR was chosen as one of the technologies for this thesis since AR has the ability to show information otherwise not easily experienced or obtained. AR can be further enhanced through the accompaniment of animation, a collection of images shown in rapid succession to highlight change or motion. These technologies have both been found to increase overall understanding and motivation to learn. However, these technologies have received limited attention in engineering literature, bringing to question how, or if, these technologies should be leveraged in engineering education. In order to identify the impact of AR and animations on student learning, a full factorial experiment was conducted with 117 engineering students. The study consisted of a product virtual dissection activity comparing AR and animation with a baseline virtual environment. The results of the study show that the virtual condition with animation exhibited increased understanding in the participants, over three other conditions, in a product dissection activity. It also showed that participants in the AR condition were not significantly different than those in a virtual environment when looking at cognitive load and recall. The results of this thesis are used to recommend how technology can be utilized in a virtual classroom.
environment, providing crucial insight into the steps needed to virtualize engineering education during the pandemic as well as future steps towards a possible education reform.
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CHAPTER 1

INTRODUCTION

“We can learn some things through this crisis about online delivery of not only instruction, but an array of opportunities for learning and support. In this way, we can make the most of the crisis to help redesign better systems of education and child development.” – Reville [1]

The global pandemic of 2020 caused a massive paradigm shift in engineering education resulting in uncertainty; education was forced to move online in an untested and unprecedented scale requiring much trial and error. [2]. In a matter of weeks, and sometimes days, faculty members across the world were forced to move their hands-on engineering courses into a remote environment to stop the spread of COVID-19 [3]. An engineering student describes the specific problems relating to engineering education in their statement “engineering-specific classes are much harder because there aren’t as many resources available to help with engineering-specific skills” [4]. This drastic shift to online learning has also resulted in an increased need to empirically understand the impact of technology on students learning, particularly when it replaces hands-on in-person instruction. It is important that the advancements gained during the pandemic remain after it is over; research to virtual education will not only be helpful to the pandemic, but will continue to aid the future of virtual engineering education.

If there is one potential silver lining in the 2020 COVID-19 pandemic, it is its role as a catalyst for educational reform. Recently, technology has become an item of necessity in engineering education rather than a luxury. During the pandemic of 2020, nearly 300 universities
in the United States were forced to close campuses and switch to remote/virtual education [5] relying heavily on technology to drive educational paths. There were also several instances of universities deciding to temporarily close rather than offer online courses [6], primarily due to the absence of technology that met their virtual educational needs [7]. While it is easy to convert lecture based education to virtual learning environments, hands-on learning, like engineering education, is more difficult to virtualize [7]. As such, testing new technology is critical in the efforts to improve virtual engineering education. Exploring technology for virtual education is not only important to current education methods being utilized in the pandemic, but an important step in a much needed educational reform [1].

Engineering education should be at the forefront of technology integration due to the exponential rate at which engineering technology grows [8]. Learning in engineering education has typically been measured in relation to real world tasks, usually an evaluation of knowledge, skills, attitudes, and values [9]. Technology has been shown to improve these metrics in other areas of education. For example, the use of virtual laboratories is on the rise due to the ease and affordability of implementing the newest available technology [10]. In fact, a study utilizing virtual reality showed that virtual experimentation allows practice to be repeated easily and provides increased freedom [11] and can aid students in understanding difficult concepts [12–14]. However, adopting technology without an understanding of how it impacts learning is problematic. Selway [15] summarizes their problematic experiences in technological implementation by saying “technology is not meant to supplant, it’s meant to enhance” (2019). One such area of engineering education that has experimented with integrating technology is product dissection.

“Product dissection is the systematic disassembly of products” and has long been a staple of engineering classrooms [16,17]. Product dissection was first introduced in engineering education in 1991 at Stanford University [16]. It was initially implemented in order to develop a basic aptitude
for engineering and engineering design, and to develop mental visualization skills [18]. While there are many educational benefits to product dissection, it also has its downfalls, for example, high costs are linked with physical product dissection; as well as significant resource usage and facility requirements which can make implementation difficult [19]. Physical product dissection also has the disadvantage of requiring maintenance in order to maintain consistency [20]. Due to these disadvantages, and with the advancement of technology, virtual product dissection has been investigated as an alternative to physical product dissection. Virtual product dissection is the use of computer software to disassemble and gain understanding of virtual objects [19]. Several studies have been conducted to investigate the differences between virtual and physical product dissection in engineering education [11,21–24]. This research has shown that there were no significant differences in student learning between virtual and physical product dissection environments [21].

The next step in the advancement of engineering education is to enhance virtual education to the point it becomes superior to the traditional methods.

A potentially beneficial technology to implement in engineering education is animation. Animation is a collection of images shown in rapid succession to highlight the changes from image to image [25]. Animation can be used to show motion and increase understanding [26,27]. It is already being utilized in many areas of education including several areas of science [28–30]. One of the biggest beneficial aspects of animation is that it is a complimentary technology [31], meaning it is a technology that has the potential to enhance other learning tools when used together. In this research the technology being paired with animation is Augmented Reality (AR). Due to recent advancements in AR technology, along with increased accessibility, this technology has potential to be an effective educational tool. Augmented reality can be defined as the utilization of computer-generated objects to coexist with and enhance real world objects [32]. This gives AR the potential to be a powerful learning tool through the addition of previously missing information to real world
scenarios [33]. Virtual Reality (VR), a similar and comparable technology to AR, is already being used as a learning tool; for example, in medical education [34,35], and employee training[36,37]. This new technology is being utilized because many complex skills cannot be learned through traditional passive learning, but require experimental learning [38], which could potentially be provided through AR. Research has shown the effectiveness of AR may stem from the reduction in cognitive load users experience, allowing them to learn material more efficiently [39]. Reaching the limits of working memory has been found to negatively impact learning ability [40]. While in theory these technologies seem greatly beneficial, no studies have been conducted. Therefore, the purpose of this research was to evaluate the impact of AR and animation on engineering student learning, cognitive load, and recall during a product-dissection educational activity in an effort to help educators identify how these technologies can be leveraged in engineering education.

1.1 Research Objectives and Significance

Due to the rate that engineering technology grows, engineering education needs to be able to keep up with the technological advancement. In response to this, this thesis was developed to evaluate the impact of Augmented Reality (AR) and animation on engineering student learning, cognitive load, and recall during a product-dissection educational activity in an effort to help educators identify how these technologies can be leveraged in engineering education. The remainder of this chapter discusses the contributions of this thesis and provides an outline of what this thesis work entails.
1.2 Expected Contributions

This thesis strives to reveal the importance of technology in virtual engineering education in order to help educators identify how these technologies can be leveraged in engineering education. Additionally, providing insight into virtual education during the 2020 COVID-19 pandemic aims to aid the difficulties education has endured. The overarching purpose of this thesis is to provide the groundwork for more efficiently utilized virtual education, as well as lay out future steps towards an educational reform.

1.3 Expected Publications

This thesis is based on work submitted for publication to the International Design Engineering Technical Conferences & Computers and Information in Engineering Conference in April 2020. This work is multiple-authored. Kevin Kearney is the lead author on the paper, while Dr. Scarlett Miller and Dr. Elizabeth Starkey helped advise the work.

1.4 Document Outline

The remainder of this thesis elaborates on the metrics elected, methodologies used, findings, and the design implications of the results in detail. Specifically, Chapter 2 presents the related work, verifying the motivation for this thesis. Chapter 3 presents the focus of this thesis through three research questions. Chapter 4 outlines the methodology utilized in this thesis to answer the research questions. Chapter 5 contains an in-depth analysis of the results obtained from the study to answer the research questions. Chapter 6 contains the discussion of our findings as they pertain to the research questions. Finally, chapter 7 contains the conclusions to this thesis.
RELATED WORK

Although Augmented Reality (AR) and animation have not specifically been studied for engineering education, there have been studies exploring AR and animation in other areas of education. This section serves to summarize the educational benefits of product dissection, augmented reality, animation, cognitive load, and recall in education to provide basis for this research.

2.1 Product Dissection in Engineering Education

Product dissection is a long-standing activity used in engineering education but due to the expense and resources required people have virtualized it. Virtual product dissection is not significantly different from physical product dissection, but differs in that virtual product dissection is more efficient [21] due to reduced time and effort [23]. Specifically, virtual product dissection is more efficient due to the ability to quickly and easily reset the dissection [41]. Due to this, multiple virtual product dissections can be performed in the same time it takes to perform a single physical product dissection [24]. While research has shown the benefits of integrating this technology, it is not without its drawbacks. Research has found that participants in both conditions still had room for better understanding. In fact, all participants scored below a 75% on their post-dissection assessments, indicating they did not have a perfect understanding of how their product worked [42].
This potentially better technology could stem from old technology, new technology, or a combination. Previous instances of virtual product dissection have utilized 3D pdfs and CAD model viewing software to allow for manipulation of products in virtual space, but have missed the opportunity to include additional details such as animations of how the product functions. With the addition of animation, the functionality of parts and mechanisms can be seen within products, which is typically unseen due to the outer casing obscuring the inner workings in physical products [26]. This can be seen in Figure 1, where the only moving parts that are visible in the physical condition are the slide (to load the spring) and the trigger to release the dart. Unlike the physical condition, in the virtual condition with animations, it can be seen that pulling back the slide loads the large spring into firing position, the mechanism that locks the spring in the firing position, and the spring that brings the slide back to the home position. Due to the core difference between how products work in physical environments as compared to virtual environments, there is an opportunity for AR and animation to provide an understanding of product functionality that is not possible in the physical world. Without a full understanding of functionality, learners fill in mental

Figure 1: Virtual nerf gun (top left), with spring engaged and casing removed (top middle), and casing removed (top right) compared to physical nerf gun (bottom left), with spring engaged (bottom middle), and with casing removed (bottom right) [85]
blanks by guessing about the purpose of different parts of a product. This could cause unnecessary mental stress (cognitive load) on the user. Although these are possible benefits of virtual environments, they have yet to be explored.

2.2 Animation and Augmented Reality in Education

Educational technology can come in many different forms, one of these forms could be animation. The definition of animation is a collection of images shown in rapid succession to highlight the changes from image to image [25]. Animation, in the simplest form, is used to show movement as a path or trajectory [27] and can be used to show motion of physical objects, energy flow, or fluids [26]. Animation, as a form of multimedia, provides effective understanding of a subject’s content [43] when supported by up-to-date technology [44]. Research has shown that animation is beneficial as a complementary learning approach and helps motivate students and build interest in learning through interactivity [31]. Animation has been used in many fields of education including engineering [28], physics [30], and mathematics [29]. In engineering education animation has been used to show fluid motion of different viscosities of fluids interacting with multiple objects [45]. Animation has also been used to show robot kinematics without the high price associated with robotics education [46,47]. Additionally, animation has been used to teach thermodynamics and material science [48]. However, animation does not come without its drawbacks. A study conducted by Tversky, Morrison, and Betrancourt [27] showed that animation was only useful when it showed more information than a static image. This study also revealed that not having control over the animation (start, stop, pause, replay, speed up, slow down) reduced the potential benefits [27].

Animation is a technology that can be described as a complimentary technology [31]. Meaning it is a technology that has the potential to enhance other technologies. In this case, the
technology being enhanced through animation is Augmented Reality (AR). AR is defined as the utilization of computer generated objects to coexist with and enhance real world objects [32]. AR was first introduced back in the 1960’s, when mechanical and ultrasonic trackers were used to display simple wireframe objects through a head mounted see-through display [49]. AR has advanced significantly since this time, and can be broadly categorized into two main areas: marker-based and markerless-based [50]. Marker-based AR acquires a location through the use of a specific image, such as a barcode or QR code; while markerless-based AR uses image recognition or location data to overlay information [50].

AR has many potential applications in education and training due to improvements in information technology as well as computers [51]. AR has the potential to increase motivation to learn as well as improve educational realism activities [52]. The ability to control objects and explore numerous perspectives through AR can attract and inspire new learners [53]. AR has a particular usefulness in its ability to demonstrate information not easily experienced in the real world [53]. Johnson, et al. [54] confirms, “AR has strong potential to provide both powerful contextual, on-site learning experiences and serendipitous exploration and discovery of the connected nature of information in the real world.” (p. 21) (2010). AR, however, is relatively new to education. An experiment performed by Shelton and Hedley [53] began its testing in formal education. The study found that AR was useful in teaching items that are more easily experienced in AR than in real life, in this case, the relationship between the sun and the earth [53]. It was found that the students who interacted with the virtual objects showed increased learning when compared to students who did not [53]. This experiment was taken further by Kerawalla, et al. [55] which showed that animating the earth and the sun in AR resulted in even greater learning. AR has also been experimented with teaching molecular structure [56], storytelling for children [57], and learning in museums and exhibits [58]. However, as AR is an up-and-coming technology it is likely
to have issues. As the most common form of AR is through the use of a smartphone/tablet, AR is limited to the capabilities of the phone/tablet [50]. AR is also susceptible to technical difficulties [59]. Additionally, studies have found that AR can either lower or raise cognitive load [59,60].

AR has proven usefulness specifically in engineering education. An early example of AR in engineering education was an AR-enhanced textbook. This textbook was used for teaching civil and construction engineering which contained simulated animations; it was reported that a majority of the students believed the AR tool was beneficial [61]. Another use of AR in engineering education was to improve orthographic and isometric drawing skills; the manipulation of a 3D object allowed students to more easily draw different views of an object when compared to 2D methods [62–64]. A study performed by Gutierrez & Fernandez [65] showed that virtual object manipulation through AR led to increased student motivation and better academic performance. Overall, these studies showed that AR-enhanced education methods were superior when compared to traditional teaching methods [61–65]. This is important to us as it provides validation that AR can further enhance engineering education.

2.3 Cognitive Load and Recall in Education

In order to assess these technologies on their ability to aid learning, a deeper understanding of learning itself was needed. Cognitive load is a large element of learning and an important aspect to consider in education. The aspect of cognitive load that is important for this research is called Working Memory. Working Memory is an area that cognitive load has an effect on, this area deals with the maximum level of elements an individual can process [40]. Extraneous Cognitive Load is useful when the goal is to strengthen working memory; on the contrary, extraneous cognitive load has been shown to interfere with learning as it requires the limits of working memory to be met [40]. For virtual learning the ideal type of cognitive load is called Effective Cognitive Load. This
type of cognitive load has been shown to enhance learning as the limits of working memory are not being reached [40]. By decreasing cognitive load, working memory limitations are less likely to occur, allowing for effective cognitive load and increased educational value. Since memory is limited, reducing cognitive load can make it easier for an individual to process information [66]. For complex tasks, these cognitive requirements are higher and require more resources [67]. Cognitive load can be broken down into different categories: perceptual/central, response, spatial, verbal, visual, auditory, manual and speech [68]. By understanding which areas of cognitive load AR and animation impact, there is a better chance of effectively implementing the technologies.

When considering cognitive load with technology, an important aspect to consider is whether the participant is familiar with the technology. It has been found that students who are not familiar with the technology they are using will experience higher cognitive load and lower levels of learning [69]. This is most likely due to split-attention effect, where the learner is required to split their attention between two different aspects [70]. Split-attention effect could be split attention between understanding the learning tool and learning the material, or between different forms of learning materials [70]. Due to this, learners who have prior experience with a form of technology will likely have lower cognitive load. With this in mind, the relatively new technology of augmented reality was looked at for this thesis.

Cognitive load has also been shown to have a relationship with recall. Recall can be defined as “the act of retrieving information or events from the past” [71]. While cognitive load is used to determine how much of working memory is being used, understanding recall can be helpful in learning whether or not the working memory is being used efficiently [72]. Working memory refers to the process of both processing and storing short-term memory for tasks [73]. Recall refers to the ability to categorize short-term memories [74]. A study conducted by Xie et al. [75] concluded that a reduction in cognitive load led to increased recall ability. Research has shown long-term memory
is obtained through short-term memory [76]. Due to this, technology that can increase recall, and therefore increase long-term memory, is vital in the efforts to enhance virtual education through technology.
RESEARCH OBJECTIVES

The purpose of this thesis was to evaluate the impact of Augmented Reality (AR) and animation on engineering student learning, cognitive load, and recall during a product-dissection educational activity in an effort to help educators identify how these technologies can be leveraged in engineering education. Specifically, this thesis sought to address the following research questions:

**RQ1: How does AR and animation in product dissection impact student cognitive load?**

This research question was developed to identify the impact of the use of AR and animation in a product dissection environment on student cognitive load. It was hypothesized that AR and the use of animation would reduce student’s overall cognitive load. The motivation for this hypothesis stems from prior research showing that increasing the amount of information shared reduced the number of working memory elements that needed to be processed mentally [40]. As working memory is limited, reducing cognitive load can make information easier to process [66].

**RQ2: How does AR and animation in product dissection impact knowledge gain?**

This research question was developed to identify the impact of the use of AR and animation in a product dissection environment as assessed by examining only new items learned through the
Student Learning Assessment (SLA). It was hypothesized that AR and animation will show increased knowledge gain in a product dissection environment. The motivation behind this hypothesis stems from research showing these technologies to be effective learning tools by themselves [43,44,61–65].

**RQ3: How do AR and animation in product dissection impact recall?**

This research question was developed to identify the impact of the use of AR and animation in a product dissection environment on student recall, as assessed through an SLA. It was hypothesized that AR and animation would show improvements in recall in a product dissection environment. The motivation for this hypothesis comes from research showing that reduction in cognitive load has been associated with improvements in recall [75].
METHODOLOGY

To answer these research questions, a study was conducted with 117 first year engineering students. The remainder of this chapter highlights the methodological approach for this thesis.

4.1 Participants

The participants reported in this thesis were first-year engineering students recruited through an introductory engineering design class. The class promotes hands-on learning as well as design-ability through design projects.

4.2 Procedure

Before any procedures took place, an overview was provided and a signed consent form was obtained from each participant. Next, participants were given a pre-Student Learning Assessment (SLA), developed by Toh, Miller, and Simpson [77] to gauge conceptual understanding of the product, before interacting with it. Participants were given 15-minutes to complete the pre-SLA. After this assessment, the participants were assigned to one of the groups. This designation was depended on the layout of the room. The room consisted of eight, four-person tables. As each table only had two computers, two virtual conditions and two AR conditions were held at each table. It was ensured that each table had either animation or no-animation conditions with no tables having both. The tables were then randomly assigned the conditions in the 2 x 2 factorial design
(see experimental design) maintaining equal distribution. After the participants have been placed, they then began a 15-minute product dissection activity. While they completed the activity, the participants were tasked with completing the during-SLA in order to gauge the effectiveness of the learning tool. Once the dissection activity was completed, participants were then asked to complete the cognitive load, novelty effect, and free-response surveys. Finally, the participants were given a post-SLA 48 hours after the dissection activity in order to assess recall. The participants had 15 minutes to complete this post-SLA.

4.3 Experimental Design

This study is designed to compare four different product dissection conditions in a 2 x 2 factorial design: Virtual dissection, virtual dissection with animation, Augmented Reality (AR) dissection, and AR dissection with animation. All participants in this study dissected the Sharp Shot Nerf Gun (https://www.engr.psu.edu/productdissection/Dart%20Gun.html). The animation was shown through two forms of media but was replicated to ensure the same information was being expressed in each. Screenshots of these animations can be seen in Figures 2 and 3.

**Virtual Product Dissection:** Participants assigned to this condition of the experiment (N = 28 participants) were tasked to dissect a product virtually. Participants were provided with the virtual files of the product as well as access to a computer with Solidworks eDrawings 2019. The
participants were not provided with any instructions on how to use the program. The goal of the product dissection activity was to break down the product into its individual components and develop a deeper understanding of the products’ functions. The participants were not provided with instructions for dissecting the product and had the freedom to manipulate the object as they saw fit.

**Virtual Product Dissection with Animation:** Participants of this condition (N = 27 participants) were tasked similarly to that of the “virtual product dissection” group, as well as being provided the same materials. However, participants in this condition were also provided with an additional animation of the product. The animation was a 15 second video showing the internal functions of the product. The animation was provided to the participants through a YouTube link.

**AR Product Dissection:** Participants in this condition (N = 30 participants) were tasked with virtually dissecting the same product as the previous conditions. However, participants in this condition were to use a different dissection tool. The dissection tool for this condition was the SimLab AR/VR Viewer version 3.1 application which was downloaded onto IOS smartphone devices. Participants were provided instructions on how to download the virtual product file but were not provided any instructions on how to use the application. Participants were also provided a file of the virtual product generated in SimLab Composer 9. Participants were not provided with instructions for dissecting the product.

**AR Product Dissection with Animation:** Participants in this condition (N = 32 participants) were given the same task as the previous conditions. Participants were provided with the same material as the “AR product dissection” condition with the exception of the virtual product file. Participants were given a file of the virtual product that included an animation. The included animation had a duration of 15 seconds and showed the internal functions of the product.
4.4 Metrics

In order to assess the differences in learning and cognitive load in the 2 x 2 factorial study design the following metrics were used.

*Student Learning Assessment (SLA):* This metric was developed and validated in prior research by Toh, Miller, and Simpson [77] to measure participant’s understanding of the components in the assigned product. The SLA used in this study can be accessed from the following link (https://www.engr.psu.edu/productdissection/instructor%20Support.html). Each participant was to complete a two-sided worksheet composed of four categories consisting of power supply, mechanism that provides primary motion, energy flow of the device, and form and outer body. Under each of these categories the participants had to provide visual representations as well as functional descriptions. Specifically, feature knowledge was computed by having an expert rater review the SLA and identify the understanding of the product’s function in each of the four categories. SLAs were rated through forty-three items that showed understanding of functionality. One point was assigned for each item that was present in the SLA, finally the scores were summed for one overall performance score (0-43). Examples of low and high scoring SLAs can be seen in Figures 4 and 5 respectively. The SLAs were graded by three independent raters. The inter-rater reliability was calculated using Cohen’s Kappa for three raters (κ = 0.80, κ = 0.74, κ = 0.84).

![Figure 4](image1.png)  
*Figure 4:* An example of a section of an SLA that received a high score (33/43).

![Figure 5](image2.png)  
*Figure 5:* An example of a section of an SLA that received a low score (6/43).
**SLA Knowledge:** This metric considers only items that were present on the during-SLA but not present on the pre-SLA. This indicates that the item was newly learned regardless of whether the participant included less detail on the during-SLA. In Figure 6 we can see that only items that were present in the during-SLA but not in the pre-SLA were included in SLA Knowledge.

![Figure 6: Visual representation of how the SLA Knowledge score was calculated.](image)

**Total Knowledge:** Total Knowledge is a combination of the pre and during-SLAs, where a point could be earned if an item was present on either or both of the SLAs. The combination of the pre and during-SLAs allowed for the participants complete understanding of the product to be calculated. In Figure 7 we can see that items from both the pre and during-SLA were included in total knowledge.

![Figure 7: Visual representation of how the Total Knowledge score was calculated.](image)

**Recall:** To assess recall, the experiment was broken down by day. **Day 1** consisted of the total knowledge score. This was selected to understand the participants full understanding after the dissection activity. **Day 2** consisted of the post-SLA score. This allowed us to compare the loss of
understanding from day 1 to day 2, a period of 48-hours, to assess recall performance of the conditions.

**Cognitive Load:** Cognitive load theory suggests that working memory is limited and that unneeded information should be reduced, thus allowing more efficient processing of information [66]. In order to measure cognitive load, the Workload Profile Assessment developed by Tsang and Velazquez [68] was utilized. This measure breaks workload into eight dimensions with four different parts of processing. The first part of processing is *Stages of Processing (Types of Attentional Resources)*, and contains Perceptual/central and Response processing. Perceptual/central processing uses resources for recognizing, detecting, and identifying objects as well as problem-solving, decision making and memorization. Response processing uses resources to select and execute a decision such as selecting the correct tool to complete a task. The second part of processing is *Processing Codes (How we Understand Information)*, which contains Spatial and Verbal processing. Spatial processing is remembering and understanding a spatial relationship, such as distance between objects. Verbal processing is remembering and understanding linguistic or verbal material. The third part of processing is *Input Modality (How we Take in Information)*, which contains Visual and Auditory processing. Visual processing is interpreting and understanding visual information gained through sight. Auditory processing is interpreting and understanding information gained through hearing. Finally, the last part of processing is *Output Modalities (How we Respond to Information)*, which contains Manual and Speech responses. Manual response is responding to a task manually, such as physically manipulating and object. Speech response is verbally interacting with an object, such as answering a question.

It is important to note that spatial and verbal information can be processed through visual and/or auditory processing. For example, someone can either listen to the radio and process verbal information auditorily or read a book and process verbal information visually. The Workload
Profile Assessment has been compared to the NASA task load index and subjective workload assessment technique, this metric has been found to be the least intrusive and that all three methods were valid [78]. This metric was a self-assessment by the participants obtained through a survey after the dissection activity. Each participant rated the proportion of attention resources they utilized to complete the task on a scale from 0-100 for each dimension. These values were used individually to assess specific areas of cognitive process, and collectively to assess overall cognitive resources required by the participant. In this study, there were no occurrences of auditory or speech activities so these forms of cognitive load were excluded from the results.
DATA ANALYSIS AND RESULTS

During the study conducted as part of this thesis, 117 products were virtually dissected. The remainder of this chapter focuses on the results according to the research questions. The results are mean ± standard error unless otherwise denoted. Effect sizes were classified according to Cohen [79]. The results are analyzed using SPSS v. 26 with a significance rating of 0.05.

RQ1: How does the use of AR and animation during product dissection impact student cognitive load?

The first research question was developed to identify the impact of the use of AR and animation in a product dissection environment on student cognitive load. Cognitive load scores were used to assess whether the technologies yielded reduced working memory in the participants, therefore showing potential for increased learning. The hypothesis was that students who dissected a product in the AR and animation condition would experience lower overall cognitive load because prior work has shown that in today’s world, people are more comfortable with technology [80]. It has been found more comfortable learning methods lead to reduced cognitive load [81].

Prior to the analysis, assumptions were checked. This analysis identified that there were no multivariate outliers in the data, as assessed by Mahalanobis distance (p > .001). Not all the data was normally distributed, as assessed by Shapiro-Wilk’s test (p > .05), no adjustments for normality were made to the data due to the robustness of two-way ANOVA [82]. There was homogeneity of variances, as assessed by Levene's test for equality of variances, p < .05. Outliers outside of three
standard deviations were removed. Multicollinearity of the data was assessed by Pearson correlation.

Because the assumption revealed multicollinearity of the data (|r| < 0.9), seven two-way analysis of variance (ANOVA) were used in lieu of a two-way multivariate analysis of variance (MANOVA) to compare the six types of cognitive load (perceptual/central, response, spatial, verbal, visual, and manual), as well as the total cognitive load between the different product dissection conditions. The results failed to show a statistically significant interaction between the technologies utilized in the two-by-two factorial for cognitive load for all seven items, see Table 1. These results refute the hypothesis by showing that AR and animation had no significant reduction in cognitive load over the other conditions.

<table>
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<th>Variable</th>
<th>Dissection Tool</th>
<th>Animation</th>
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<tr>
<td></td>
<td>Mean (SE)</td>
<td>Mean (SE)</td>
</tr>
<tr>
<td>Perceptual/Central</td>
<td>72.94 (2.35)</td>
<td>74.24 (2.29)</td>
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<td>73.02 (2.20)</td>
<td>71.71 (2.26)</td>
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<tr>
<td>Response</td>
<td>62.06 (3.12)</td>
<td>59.40 (3.07)</td>
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<tr>
<td></td>
<td>60.97 (3.18)</td>
<td>63.63 (3.21)</td>
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<tr>
<td>Spatial</td>
<td>77.32 (2.96)</td>
<td>79.40 (2.93)</td>
</tr>
<tr>
<td></td>
<td>77.03 (2.85)</td>
<td>74.95 (2.87)</td>
</tr>
<tr>
<td>Verbal</td>
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<td>23.17 (3.19)</td>
</tr>
<tr>
<td></td>
<td>24.79 (3.13)</td>
<td>24.20 (3.24)</td>
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<tr>
<td>Visual</td>
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<td>92.03 (1.59)</td>
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<tr>
<td></td>
<td>89.71 (1.56)</td>
<td>89.87 (1.63)</td>
</tr>
<tr>
<td>Manual</td>
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<td>78.45 (2.98)</td>
</tr>
<tr>
<td></td>
<td>78.80 (2.86)</td>
<td>74.97 (3.06)</td>
</tr>
<tr>
<td>Total</td>
<td>379.22 (9.73)</td>
<td>386.53 (9.47)</td>
</tr>
<tr>
<td></td>
<td>385.97 (9.28)</td>
<td>378.66 (9.55)</td>
</tr>
</tbody>
</table>

Table 1: Main effects of dissection tool and animation on participants cognitive load values.

RQ2: How does the use of AR and animation during product dissection impact knowledge gain?

The second research question was developed to identify the impact of the use of AR and animation in a product dissection environment as assessed by SLA knowledge score during the product dissection activity. The hypothesis was that participants in the AR and animation condition would have higher SLA knowledge scores when compared to the other conditions. This was hypothesized because prior research has shown that students who interact with virtual objects show
increased learning compared to students who do not [53]. Prior research also indicated that animation, as a complementary technology, can strengthen AR by increasing motivation and interest [28].

Prior to the analysis, assumptions were checked in preparation of running a two-way analysis of variance (ANOVA) comparing the SLA knowledge score to the conditions of the factorial design. While outliers were present in the data set, no changes were made to the data due to the robustness of the ANOVA [82]. In addition, data was found to be normally distributed, as assessed by Shapiro-Wilk's test ($p > .05$). Finally, there was homogeneity of variances, as assessed by Levene's test for equality of variances, $p = 0.076$.

The results of the two-way ANOVA failed to reveal a statistically significant interaction between dissection conditions for SLA knowledge score, $F(1, 113) = 2.385$, $p = .125$, partial $\eta^2 = .021$. Therefore, an analysis of the main effects was performed. This analysis also failed to reveal a statistically significant difference for SLA knowledge score between the AR and virtual conditions, $F(1, 113) = .662$, $p = .418$, partial $\eta^2 = .006$. However, there was a statistically significant main effect between animation and no-animation, $F(1, 113) = 5.280$, $p = .023$, partial $\eta^2 = .045$. All pairwise comparisons were run where reported 95% confidence intervals and p-values are Bonferroni-adjusted. The unweighted marginal means of SLA knowledge scores for the animation and no-animation were $9.62 \pm .526$, and $7.91 \pm .529$ respectively. Animation was associated with a mean SLA knowledge score $1.71$, 95% CI $[0.24, 3.19]$ higher than no-animation, a statistically significant difference, $p = .023$. The results can be seen in Figure 8. These results partially supports the hypothesis by indicating that animation was shown to have a statistically
significant improvement in SLA knowledge score over the other conditions. However, AR showed no statistically significant improvement in SLA knowledge score over the other conditions.

RQ3: How does the use of AR and animation during product dissection impact recall?

The final research question was developed to identify if AR and animation impacted a student's ability to recall previously learned information in a product dissection environment. The hypothesis was that AR and animation would both show improvements in recall in a product dissection environment because prior research has shown that reductions in cognitive load can result in improvements to recall [75].

Prior to the analysis, assumptions were checked. This analysis revealed homogeneity of variances for both day 1 (p = .743) and day 2 scores (p = .911), as assessed by Levene's test for equality of variances. Assumption of sphericity was also automatically met as there were only two levels of within subject factors. There was no statistically significant three-way interaction between time, gender and anxiety, F(1, 102) = .991, p = .342, partial η2 = .009. Finally, all two-way interactions were not statistically significant (p > .05).
Because of this, a three-way analysis of variance (ANOVA) was conducted to examine the day 1 to 2 differences between the four conditions. The results failed to reveal a statistically significant main effect between AR and virtual, $F(1, 102) = .037$, $p = .849$, or between animation and no-animation, $F(1, 102) = 2.364$, $p = .127$. Next, all pairwise comparisons were performed for simple simple main effects. Bonferroni corrections were made with comparisons within each simple simple main effect, considered a family of comparisons. Adjusted $p$-values are reported. The results revealed that mean day 2 scores were statistically significantly higher in the virtual condition ($17.40 \pm 5.03$) compared to the AR condition ($17.36 \pm 4.63$), a mean difference of 0.18 ($95\% CI, -1.69$ to 2.05). In addition, mean day 2 scores were higher in the animation condition ($18.10 \pm 4.71$) compared to the no-animation condition ($16.69 \pm 4.81$), a mean difference of 1.45 ($95\% CI, -0.42$ to 3.32). The results are shown in Figure 9. These results refute the hypothesis by showing that there were no statistically significant improvements to recall for AR and animation when compared to the conditions of the two-by-two factorial.

![Figure 9: Means and standard error of recall for the four conditions](image-url)
DISCUSSION

The goal of this thesis was to identify the impact of Augmented Reality (AR) and animation on engineering student learning and cognitive load. The main findings of this thesis are as follows:

- AR and animation did not show a significant difference in cognitive load compared to the other conditions.
- Participants who completed the virtual dissection with animation had significantly higher SLA Knowledge Score than those in the other conditions.
- AR and animation did not show significant difference in recall compared to the other conditions.

The first main findings of the thesis were that AR and animation did not show a significant difference in cognitive load compared to the other conditions. The results did not show significant improvements over the other conditions. A reason for this may be the large standard deviation. This is possibly due to the fact that self-reported measures of cognitive load are often not easily assessed by the participant. While the results did not show significant differences, there were numeric differences. The AR condition had a lower total cognitive load score than the virtual condition. The results also showed the no-animation condition had a lower total cognitive load score over the animation condition. Even though cognitive load is higher in the animation condition it does not mean it should be avoided. The likely cause for the higher cognitive load in the animation condition is split-attention effect [70]. In the animation condition the participants were given the 3D model...
of the product, as well as an animation showing the function of the product. While these two learning materials likely increased learning, it is likely this also caused the increase in cognitive load as well. As digital natives, students are very comfortable with computers and their phones. The average person accumulate roughly five and a half hours of daily screen time between their phone and computer [80]. While both the virtual computer-based dissection and the AR dissection required learning a new software/app, the computer-based software may be more intuitive than the AR app. For reference, the first version of eDrawings was released in 2003 and is very similar to other programs the students use regularly for their engineering classes, while the SimLab AR/VR viewer was initially released in 2017, and is unlike other programs used in engineering classes. Prior work has found that higher cognitive load can be associated with unfamiliar technologies, which may be the culprit in this situation. In fact, previous research states that participants that are not familiar with the technology might have higher cognitive load and lower levels of learning [69].

The second main finding of this thesis showed that participants who completed the virtual dissection with animation had significantly higher SLA Knowledge Score than those in the other conditions. In order to increase the accuracy of the study, SLA knowledge score was utilized. The results that have been observed in both of these methods show that the virtual condition paired with animation proved to be the best of the four conditions. The results indicate that animation may be beneficial as a complementary learning approach. This is in line with prior work that showed support for animation to motivate students and build interest in learning through interactivity [31]. While only virtual with animation showed a significant increase over no-animation, there was a numeric increase in the AR with animation condition. One reason there may not have been as big of an increase in the AR with animation condition may be due to the different versions of animation. AR had an animation included within the 3d model, while the virtual condition contained an animation in the form of a video clip. Both forms of animation showed the same information about the product. However, it is likely the participants found the video clip more intuitive, allowing the
participant to more efficiently navigate the information. It was hypothesized that the highest SLA knowledge score would be seen in the AR condition. The results showed that there was not a significant increase in SLA knowledge score in this condition. Previous research into AR has shown that it has the potential to be an effective learning tool [53–55]. However, previous research in virtual learning, specifically in virtual product dissection has shown it to be an effective learning tool as well [21–23,29,83]. While the results show that the AR condition was not significantly different from the virtual condition, it did not disprove AR as a valid means of education. It was found to be a comparable tool to virtual learning in the context of product dissection. Along with being a comparable tool, AR has the added benefit of increasing motivation in the classroom [52].

The final finding of this thesis was that AR and animation did not show significant difference in recall compared to the other conditions. In fact, the results did not show significant differences in recall between any of the conditions. These results do not match the hypothesis. While the results did not show a significant difference, they did show numeric differences. When comparing numeric differences AR showed a slight advantage over virtual, and animation showed an advantage over no-animation. While virtual had a higher mean than AR for day 1 scores, AR had a higher day 2 score. This led AR to have the lowest difference in mean SLA score between day 1 and day 2. While not significant this leads us to believe that further research in AR could yield significant results proving its value as an educational tool. Numerous studies have shown a correlation between the interest and curiosity of a student and its positive benefits on memory [84–87]. It is possible AR’s better recall score is a result of the technologies ability to increase interest and curiosity. This gives us further reason to believe that further testing of AR could result in increased recall ability. When looking at animation, it had the highest day 1 mean as well as the highest day 2 mean. While not significant this provide evidence that animation is not only a valuable complimentary learning tool, but a valuable learning tool itself. However, when looking at the difference between day 1 and day 2 scores, animation had a very slight advantage over the
no-animation condition. While animation has not been shown statistically better than no-animation in the context of recall, it can be seen as comparable to the current no-animation teaching methods. As animation is comparable in the context of recall, its highest day 1 and day 2 scores show it has a net positive value on education.
CHAPTER 7

CONCLUSIONS AND FUTURE WORK

Due to the educational difficulties associated with the 2020 COVID-19 pandemic, research in virtual education has become vital in the fight to maintain quality education. The silver lining of the 2020 COVID-19 pandemic has been its ability to show the weaknesses in our current education system – namely that some universities find such difficulty adapting to their educational needs, it is deemed better to halt education altogether [6]. Research in virtual education and technology is not only important in adapting to untraditional circumstances, but an important step towards a needed educational reform. The purpose of this thesis was to evaluate the impact of Augmented Reality (AR) and animation on engineering student learning, cognitive load, and recall during a product-dissection educational activity in an effort to help educators identify how these technologies can be leveraged in engineering education. This was accomplished through an experiment with 117 first-year engineering students. Overall, the results showed that AR was not statistically different from virtual (computer-based) learning. The results also showed that the virtual condition, when paired with animation, was able to add statistically significant value to education over the other conditions. Importantly, these results show that while AR is not a statistically different tool than virtual dissection, it is still a valuable learning tool with the potential to gain value with increased understanding. The results also show us that animation has value as a complimentary learning tool with the potential to be a valuable learning tool by itself. Overall, it was noticed while these technologies might not be statistically better than current methods, they are comparable.
While the study has insights into the educational value of AR and animation there are limitations to be considered. The study was conducted in the context of product dissection, so while product dissection education can benefit from the results, future work should focus on AR and animation outside of this context. In addition, AR and animation can take many forms, but in this study they were limited. One of the biggest limitations of this study was the restriction to one product. Adding a second, or multiple products, could show the potential each product type has to influence the effect of AR and animation as learning tools. Finally, the last notice limitation was the amount of effort required to set up AR. This effort potentially affected cognitive load scores.

Future work should explore the different forms of AR and animation in order to gain a longitudinal understanding of which methods are most effective for learning. Along with exploring different forms of AR and animation, different types of products should be tested as well. The product chosen in this study was selected due to its level of complexity and the amount of motion. Selecting products with different levels of complexity as well as different levels of motion could show which types of products AR and animations are better suited for. Finally, to improve these technologies for educational purposes, it would be beneficial to make the technology more accessible and user friendly. More access to AR for students would allow them to become more comfortable with the technology, potentially increasing its value as an educational tool. This technology should not only be more accessible for the student, but for the teacher as well. Allowing the teacher control over the content enhanced by this technology would give this technology a greater chance to be beneficial. Further research in educational technology can lead towards higher-quality virtual education. Allowing educators to provide their students with more efficient methods of learning, ultimately leading to more educated future generations.
## APPENDIX – CODEBOOK FOR CONTENT ANALYSIS

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BIBLIOGRAPHY


Wu, H., Lee, S. W., Chang, H., and Liang, J., 2013, “Current Status, Opportunities, and
Winter Simulation Conference, pp. 3074–3085.
Comparative Study of Augmented Reality Systems for Engineering Visualizations in
Education,” IEEE Frontiers in Education Conference.
and Holograms for the Visualization of Mechanical Engineering Parts,” 18th
International Conference on Information Visualisation.
Gonzalez, C., Dominguez, M., Martin-Gutierrez, J., Contero, M., and Alcaniz, M., 2012,
“Training with Augmented Reality on Engineering Degrees,” ASME 2012 11th Biennial
Conference on Engineering Systems Design and Analysis, Nantes, France.
Feinberg, S., and Murphy, M., 2000, “Applying Cognitive Load Theory to the Design of
Workload Ratings,” Ergonomics, 39(3), pp. 358–381.
Predictions on Individual Differences in Multimedia Learning,” EdMedia + Innovate
Learning, Denver, Colorado.
Paas, F., and Ayres, P., 2014, “Cognitive Load Theory: A Broader View on the Role of
Baddeley, A. D., 2000, “The Episodic Buffer: A New Component of Working Memory?,”
Clair-Thompson, H. L., 2009, “Backwards Digit Recall: A Measure of Short-Term
Total Cognitive Load Is Reduced by Cues, the Better Retention and Transfer of
12(8), pp. e0183884–e0183884.


