DESIGN LEARNING AND CREATIVITY IN ENGINEERING EDUCATION: 
THE IMPACT OF PRODUCT INTERACTIONS 

A Thesis in 
Mechanical Engineering 
by 
Christine A. Toh 

© 2014 Christine A. Toh 

Submitted in Partial Fulfillment 
of the Requirements 
for the Degree of 

Master of Science 

May 2014
The thesis of Christine A. Toh was reviewed and approved* by the following:

Scarlett. R. Miller  
Professor of Mechanical and Industrial Engineering  
Thesis Adviser

Timothy W. Simpson  
Professor of Mechanical and Industrial Engineering

Karen A. Thole  
Professor of Mechanical Engineering  
Head of the Mechanical and Nuclear Engineering Department

*Signatures are on file in the Graduate School
ABSTRACT

Interacting with example products is an essential and widely practiced method in engineering design, yet little information exists on how the representation (pictorial or physical) or interaction a designer has with an example impacts design creativity and learning. In addition, factors such as the designer’s own personality traits as well as the medium in which the designer interacts with the example can also affect design cognition and learning. These knowledge gaps are problematic because we do not yet fully understand how examples affect idea generation and learning of key engineering concepts, or how we can effectively modify or develop design methods to support example usage practices and instruction. In this thesis, the results of three experimental studies with a total of 95 engineering students are reported. The results of these studies show that personality traits affect involvement in team-based dissection activities and thus, design creativity. Additionally, the modality of the example (2-dimensional or 3-dimensional) used during early design ideation practices influence the resulting creativity of design outcomes. Lastly, the results show that the medium of interaction (virtual or physical) result in the same amount of student learning, but differ in terms of the amount of self-efficacy gains experienced by the students. The contributions of this thesis are threefold. First, the results add to our understanding of the role that individual attributes such as personality and the type of designer-product interaction play on design cognition and creativity. Second, the findings of this thesis highlight the effect that virtual dissection interfaces have on student learning and self-efficacy. Lastly, these results provide an empirical basis for the development of recommendations and guidelines for enhancing example usage in engineering design practice and education. Overall, the results add to our understanding of how individual traits and different designer-product interactions affect design creativity, learning, and retention in engineering education. These results are used to derive new ways for improving student-product interactions in engineering design courses.
Table of Contents

List of Figures .................................................................................................................. vii

List of Tables .................................................................................................................... viii

Acknowledgements .......................................................................................................... ix

Chapter 1 .......................................................................................................................... 1

1.1 Background & Motivation ......................................................................................... 2
1.2 Objective ..................................................................................................................... 4
1.3 Summary of Thesis Papers ....................................................................................... 5
    1.3.1 Paper I – Exploring the Role of Personality and Exposure to Team-Based
        Dissection on Design Fixation .............................................................................. 6
    1.3.2 Paper II - The Impact of Exposure to Team-Based Dissection Activities on
        Design Novelty ...................................................................................................... 7
    1.3.3 Paper III – The Impact of Virtual Product Dissection Environments on
        Engineering Student Learning and Self-Efficacy ................................................ 8
1.4 References .................................................................................................................. 10

Chapter 2........................................................................................................................ 13

2.1 Introduction .................................................................................................................. 14
2.2 Background ................................................................................................................ 15
    2.2.1 Design Fixation ............................................................................................... 15
    2.2.2 Product Dissection ......................................................................................... 16
    2.2.3 Personality, Team Performance, and Creativity ........................................... 17
    2.2.4 Research Objectives ....................................................................................... 19
2.3 Exploratory study to examine design fixation ............................................................. 19
    2.3.1 Participants .................................................................................................... 19
    2.3.2 Procedure ..................................................................................................... 20
    2.3.3 Metrics .......................................................................................................... 22
    2.3.4 Statistical analysis ......................................................................................... 25
2.4 Results ......................................................................................................................... 26
    2.4.1 The Relationship between Personality and Exposure to Dissection .......... 26
    2.4.2 The Effect of Personality and Exposure to Dissection on Fixation ........... 28
    2.4.3 The Impact of Dissecting Different Products on Fixation ......................... 29
2.5 Discussion ................................................................................................................... 30
2.6 Conclusion .................................................................................................................. 33
2.7 References .................................................................................................................. 35

Chapter 3........................................................................................................................ 39

3.1 Introduction .................................................................................................................. 40
3.2 Background & Previous Work ................................................................................... 41
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.2.1 Design Novelty</td>
<td>41</td>
</tr>
<tr>
<td>3.2.2 Methods and Techniques for Supporting Design Novelty</td>
<td>43</td>
</tr>
<tr>
<td>3.2.3 Product Dissection in Engineering Design</td>
<td>44</td>
</tr>
<tr>
<td>3.2.4 Research Questions</td>
<td>46</td>
</tr>
<tr>
<td>3.3 Methodology</td>
<td>47</td>
</tr>
<tr>
<td>3.3.1 Participants</td>
<td>47</td>
</tr>
<tr>
<td>3.3.2 Procedure</td>
<td>47</td>
</tr>
<tr>
<td>3.3.3 Metrics</td>
<td>49</td>
</tr>
<tr>
<td>3.4 Results</td>
<td>55</td>
</tr>
<tr>
<td>3.4.1 The Effect of Dissecting Different Products on Design Novelty</td>
<td>56</td>
</tr>
<tr>
<td>3.4.2 The Effect of Number of Ideas Generated on Novelty</td>
<td>57</td>
</tr>
<tr>
<td>3.4.3 The Relationship between Exposure to Dissection and Design Novelty</td>
<td>58</td>
</tr>
<tr>
<td>3.5 Discussion</td>
<td>59</td>
</tr>
<tr>
<td>3.5.1 Hypothesis 1: The Type of Product Dissected Affects the Novelty of the Generated Concepts</td>
<td>59</td>
</tr>
<tr>
<td>3.5.2 Hypothesis 2: The Number of Ideas Generated Affects the Novelty of the Generated Concepts</td>
<td>61</td>
</tr>
<tr>
<td>3.5.3 Hypothesis 3: Exposure to the Dissection Activity Impacts Design Novelty</td>
<td>61</td>
</tr>
<tr>
<td>3.6 Conclusion</td>
<td>62</td>
</tr>
<tr>
<td>3.7 Acknowledgements</td>
<td>64</td>
</tr>
<tr>
<td>3.8 References</td>
<td>64</td>
</tr>
<tr>
<td>Chapter 4 The Impact of Virtual Product Dissection Environments on Student Learning and Self-Efficacy</td>
<td>68</td>
</tr>
<tr>
<td>4.1 Introduction</td>
<td>69</td>
</tr>
<tr>
<td>4.2 Background &amp; Motivation</td>
<td>71</td>
</tr>
<tr>
<td>4.2.1 Learning and Product Dissection</td>
<td>71</td>
</tr>
<tr>
<td>4.2.2 Virtual Learning Advances in Education</td>
<td>73</td>
</tr>
<tr>
<td>4.2.3 Research Objectives</td>
<td>74</td>
</tr>
<tr>
<td>4.3 Experiment 1: Impact of Virtual Dissection on Learning and Self-Efficacy</td>
<td>75</td>
</tr>
<tr>
<td>4.3.1 Participants</td>
<td>76</td>
</tr>
<tr>
<td>4.3.2 Procedure</td>
<td>76</td>
</tr>
<tr>
<td>4.3.3 Experimental Design</td>
<td>77</td>
</tr>
<tr>
<td>4.3.4 Metrics</td>
<td>79</td>
</tr>
<tr>
<td>4.3.5 Data Analysis</td>
<td>80</td>
</tr>
<tr>
<td>4.4 Experiment 1: Results &amp; Discussion</td>
<td>81</td>
</tr>
<tr>
<td>4.4.1 Impact of Dissection Method on Student Learning and Knowledge Retention</td>
<td>81</td>
</tr>
<tr>
<td>4.4.2 Effect of Dissection Method on Electro-Mechanical Self-Efficacy</td>
<td>83</td>
</tr>
<tr>
<td>4.4.3 Interaction Effects of Product Complexity</td>
<td>84</td>
</tr>
<tr>
<td>4.5 Experiment 2: Exploring Virtual Dissection in the Engineering Classroom</td>
<td>85</td>
</tr>
<tr>
<td>4.5.1 Participants</td>
<td>86</td>
</tr>
<tr>
<td>4.5.2 Procedure</td>
<td>86</td>
</tr>
<tr>
<td>4.5.3 Data Analysis</td>
<td>87</td>
</tr>
</tbody>
</table>
4.6 Experiment 2: Results and Discussion ................................................................. 88
  4.6.1 Advantages of Physical Dissection ................................................................. 88
  4.6.2 Advantages of Virtual Dissection ................................................................. 88
  4.6.3 Improvements to the Virtual Learning Environment ...................................... 90
4.7 Implications of Experiments .................................................................................. 91
  4.7.1 Virtual and Physical Dissection Environments Have the Same Effect on
        Student Learning and Knowledge retention but Different Effects on Self-Efficacy
        ......................................................................................................................... 92
  4.7.2 Virtual Dissection in Engineering Education and a Framework for
        Improvements .................................................................................................... 94
4.8 Conclusion ............................................................................................................. 97
4.9 References ............................................................................................................ 99

Chapter 5.................................................................................................................... Summary, Contributions, & Future Work
                                                                .......................... 102

Appendix A .................................................................................................................. 105
  Toothbrush Rating Statements ................................................................................. 105

Appendix B .................................................................................................................. 107
  Student Learning Assessment (SLA) Questionnaire .............................................. 107
  Student Self-Efficacy Questionnaire ...................................................................... 108
  Virtual Dissection Survey Questions ..................................................................... 109
  Virtual Dissection Interview Questions ................................................................. 110
List of Figures

Figure 2-1: Electric toothbrushes used for the design project. Left: Oral-B Cross Action Power, right: Oral-B Advance Power 400 ................................................................. 20

Figure 2-2. Sequential concepts generated for the energy mechanism design by participant 45. 22

Figure 2-3: Participant 25’s brush head design that uses writing to supplement the sketch in order to communicate the design idea ............................................................. 23

Figure 2-4: Example energy mechanism rating question with numbered rating scale ............ 24

Figure 2-5. Personality trait distribution of the participants ............................................. 27

Figure 2-6. Means of % fixation vs. toothbrush type ...................................................... 29

Figure 3-1. Electric toothbrushes used for the design project. Left: Oral-B Cross Action Power, right: Oral-B Advance Power 400 ................................................................. 48

Figure 3-2. Sequential concepts generated for the body design by participant 45 .............. 49

Figure 3-3. (top) Participant 25’s brush head design that uses writing to supplement the sketch in order to communicate the design idea. (bottom) Example question with rating scale used to identify the features the idea focused on. Raters answered the question with option 4 (completely disagree). ................................................................. 50

Figure 3-4. Examples of highly novel ideas for the body design category generated by Participant 45 (left) and energy mechanism category generated by Participant 12 (right) .......... 58

Figure 3-5. The means and standard deviations of participant novelty for low and high levels of exposure within team for the body design and energy mechanism category. ............... 59

Figure 4-1. A bill of materials of the milk frother completed by participant 67. The Subtract and Operate Procedure (SOP) was used to encourage students to think about the purpose of a part and the consequences that may arise from the part being subtracted from the product. ...................................................................... 77

Figure 4-2: Student learning assessment (SLA) sketches of the power supply by participant S24RD that scored 0/3 for the (a) pre-test sketch and 3/3 for the (b) post-test sketch. .... 79

Figure 4-3. Pre and post-test feature knowledge scores for students across all conditions ........ 82

Figure 4-4. The pre-test, post-test, and knowledge retention self-efficacy scores of students who performed physical and virtual dissection ................................................. 84

Figure 4-5. A screen capture of the virtual dissection interface where participants virtually dissected the Accentra PaperPro stapler .................................................................. 86
### List of Tables

Table 2-1. Partially dissected toothbrushes with the number of and percentage of parts by category for the 2 toothbrushes. ........................................................................................................ 21

Table 2-2: Example body design ideas rated using the questions discussed above. Ratings of 1 or 2 were rated as ‘agree’ whereas 3 or 4 were rated as ‘disagree’ ................................................. 24

Table 2-3. The # of parts participant 45 was exposed to during the product dissection activity. The % parts exposure metric was calculated out of the total number of parts in each category ................................................................. 25

Table 2-4. Summary of the multivariate regression analysis. The bolded results indicate significant findings .................................................................................................................. 28

Table 2-5. Summary of the multiple regression analysis with coefficients and significance values. The bolded result indicates a significant finding .................................................. 29

Table 3-1. Partially dissected toothbrushes ........................................................................................................ 48

Table 3-2. Example body design ideas rated using the questions discussed above. Assessments of 1 or 2 were rated as ‘agree’ whereas 3 or 4 were rated as ‘disagree’. ............................... 51

Table 3-3. Example calculation of feature novelty for feature 1: number of brush heads, 2: brush head shape, and 3: bristle length, hardness, and/or direction. Feature 2 is the most novel. ............................................................................................................................ 52

Table 3-4. Examples of highly novel concepts generated by participants for each of the 4 toothbrush categories ........................................................................................................ 54

Table 3-5. The means and standard deviations of the number of ideas generated for each toothbrush type and for all toothbrush types ........................................................................ 55

Table 3-6. Summary of the independent t-tests between average novelty and # ideas of the two toothbrushes. Bolded cells indicate significant results .............................................. 57

Table 3-7. Summary of the Pearson Correlation tests between participant novelty and # ideas. Bolded cells indicate significant results ................................................................. 58

Table 4-1: Dissected milk frothers and toothbrushes in the physical and virtual dissection conditions .......................................................................................................................... 78

Table 4-2. Summary of MANOVA and MANCOVA results conducted on pre-test, post-test, and retention student feature knowledge scores and electro-mechanical self-efficacy scores. Bolded rows indicate significant findings at the 0.05 significance level .................. 81

Table 4-3. The SWOT matrix for virtual dissection interface for increasing student learning, knowledge retention, and self-efficacy ................................................................. 96
Acknowledgements

First, I would like to thank my advisor, Dr. Scarlett Miller for guiding me down this path with the most respect, compassion, and dedication any graduate student could ask for. She has taught me numerous lessons regarding academia that has brought me to where I am today. She transcends the role of advisor, and has instead been my mentor of not just research, but also academics, teaching, and work-life balance. She has expected the very best of me, but at the same time, shown me understanding and empathy in a balance that I can only imagine to be an art. I am grateful and honored to have worked with such an exceptional example of researcher, teacher, and mentor.

I would also like to extend my gratitude to my friends and family who have seen me through this trying journey. To my lovely wife- I am sure you know how grateful I am for your patience and support through the late nights I have spent working and your continued conviction in my success. You are my #1 cheerleader even when I doubted myself. I also want to thank my friends (The Awesome Ladies Club, Brant ‘Chef’ Rosenberger, and the Videon Guys) who have given me words of encouragement and who have helped me de-stress through cooking marathons, road-trips, swing dancing, and game nights. You have truly made graduate school a unique life experience!

Finally, I would like to thank Britelab members Arti Patel, Boyd Warwick-Clark, Connor Disco, Kristen Murray, Kelly Gagnon, and Clay Meisel who have endured my practice presentations and who have assisted with the research in invaluable ways. I am also thankful to Dr. Gül Okudan Kremer and Dr. Timothy Simpson for their help with conducting this research and useful feedback that only experience can provide.
Chapter 1

Introduction

Examples are commonly used in engineering design as a means to aid in the development of novel ideas through the transformation, combination or adaption of elements of existing products [1, 2]. Prior studies have shown that the use of examples is pervasive in design [3, 4], with many different formats of examples available for the designer to choose from. However, the impact of variations in designer-product interactions have yet to be thoroughly investigated, leaving it unclear which formats of examples are most useful in different design contexts. Universal application without systematic assessment of these variants is problematic because without this knowledge we do not know which types of designer-product interactions promote cognitive stimulation and the flow of useful ideas, or which methods inhibit this process. It is essential that such a knowledge gap be filled since prior research has shown that interacting with examples can limit creative thinking [5], but hands-on interactions play a crucial role in enhancing engineering instruction [6]. Therefore, research that explores and investigates that impact of example usage and exposure in engineering design can add to our understanding of design creativity and allow us to improve engineering education.

Interactions and exposure to examples in engineering practice and education vary in several important ways. First, designers can have varying levels of exposure to examples due to individual factors such as personality attributes [7, 8]. Second, the complexity and familiarity of the presented example can vary significantly, and prior research has shown that this factor can significantly impact design creativity [9]. Lastly, new methods of interacting with examples, such as virtual dissection, have been developed in an effort to reduce costs and increase accessibility of these techniques. However, research in other areas provides compelling evidence to suggest differences in learning and perceived competency while using these virtual learning environments [10]. While these differences in designer-product interactions are pervasive in engineering practice and education, research is needed to uncover the exact impact that different forms of examples can have on design cognition, creativity, and learning.
1.1 Background & Motivation

Examples help designers gain a better understanding of the solution space [11] and improve understanding and comprehension of key engineering concepts [12, 13]. However, while examples are considered the cornerstone of the engineering design process [1, 4] they can also negatively impact idea development by fixating designers on the information contained within the example set. This limiting adherence to existing examples is termed design fixation [5] and has been shown to affect different levels of expertise [14] and different design disciplines [15]. Fixation on existing examples can negatively impact the creative process by inhibiting the generation of novel ideas. In engineering design, novelty is often used as a metric for measuring idea creativity in conjunction with the quality, quantity, and variety metrics [16]. Design novelty refers to “how unusual or unexpected an idea is compared to other ideas” ([16], pg. 117). Thus, novel ideas expand the design space and help loosen the tight grip on the design goal that engineers often have. Novelty also offers opportunities to find better designs that do not yet exist [16], ultimately leading to better design outcomes [17]. As engineers, developing novel solutions is a vital step in moving the field forward and generating useful solutions for society. Therefore, understanding methods and tools that increase novelty and reduce fixation effects in the design process is of fundamental importance.

Most research on encouraging creativity in engineering design has focused on understanding and developing formal idea generation techniques such as Brainstorming [18], C-Sketch [19], and TRIZ [20] as opposed to studying the impact of naturally occurring design practices. This is problematic because these formalized methods often require additional information to be provided at the start of the idea generation activity [14, 21], or they require the implementation of specific techniques during ideation [19, 20]. These factors significantly reduce the practicality and implementation of these methods in the broader-spectrum of design. In fact, many designers opt not to use formal ideation methods because the burdensome steps involved in these methods often bring about “doubt, ambiguity, and a lack of perseverance that can lead people to abandon the creative process (p. 366) [22].” Therefore, design research that focuses on studying isolated, formal techniques often do not bridge the gap between design practice and research [23]. For that reason, it is essential that we study methods currently utilized in engineering practice and understand the impact on design novelty.
Researchers have started to explore the implications of currently practiced design techniques, and have found that methods such as physical prototyping encourage designers to reuse less features from example concepts [24]. Case studies conducted in engineering industry provide compelling evidence that prototypes can provide inspiration and encourage the generation of new ideas during the design process [25]. Other studies conducted in engineering education have found that design teams that use prototypes in the early phases of design were more successful since physical prototypes “provide unique and various ways of acquiring approximations for upcoming technical and functional constraints” (p. 1283) [26]. This result is supported by other similar studies that have revealed that the time spent on early prototyping practices is positively related to design outcomes [27]. While these prior research studies highlight the benefits of physical interactions in engineering design, they focus on the effects of building and interacting with prototypes, rather than interacting with commercially available products. This is important to study because designers are often exposed to existing products in the early stages of design in an effort to gain knowledge and insights into the solution space. One such activity that involves examining and taking apart existing products is product dissection; it has not been studied extensively for its impact on design novelty or fixation, however.

The use of product dissection as a design tool is widely practiced in both engineering academia and industry as a method of gaining knowledge about a system’s internal structures and uncovering opportunities for re-design [28]. Research has shown that students who perform product dissection in a team environment are more creative, develop more ideas, and explore both the form and function of a design compared to those who do not [28]. This deeper exploration of the design space as a result of dissection activities suggests that product dissection could have an impact on design fixation and thus, impact the way dissection is utilized in an educational setting. In addition, prior work has shown that designers who are exposed to examples that are common to the field or on the market often are more fixated than those exposed to novel examples [29]. However, researchers in engineering design have yet to explore how dissection activities and the type of product dissected affects fixation or how individual factors such as personality traits can mediate involvement in dissection activities.

While dissection activities are beneficial to the application of knowledge [30] and development of hands-on skills [31], they are often seen as cost prohibitive due to the cost of the materials, space requirements, preparation, and instructional materials needed to effectively
perform product dissection [32]. The costly nature of dissection has lead researchers to develop virtual dissection tools [32]. Recent studies that examined the use of virtual dissection in engineering education reveal that there is limited difference in learning and performance between groups that utilize virtual dissection and those that performed physical dissection [33]. In fact, researchers have found that virtual dissection can encourage more variety during idea generation [34], and may provide more detailed information to students that can help with learning [35]. However, little data exists on how objective measures of student learning and self-efficacy, an important construct in education, are affected by virtual dissection environments. This is problematic because it is not fully known if virtual product dissection helps or hinders the positive effects of product dissection in engineering education.

1.2 Objective

The objective in this thesis is to investigate the impact of different designer-product interactions on design creativity and engineering learning and retention. Thus, the three major goals of this thesis are identified as follows:

Goal 1: To explore the role that individual attributes such as personality traits play on the amount of exposure to existing examples during team-based design activities. Since personality traits have been shown to play a crucial role in team interactions [7, 8], research that investigates how personality affects involvement in fixation-reducing techniques such as product dissection can add to our understanding of how to best mitigate design fixation and increase engineering creativity.

Goal 2: To investigate the impact of involvement in team-based product dissection activities on design fixation and novelty during idea generation. Researchers in engineering design have touted the benefits of hands-on activities such as product dissection [36], but much is still unknown about the exact impact of involvement in these activities on novice designer cognition and creativity. Therefore, research that provides empirical evidence
on the impact of team-based dissection activities can help researchers and educators better understand how to best utilize these practices to enhance engineering creativity.

Goal 3: To gain an understanding of the effects of virtual dissection environments on student learning, knowledge retention, and self-efficacy. While research in education provide compelling evidence to suggest differences in learning and perceived competency while using virtual learning environments [10], there exist little data on how these virtual dissection environments affect engineering student learning. Therefore, findings from research that fills this knowledge gap allow us to understand how to leverage virtual product dissection to increase the sustainability and accessibility of dissection practices without sacrificing student knowledge and competency gains.

1.3 Summary of Thesis Papers

The three manuscripts presented in this thesis address these research goals. Specifically, the first manuscript, published by the Advances in Engineering Education journal [37], found in Chapter 2, investigates the impact of personality and involvement in team-based dissection activities on design fixation. The second paper of this thesis, accepted by the ASME Journal of Mechanical Design [38] and found in Chapter 3, seeks to understand the impact of product dissection, a method commonly utilized in academia and industry [39], on engineering design novelty. The final paper of this thesis, submitted to Design Studies and found in Chapter 4, explores the impact that virtual dissection tools can have on student learning, knowledge retention, and self-efficacy in the engineering classroom through two studies conducted with first-year engineering students. A summary of these papers is presented next, followed by a general discussion of the findings and implications to engineering practice and instruction.
1.3.1. Paper I – Exploring the Role of Personality and Exposure to Team-Based Dissection on Design Fixation


The first manuscript produced as part of this research explores the role of product dissection and personality traits on design fixation in an engineering design classroom setting. Design fixation has been found to be complex in its definition and expression, but it plays an important role in design idea generation. Identifying the factors that influence fixation is crucial in understanding how to enhance the design process and reduce the negative effects of fixation. One way to potentially mitigate fixation is through product dissection activities since this activity has been shown to increase creativity and design space exploration in engineering design. However, product dissection has not been studied in the context of design fixation, so it is unclear if, or how, this type of activity influences fixation. Additionally, although prior work studied product dissection in a team environment, it did not examine how individual factors such as personality attributes influence one’s involvement or exposure to the activity. This is important because the participation of each team member can be affected by individual factors such as personality traits. Therefore, this study explores the role of product dissection and personality traits on design fixation in an engineering design classroom setting.

In order to examine the link between personality traits, involvement in team-based dissection activities, and design fixation, an exploratory study was conducted with 76 first-year engineering design students that formed 3 and 4-member design teams and were tasked with redesigning an electric toothbrush for increased portability. Each team was given 90 minutes during one class period to dissect their assigned electric toothbrush. A week later, the participants attended a brainstorming session where each team member was given 30 minutes to generate as many ideas as they could for the re-designed toothbrush without consulting with the other participants. Personality measures for each participant were captured prior to the start of the study using the short Five Factor Model (FFM) online questionnaire (Short Form for the IPIP-NEO (International Personality Item Pool Representation of the NEO PI-R™) [40]).

Our results show that exposure to dissection activity was related to the individual personality traits of the team members, and design fixation was, in turn, affected by the
individual’s exposure to the dissection activity. These findings demonstrate a relationship between personality and exposure to the product dissection activity, and also indicate product dissection as a way to mitigate fixation effects in engineering design education. The results from this study can be used to enhance our understanding of the design process, and help reduce fixation effects in the engineering classroom.

1.3.2 Paper II - The Impact of Exposure to Team-Based Dissection Activities on Design Novelty


The goal in this manuscript is to understand the impact of product dissection, a design method widely utilized in academia and industry, on design novelty in order to produce recommendations for the use or alterations of this method for supporting novelty in design. Although design novelty is a critical area of research in engineering design, most research in this space has focused on understanding and developing formal idea generation methods instead of focusing on the impact of current design practices. This is problematic because formal techniques are often not adopted in industry due to the burdensome steps included in these methods, which limit the practicality and adoption of these methods. This study seeks to understand the impact of product dissection, a design method widely utilized in academia and industry, on design novelty in order to produce recommendations for the use or alterations of this method for supporting novelty in design.

To investigate the impact of dissection, a study was conducted with 76 engineering students who completed a team-based dissection of an electric toothbrush and then individually generated ideas. The students formed 3 and 4-member design teams and were tasked with redesigning an electric toothbrush for increased portability. Forty-four students redesigned the Oral-B Advance Power 400 electric toothbrush while 32 students redesigned the Oral-B Cross Action Power electric toothbrush. Each team was given 90 minutes during one class period to dissect the electric toothbrush that they were assigned to redesign, and each member’s involvement in the dissection activity was recorded. A week later, the participants attended a
brainstorming session where each team member was given 30 minutes to generate as many ideas as they could for the re-designed toothbrush without consulting with the other participants.

The relationships between involvement in the dissection activity, the product dissected, the novelty and quantity of the ideas developed were investigated. The results reveal that team-members who were more involved in the dissection activity generated concepts that were more novel than those who did not. In addition, the type of the dissected product also had an influence on design novelty, where participants that received the more innovative design (Cross Action Power) for product dissection produced concepts that were more novel than those that received the less innovative design (Advanced Power). Finally, a positive correlation between the number of ideas generated and the novelty of the design concepts was identified. The results from this study are used to provide recommendations for leveraging product dissection for enhancing novelty in engineering design education and practice.

1.3.3 Paper III – The Impact of Virtual Product Dissection Environments on Engineering Student Learning and Self-Efficacy

Submitted for consideration to Design Studies, April 2014

The final manuscript produced as part of this research sought to explore the utility of virtual dissection environments for encouraging student learning, knowledge retention, and self-efficacy in the engineering classroom. Product dissection activities are widely practiced in engineering education as a means of increasing student learning and understanding of core engineering concepts. While recent efforts in this area of research have sought to develop and utilize virtual dissection tools in order to reduce and mitigate the costs of physical dissection activities, little data exists on how virtual dissection impacts student learning and understanding. This lack of data makes it difficult to draw conclusions on the utility of virtual dissection tools for enhancing engineering instruction. This work fills the research voids identified in the literature by examining the impact of dissection method and product complexity on student learning, understanding, and self-efficacy in the engineering classroom. Thus, two studies were developed to understand the impact of these factors in engineering education.
The first study was a controlled study that examined the impact of the dissection method and product complexity on student learning, knowledge retention, and engineering self-efficacy. Participants were 19 first-year students from an undergraduate engineering design course who were asked to participate in a design activity as part of the course. Participants completed a pre-test learning and self-efficacy assessment that measured each students’ knowledge of the internal structures of a milk frother or an electric toothbrush (randomly assigned to each student). Following the pre-test assessment, participants completed either a physical dissection or virtual dissection activity of their assigned product. Three hours after all dissection activities were completed, students completed a post-test learning and self-efficacy assessment, as well as a retention learning and self-efficacy assessment 10 weeks after the study.

The second study was conducted to build upon the findings of the first experiment by exploring the differences between physical and virtual dissection activities for its effects on student comprehension of the dissected product through an exploratory qualitative study. In this study, participants in a product dissection course formed two-member teams and completed a physical dissection of a stapler as well as a virtual dissection of a different stapler. Once participants completed the dissection activities for both staplers (physical and virtual), they were asked to complete an online survey on their experiences with the physical and virtual dissection activities. Following the online survey, focus groups and semi-structured interviews were conducted. The results from the surveys and interviews were analyzed in order to determine which aspects of virtual dissection could be improved.

Our results show that student learning and knowledge retention was not affected by the use of the virtual dissection interface, but increases in electro-mechanical self-efficacy three hours after the dissection activity was reduced in students who performed virtual dissection compared to students who performed physical dissection. These results add to our knowledge of the impact that virtual dissection tools can have on student learning and self-efficacy. The results of the qualitative study also provide a foundation for future work on virtual dissection interfaces and enable us to develop recommendations and guidelines for improving the effectiveness of these tools in engineering education in order to enhance engineering instruction. These improvements also help increase the effectiveness of virtual dissection environments and encourage the adoption of more sustainable and accessible dissection practices.
1.4 References


[40] Johnson, J., "Short Form for the IPIP-NEO (International Personality Item Pool Representation of the NEO PI-R™)," http://www.personal.psu.edu/j5j/IPIP/ipipneo120.htm.
Chapter 2
Exploring the Role of Personality and Exposure to Team-Based Dissection on Design Fixation

Christine Toh, Dr. Scarlett Miller, and Dr. Gül Okudan Kremer


Design fixation has been found to be complex in its definition and expression, but it plays an important role in design idea generation. Identifying the factors that influence fixation is crucial in understanding how to enhance the design process and reduce the negative effects of fixation. One way to potentially mitigate fixation is through product dissection activities since this activity has been shown to increase creativity and design space exploration in engineering design. However, product dissection has not been studied in the context of design fixation, so it is unclear if, or how, this type of activity influences fixation. Additionally, although prior work studied product dissection in a team environment, it did not examine how individual factors such as personality attributes influence one’s involvement or exposure to the activity. This is important because the participation of each team member can be affected by individual factors such as personality traits. Therefore, this study explores the role of product dissection and personality traits on design fixation in an engineering design classroom setting. Our results show that exposure to dissection activity was related to the individual personality traits of the team members, and design fixation was, in turn, affected by the individual’s exposure to the dissection activity. These findings demonstrate a relationship between personality and exposure to the product dissection activity, and also indicate product dissection as a way to mitigate fixation effects in engineering design education. The results from this study can be used to enhance our understanding of the design process, and help reduce fixation effects in the engineering classroom.
2.1 Introduction

Vilfredo Pareto said that “An idea is nothing more or less than a new combination of old elements” [1]. This is found to be true in engineering design where designers transform, combine, or adapt elements of existing designs in order to generate new ideas [2]. In fact, educators often use examples as a tool to teach design in engineering education. Although examples are now considered the cornerstone of the engineering design process [2, 3], they can also negatively impact idea development by fixating designers on the information contained within the example set. This limiting adherence to existing examples is termed design fixation [4] and has been shown to affect different levels of expertise [5] and different design disciplines [6]. Therefore, it is important to identify design methods that mitigate fixation effects in order to improve strategies for teaching design in engineering education and to improve our overall understanding of the design process.

One way that fixation effects can potentially be reduced is through product dissection, as dissection has been shown to increase creativity and design exploration in engineering design [7]. However, since product dissection has not been studied in the context of design fixation, it is unclear if, or how, this type of activity influences fixation. In addition, although prior work studied product dissection in a team environment [8], it did not study how individual factors such as personality influences one’s involvement in a dissection activity. Therefore, the purpose of this paper is two-fold. First, we seek to understand how individual factors such as personality attributes affect the individual’s exposure to team-based dissection activities. Second, we aim to explore the impact of product dissection activities on design fixation in a team environment. The results from this study are used to derive recommendations to mitigate fixation effects through dissection activities and identify new research directions that explore methods for reducing fixation through new engineering pedagogical practices.
2.2 Background

2.2.1 Design Fixation

Anecdotal and historical accounts have shown that even the most creative ideas are developed through minor extensions of familiar concepts [9]. Although this mapping of old to new can facilitate progress, it can also limit an individual’s ability to ‘think outside the box’ or move beyond familiar concepts to develop something truly unique. Jansson and Smith [4] were the first to study fixation effects in design. They hypothesized that designers who were shown pictorial examples prior to idea generation would experience a mental block that would limit their ability to solve the problem in other ways. Their research validated this theory, when they found that designers who were shown examples prior to idea generation reused more features from the example set compared to those who were not shown examples. This was found to be true for both novice (students) and expert (practitioners) designers even when example features were deemed inappropriate. They defined this lack of flexibility in the design process as design fixation, or a “blind and sometimes counter-productive adherence to a limited set of ideas in the design process” (p. 4) [4]. Follow up studies also reported similar findings on the fixation effects of example usage during the design process [5, 10-12].

While these studies highlight the presence of fixation in design, other research has explored the complex nature of fixation. For example, Purcell and Gero [6] found that although designers can become focused on examples during the design process, fixation might be dependent on variables such as designer’s domain knowledge. Tseng et al. [13] also explored the factors that impact design fixation and found that the timing and analogical similarity of the examples presented impacted fixation effects. Other studies, such as those done by Purcell and Gero [14] found that the designer’s familiarity with the example presented plays a role in the fixation effects experienced. This result is thought provoking because it suggests that the type of example presented before idea generation may impact the fixation apparent in generated designs. Linsey et al. [5] also studied the complexity of fixation, and their results showed that engineering design faculty who research fixation effects can become fixated during the design process, without even realizing that fixation is happening. The complexity of fixation has also been shown to effect engineering education, as research on fixation has been shown to reduce a
students’ performance when examples with inappropriate solutions are presented [12]. These studies highlight the complexity of fixation and its negative impact on idea generation and motivate studies that identify methods to reduce fixation effects in order to properly modify engineering pedagogical practices.

Although design fixation has been shown to be limiting in the design process, researchers have shown that it is possible to overcome fixation by providing participants with debiasing instructions [12] or by providing useful analogies [5]. The results from these studies highlight the possibility of mitigating fixation effects but both of the studies required the researcher to provide additional information (instructions and analogical operators) to the participants during the design activity reducing the practically of this type of approach in design. In addition, because fixation happens in an unconscious manner [15], it is not always easy to perform an intervention at the design stage. Nevertheless, these works direct researchers to focus on methods of mitigating design fixation effects, starting with understanding the factors that contribute to fixation in existing design activities. Therefore, the goal of this study is to understand how product dissection activities, a tool frequently used during the re-design process in engineering education, affects fixation. Product dissection is particularly apt for mitigating fixation effects as it can be implemented without specificity to the problem and it has previously been shown as a beneficial activity in engineering education [16-18].

2.2.2 Product Dissection

Product dissection has been utilized in various engineering design settings, and it is often used during the design process as a way to systematically uncover opportunities for re-design [7]. Dissection involves taking apart or analyzing all components and subcomponents of a product [18], and thereby adding to the understanding of its structure and properties while uncovering opportunities for product improvement [16]. Ultimately, the goal of dissection is to improve the maintainability and reliability of a product, implement new technologies, and increase the functionality of the product [19] through the examination, study, capture, and modification of existing products.
The benefits of product dissection activities are realized in both industry and academia. At the industry level, companies perform product dissection to provide competitive benchmarks and gain knowledge and insight of a particular product [8]. In the classroom setting, product dissection provides students insight into industry practices [16] and ‘hands-on’ experience [20]. In fact, studies have shown that product dissection can help students relate classroom material to real-life engineering problems [21], help engage first year engineering students in learning [22], improve the effectiveness of instruction [23], improve student’s practical knowledge [24], increase student learning and enjoyment [25], and allows students to learn about team dynamics and the importance of inter-personal communication [21]. Research has also shown that students who perform product dissection in a team environment are more creative, develop more ideas, and explore both the form and function of a design compared to those who do not [7]. This deeper exploration of the design space as a result of dissection activities suggests that product dissection could have an impact on design fixation and thus, impact the way dissection is utilized in an educational setting. However, no research to date has explored how dissection affects fixation or how individual factors such as personality traits can mediate involvement in dissection activities. This study was developed to respond to these research gaps.

2.2.3 Personality, Team Performance, and Creativity

While the previous section outlined the potential positive effects of team-based product dissection activities, a team member’s level of involvement in the dissection may impact the extent of these positive effects. Factors that impact team participation have been widely studied in the literature and include variables such as motivation [26], status difference [27], and self-knowledge [28]. In addition, individual personality attributes have been shown to have a strong influence on team member participation [29, 30]. Due to the fact that personality traits largely influence the way in which individuals behave and interact with each other [31], it is important that this factor be studied for its impact on team involvement. This is crucial because design is being recognized and taught as a team process in engineering [32], in part, because products developed by teams have been shown to be of higher quality than those produced solely by an individual [33] and, in part, because teams foster a wider range of knowledge and expertise which aid in the development of ideas [34]. In addition, teamwork has been shown to increase
classroom performance [35] and encourage more creative analysis and design [36] in engineering education. Therefore, it is important that we study personality attributes as they relate to the exposure to the dissection activity in team environments and design fixation.

One way in which personality traits can be assessed is through The Big Five Factors of Personality (Five Factor Model) framework developed by Costa and McCrea [37]. This framework has been used extensively in the literature, and is recognized as a reliable instrument. The Five Factor Model states that personality has five dimensions: (1) Neuroticism, (2) Extraversion, (3) Openness to Experience, (4) Agreeableness, and (5) Conscientiousness. These personality traits have been found to differ across genders [38-40] (e.g., females scoring higher on Neuroticism and Agreeableness than males). Importantly, these attributes have been shown to play a significant role in small team performance [30], a setting that is common in engineering design. For instance, those that score high on agreeableness tend to engage in teamwork, are more cooperative, and have a higher quality of personal interaction, while those who score high in neuroticism tend to be less cooperative in a team environment [41]. On the other hand, the extraversion personality trait has also been positively linked to successful team performance [42], while conscientiousness has been shown to be negatively correlated with social loafing [43]. Therefore, we hypothesize that personality attributes will affect team member involvement and interactions, and hence, the individual exposure to the product dissection activity.

In addition to linking personality attributes to team performance, several scholars have summarized the role of personality in creative achievement. For instance, McCrae [44] found that openness to experience had a strong effect on creative achievement, while Steel et al. [45] linked innovation to both openness to experience and conscientiousness. Hoff et al. [46] suggested that creative individuals are low on agreeableness and “do not adapt to others, but go their own way” (p. 254) while Stafford et al. [47] linked creative achievement to high levels of extraversion. Other researchers have also found highly neurotic individuals to be less likely to have boosts in creativity due to anxiety [48]. Although work in this research area has revealed a relationship between personality attributes and creative achievements, the results are mixed and the participants used in these studies were mostly undergraduate psychology students, and not engineers. This makes their results questionable for application in the engineering domain. Therefore, the current study seeks to understand how personality traits affect involvement in team product dissection activities, and hence, how this factor affects design fixation.
2.2.4 Research Objectives

The purpose of this study is to examine the interactions between individual personality traits, exposure to a team-based dissection activity, and design fixation. Our two primary research hypotheses are as follows: (1) personality traits affect the involvement in the dissection activity, and (2) exposure to the dissection activity and personality traits affect design fixation. For the second hypothesis, the personality traits and the exposure to the dissection activity variables are anticipated to be correlated to one another and thus, are analyzed concurrently for their effects on design fixation. Additionally, we seek to determine how the product that is dissected affects the involvement in the dissection activity as well as the amount of fixation apparent in the generated ideas, as prior research has linked fixation to participants’ familiarity with provided examples. To test these hypotheses, an exploratory study was conducted in a first-year engineering design classroom involving the dissection and a re-design of an electric toothbrush. It should be noted that this study was exploratory in nature and thus, did not seek to control the extent to which exposure to the product dissection activity affects design fixation, but rather sought to find a relationship between these two quantities in a natural classroom setting. Hence, a control group was not utilized for this study, as we wanted to see how the personality attributes naturally affected team member participation in the activity. The results obtained from this study to contribute to the understanding of how team-based dissection activities influence design fixation in order to derive implications for engineering education and help identify new research paths that extend the knowledge of de-fixating methods.

2.3 Exploratory study to examine design fixation

2.3.1 Participants

The participants in this experiment were undergraduate students in a first-year engineering design course at a large northeastern university. There were 76 students (61 males, 15 females) that participated in this study from three different sections of the course. Each section consisted of 3- and 4-member design teams (20 teams in total, with 4 teams consisting of 3 members). Teams were assigned by the instructor based on prior expertise and knowledge of
engineering design so as to balance the performance of the teams. This was accomplished through questionnaires that were given at the start of the semester that asked about student proficiencies in the following three areas: (1) 2D and 3D modeling, (2) sketching, and (3) engineering design experience.

Personality measures for each participant were captured prior to the start of the study using the short Five Factor Model (FFM) online questionnaire (Short Form for the IPIP-NEO (International Personality Item Pool Representation of the NEO PI-R™) [49]).

2.3.2 Procedure

The design teams were tasked with redesigning an electric toothbrush for increased portability. Two of the three sections (44 students) re-designed the Oral-B Advance Power 400 electric toothbrush while the other section (32 students) redesigned the Oral-B Cross Action Power electric toothbrush, both seen in Figure 2-1. Two toothbrushes were chosen because we were interested in understanding if the product provided to the students affected their involvement in the dissection activity or their degree of fixation.

![Figure 2-1: Electric toothbrushes used for the design project. Left: Oral-B Cross Action Power, right: Oral-B Advance Power 400](image)
Each team was given 90 minutes during one class period to perform a product dissection of the electric toothbrush they were assigned to redesign. During this activity, participants were asked to develop a bill of materials (BOM) for each subcomponent and identify the team member that led each individual part dissection. Examples of the partially dissected toothbrushes with the number of parts for each category are shown in Table 2-1.

Table 2-1. Partially dissected toothbrushes with the number of and percentage of parts by category for the 2 toothbrushes.

<table>
<thead>
<tr>
<th># of Parts</th>
<th>Oral-B Advance Power 400</th>
<th>Oral-B Cross-Action Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brush Head</td>
<td>8 (29.7%)</td>
<td>7 (28.0%)</td>
</tr>
<tr>
<td>Body</td>
<td>9 (33.3%)</td>
<td>6 (24.0%)</td>
</tr>
<tr>
<td>Energy Mechanism</td>
<td>7 (25.9%)</td>
<td>7 (28.0%)</td>
</tr>
<tr>
<td>Power Generation</td>
<td>3 (11.1%)</td>
<td>5 (20.0%)</td>
</tr>
<tr>
<td>Total Number of Parts</td>
<td>27</td>
<td>25</td>
</tr>
</tbody>
</table>

A week later, the participants attended a brainstorming session where each team member was given 30 minutes to generate as many ideas as they could for the re-designed toothbrush without consulting the other participants. The participants were not informed of the brainstorming session prior to attending class the following week. During the brainstorming session, participants were asked to sketch as many concepts as possible, writing notes on each sketch such that an outsider would be able to understand the concepts upon isolated inspection. Each participant was provided with paper that had boxes on it to clearly distinguish each idea. Participants were asked to focus their ideas on four general categories: (1) brush head, (2) body design, (3) energy mechanism, and (4) power supply/accessories, refer to the example in Figure 2-2. Each team had to select two team members to develop ideas in each of the four categories.
For example, team member 1 may have developed ideas for the brush head and power supply; team member 2, the brush head and energy mechanism; team member 3, the energy mechanism and body design; and team member 4, the body design and power supply. In total, there were 40 participants that generated ideas for each category. On average, participants generated 4.5 ideas for the toothbrush head, 3 ideas for the toothbrush body, 3.9 ideas for the energy mechanism, and 4.4 ideas for the power generation category.

![Sequential concepts generated for the energy mechanism design by participant 45](image)

**Figure 2-2.** Sequential concepts generated for the energy mechanism design by participant 45

### 2.3.3 Metrics

To quantify the degree of design fixation for the participants’ solutions, a fixation metric was developed based on the method used by Linsey et al. [50]. In their study, Linsey et al. [50] measured fixation as the number of times a feature from an example was present in a participant’s solution. In order to calculate this metric, they identified a set of features from the example solution provided to participants and had two judges independently rate whether the feature was present or not in the participants solution. Similar to this method, 52 features of the toothbrush provided to participants in the current study were identified and were later categorized into one of four subcategories for analysis: brush head, body, energy mechanism and power generation design, see Table 2-1. Two independent raters were then used to determine the degree of similarity between the features in the generated solution and the features in the provided toothbrush. This differed from Linsey et al.’s [50] study because rather than merely judging if the feature was present in the participant’s solution, the raters were tasked with rating how similar the feature was to the original toothbrush’s design. The development of a rating...
scale was necessary to aid raters in this judgment process due to the improved granularity in the rating system and also because of the varied ways participants presented their design concepts during the study.

During the study, participants were asked to produce both a sketch and a written description of their idea. However, on inspection of the ideas, the authors found that participants often created simple drawings and described additional features in the written design description for complex ideas. For example, participant 25 sketched a simple toothbrush head design but added features such as the motion of the toothbrush only in the written description, see Figure 2-3. Therefore, in order to help raters judge how similar the feature in the idea was to the original design, a 5-point rating system was developed through discussions and training sessions with the raters, see Figure 2-4. Ratings of 1 or 2 were deemed as the solution having a similar feature to the original design (fixated) with a rating of 1 indicating that the idea addressed the feature through sketches and writing and 2 indicating that the idea addressed the feature through sketches or writing alone. A similar system was employed for ratings of 3 and 4 that were deemed as not similar to the original design (not fixated). A rating of 5 was used when the participant did not address the feature in their design. A design-benchmarking handbook was developed to assist the raters and provide a reference during the rating process. Since the goal of this study did not focus on how the participants presented their ideas (pictorial or written), ratings of 1 and 2 and ratings of 3 and 4 were combined for analysis in the study. Examples of designs rated according to this scale are shown in Table 2-1.

![Figure 2-3: Participant 25’s brush head design that uses writing to supplement the sketch in order to communicate the design idea.](image)
The inter-rater reliability for this rating system was 85.2% with a Cohen’s Kappa of 0.76. Disputes were settled in conference between the raters as was done previously by Chrysikou et al. [51].

The idea has the same size?

| 1. Completely agree because it is explicitly shown visually AND in writing | 2. Slightly agree because it is shown either only visually OR in writing | 3. Slightly disagree because it is shown either only visually OR in writing | 4. Completely disagree because it is explicitly shown visually AND in writing | 5. Not explicitly stated |

**Figure 2-4:** Example energy mechanism rating question with numbered rating scale.

**Table 2-2:** Example body design ideas rated using the questions discussed above. Ratings of 1 or 2 were rated as ‘agree’ whereas 3 or 4 were rated as ‘disagree’.
These ratings were then used to calculate the following fixation metric:

% Fixation: The number of similar features that appeared in the generated concept (rating of 1 or 2) is taken as a percentage out of the total number of features that design addressed to give a % fixation value, as seen in Table 2-2. Each participant’s % fixation is then taken as the average % fixation of the participant’s generated designs.

In order to examine the effects of the dissection activity on the amount of fixation present in the designs, an exposure metric was defined:

% Parts Exposure: The number of parts each participant dissected out of the total number of parts in the original design within each category. Table 2-3 shows the computation of % parts exposure for each category for participant 45.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td># of parts dissected</td>
<td>1</td>
<td>1</td>
<td>5</td>
<td>3</td>
</tr>
<tr>
<td>% parts exposure</td>
<td>14.2%</td>
<td>16.7%</td>
<td>71.4%</td>
<td>60%</td>
</tr>
</tbody>
</table>

2.3.4 Statistical analysis

Our first hypothesis was that personality traits affect the involvement in the dissection activity. In order to investigate this relationship, multivariate regression analyses were performed with the dependent variables being the % parts exposure for the four separate categories, and the independent variables being each individual personality trait. For the purposes of this analysis, the % exposure and % fixation variables were considered for each category of the toothbrush. There were 40 participants who generated ideas for each category, bringing the total sample size
for the analysis to 160. In order to address the problem of multiple comparisons and maintain a family-wise error rate, a correction of \( \frac{\alpha}{n} \) was applied to the significance level, where \( \alpha = 0.05 \), and \( n \) is the number of hypotheses in the multivariate regression (\( n=4 \)) \[52\]. This correction ensures that the significance level for the whole family of tests is, at most, \( \alpha \). Therefore, the significance level for each of the individual multivariate tests was 0.01.

In order to address our second hypothesis, stating that exposure to the dissection activity and personality traits affect design fixation, we ran a multiple regression analysis with the dependent variable being % fixation and the independent variables being the % parts exposure for the 4 separate categories, and the 5 personality traits. In addition, in order to investigate the difference between dissection of the Oral-B Advance Power 400 toothbrush and the Oral-B Cross Action Power toothbrush, an independent t-test was performed to compare % fixation for these two products. SPSS v 20.0 was used to perform all of the statistical tests. The level of significance was 0.05.

2.4 Results

The purpose in this paper was to investigate the interactions between exposure to a product dissection activity, individual personality traits, and design fixation, and to examine the impact of the product used for dissection on design fixation. Therefore, these interactions were analyzed in 3 phases. The first phase was to explore the interaction between personality traits and exposure to the dissection activity. The second phase explored the combined effect of personality traits and exposure to the dissection activity on the resulting design fixation. Finally, a third analysis was performed in order to understand how the product chosen for dissection effects design fixation.

2.4.1 The Relationship between Personality and Exposure to Dissection

To examine the relationship between personality traits and the exposure to the dissection activity, multivariate regression analyses were performed using the 4 categories of % parts exposure as the dependent variables, and each individual personality trait as the independent
variable. The personality trait distribution of the participants can be seen in Figure 2-5. A corrected significance level of 0.01 was used in order to maintain a familywise error rate.

![Figure 2-5. Personality trait distribution of the participants](image)

The results revealed significant relationships between the personality traits and the % parts exposure, see Table 2-4. The results indicate the personality traits were significantly related to the exposure to the dissection activity. In particular, the extraversion and conscientiousness personality traits were highly correlated to the energy mechanism and power generation % parts exposure categories, and to the body design, energy mechanism, and power generation % parts exposure categories respectively. Similar effects were found for all toothbrush dissection categories. This suggests that personality traits play a significant role in determining each individual’s exposure to dissection of various types of products in a group setting. It also shows that the different levels of complexity of the dissection categories affect team member involvement. Therefore, these two related variables should be explored for their combined effect on design fixation.
Table 2-4. Summary of the multivariate regression analysis. The bolded results indicate significant findings.

<table>
<thead>
<tr>
<th></th>
<th>Brush Head</th>
<th>Body Design</th>
<th>Energy Mechanism</th>
<th>Power Generation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Extraversion</td>
<td>R²</td>
<td>0.36</td>
<td>0.36</td>
<td>0.80</td>
</tr>
<tr>
<td></td>
<td>F(4,136)</td>
<td>1.36</td>
<td>1.33</td>
<td>9.51</td>
</tr>
<tr>
<td></td>
<td>p-value</td>
<td>&lt; 0.10</td>
<td>&lt; 0.29</td>
<td>&lt; 0.002</td>
</tr>
<tr>
<td>Coefficients, B</td>
<td>0.001</td>
<td>0.001</td>
<td>0.002</td>
<td>0.002</td>
</tr>
<tr>
<td>Agreeableness</td>
<td>R²</td>
<td>0.36</td>
<td>0.27</td>
<td>0.26</td>
</tr>
<tr>
<td></td>
<td>F(4,136)</td>
<td>1.64</td>
<td>1.05</td>
<td>1.01</td>
</tr>
<tr>
<td></td>
<td>p-value</td>
<td>&lt; 0.02</td>
<td>&lt; 0.41</td>
<td>&lt; 0.47</td>
</tr>
<tr>
<td>Coefficients, B</td>
<td>0.001</td>
<td>0.000</td>
<td>0.000</td>
<td>0.002</td>
</tr>
<tr>
<td>Conscientiousness</td>
<td>R²</td>
<td>0.29</td>
<td>0.88</td>
<td>0.98</td>
</tr>
<tr>
<td></td>
<td>F(4,136)</td>
<td>1.13</td>
<td>20.06</td>
<td>98.98</td>
</tr>
<tr>
<td></td>
<td>p-value</td>
<td>&lt; 0.297</td>
<td>&lt; 0.001</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Coefficients, B</td>
<td>0.002</td>
<td>0.000</td>
<td>0.001</td>
<td>0.002</td>
</tr>
<tr>
<td>Neuroticism</td>
<td>R²</td>
<td>0.43</td>
<td>0.22</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>F(4,136)</td>
<td>2.06</td>
<td>0.77</td>
<td>3.18</td>
</tr>
<tr>
<td></td>
<td>p-value</td>
<td>&lt; 0.001</td>
<td>&lt; 0.833</td>
<td>&lt; 0.001</td>
</tr>
<tr>
<td>Coefficients, B</td>
<td>-0.001</td>
<td>-0.001</td>
<td>-0.001</td>
<td>-0.001</td>
</tr>
<tr>
<td>Openness</td>
<td>R²</td>
<td>0.23</td>
<td>0.42</td>
<td>0.34</td>
</tr>
<tr>
<td></td>
<td>F(4,136)</td>
<td>0.98</td>
<td>2.34</td>
<td>1.71</td>
</tr>
<tr>
<td></td>
<td>p-value</td>
<td>&lt; 0.516</td>
<td>&lt; 0.001</td>
<td>&lt; 0.016</td>
</tr>
<tr>
<td>Coefficients, B</td>
<td>0.000</td>
<td>0.000</td>
<td>-0.001</td>
<td>0.000</td>
</tr>
</tbody>
</table>

2.4.2 The Effect of Personality and Exposure to Dissection on Fixation

The previous section revealed a relationship between exposure to the dissection activity and personality attributes. Further tests were required to investigate whether exposure to the dissection activity and individual personality traits affected design fixation. The regression results revealed that there was a significant relationship between % fixation and % parts exposure coefficient for the body design category (b = -0.358, p < 0.02), as seen in Table 2-5. The analysis for the other three categories (brush head, energy mechanism, and power generation) and personality traits indicated no significant relationships with % fixation. These results suggest that the more an individual participates in the dissection activity for the body design category, the less fixated they appear to be in their generated designs.
Table 2-5. Summary of the multiple regression analysis with coefficients and significance values. The bolded result indicates a significant finding.

<table>
<thead>
<tr>
<th>Model</th>
<th>Coefficients, B</th>
<th>Sig.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant</td>
<td>0.461</td>
<td>0.06</td>
</tr>
<tr>
<td>% parts exposure (brush head)</td>
<td>0.089</td>
<td>0.89</td>
</tr>
<tr>
<td>% parts exposure (body design)</td>
<td>-0.358</td>
<td>0.02</td>
</tr>
<tr>
<td>% parts exposure (energy mechanism)</td>
<td>0.025</td>
<td>0.44</td>
</tr>
<tr>
<td>% parts exposure (power generation)</td>
<td>0.017</td>
<td>0.50</td>
</tr>
</tbody>
</table>

2.4.3 The Impact of Dissecting Different Products on Fixation

In order to investigate if the product being dissected influences the fixation effects found, an independent t-test was performed to compare the % fixation of the two toothbrushes dissected. The results revealed a significant relationship between type of toothbrush and % fixation (F=0.76, p< 0.01). Therefore, profile plots were used to explore this relationship in more detail, see Figure 2-6. These results indicate that participants that dissected the Oral-B Advance Power 400 toothbrush generated designs that were slightly more fixated (M=0.48, SD=0.16) than those that dissected the Oral-B Cross Action Power toothbrush (M=0.39, SD=0.19).

![Figure 2-6. Means of % fixation vs. toothbrush type.](image)
2.5 Discussion

The purpose in this study was to explore the link between product dissection, personality traits, and design fixation in engineering design education. It was hypothesized that the fixation experienced by engineering students could potentially be mitigated through product dissection activities since this activity has been shown to increase creativity and design exploration in engineering design [7]. However, product dissection activities have not been explored for its effect on design fixation. Additionally, because product dissection is often performed in a team environment, individual factors such as personality traits may influence each team member’s involvement in the dissection activity, ultimately affecting the potential positive effects of this activity on design fixation. Therefore, the current study was conducted to understand how individual personality traits and exposure to a dissection activity affect design fixation.

The results from the study indicate that personality traits are related to the amount of exposure to a dissection activity in an engineering classroom. In particular, participants that scored high on the extraversion, conscientiousness, agreeableness, and openness personality traits and low on the neuroticism personality trait were found to participate more in the dissection activity. However, not all toothbrush categories had significant relationships with all personality traits, indicating a complex and multi-faceted effect of personality traits on the amount of involvement in a product dissection activity. In other words, individuals may be involved at varying levels in product dissection based on both personality traits and type of part being dissected. This result points toward the fact that individuals, if left to self-select their involvement in dissection activities, will not participate equally in a team setting. Thus, it may be necessary to conduct more structured dissection activities that ensure equal involvement by all individuals to reap the positive effects of this activity in engineering education. For example, having each student perform the dissection, or having each student fill out a bill of materials could contribute to a more equally distributed work load in an educational setting. However, the fact that significant results were found between all personality traits and the overall involvement in product dissection suggests that personality can indeed be more generally linked to involvement in team-based product dissection. For example, prior research that found that extraverted individuals contributed more to successful team performance [42] agrees with the finding that extraverted individuals participated more in complex dissection categories (energy
mechanism and power generation). Similarly, individuals that scored high on conscientiousness and low and neuroticism tended to be more involved in 3 out of 4 dissection categories, as predicted by prior research [41, 43]. However, the results not only linked these personality attributes to exposure to the dissection activity, but also explored the potential role of personality traits on the amount of fixation experienced by designers.

The results also revealed that fixation effects were significantly related to the participant’s involvement in the dissection activity for the brush head category of both toothbrushes, indicating that the dissection activity could be used to mitigate design fixation in different products. It was also revealed that participants that dissected the Oral-B Advance Power 400 toothbrush were significantly more fixated in their generated designs than those that dissected the Oral-B Cross Action Power toothbrush. This result indicates that the example presented prior to product dissection and thus, idea generation, plays an important role in the amount of fixation apparent in the generated designs, agreeing with prior studies [4].

Engineering educators should consider the products chosen for dissection carefully, as the type of product being dissected can impact fixation effects. One possible reason for the difference in fixation between the two toothbrushes could be that one model of electric toothbrush could have appeared more familiar to the participants than the other. For example, the Oral-B Advance Power 400 toothbrush only utilizes one rotating brush head, as is the standard in the electric toothbrush market. On the other hand, the Oral-B Cross Action Power toothbrush utilizes 2 toothbrush heads, neither of which are rotating, but are in fact pulsating and moving linearly. Therefore, participants that were exposed to the more typical design of electric toothbrush could have been more fixated on the example than those that were exposed to a more distantly related example, as was suggested by Tseng et al. [13] Other extraneous factors such as the ‘gender’ of a consumer product could also impact an individual’s perception of the product [53], potentially affecting the relationship between the type of product chosen for dissection and the resulting design novelty.

Additionally, the results showed that the more an individual participates in the dissection activity for the body design category, the less fixated they appeared to be in their generated designs. This finding agrees with prior research that has suggested that fixation is more likely to affect the design process if the design problem is more familiar to the designer [4]. For example, given that participants likely interact with toothbrush handles and other various kinds of handles
regularly, it is not surprising that exposure to this category of dissection played a role on fixation effects. In addition, it was observed that participants generated fewer ideas on average for the body design category than any other category, suggesting less variety in the generated designs of those not exposed to the dissection of this category. Furthermore, the complexity of problems can also impact the role of fixation in the overall design process. For instance, the energy mechanism category is considered to be the most complex of all 4 categories for first-year engineering design students due to the fact that it involves domains of knowledge not covered within a first year engineering curriculum. On the other hand, the body design category is considered to be the least complex because it involves concepts that are likely familiar to first year engineering students (grip, comfort, etc). However, the fact that the body design category was a substantial part of the dissected toothbrush (see Table 2-1) indicates that fixation effects can be affected by exposure to a dissection activity.

In sum, the results reveal that certain personality traits affect involvement in specific categories of product dissection, and exposure to product dissection of familiar parts impact design fixation effects. They also highlight the positive effects of individual involvement in product dissection activities on design fixation in a classroom setting. This is an important finding because reduced fixation can expose students to a wider variety of design solutions [4] and encourage learning. From this study, the complex nature of individual difference and personality traits is recognized as both a challenge, and something to leverage in engineering education research. For example, while significant relationships were found between exposure to the dissection activity and personality traits, and between exposure to the dissection activity and design fixation, no significant results were found for the direct relationship between fixation and personality traits. These results suggest that personality traits may, in fact, not have a direct relationship with design fixation, but may be a mediating variable in this interaction. In fact, prior research has shown that personality traits are related to creative achievement [45-48], and therefore, may interact with design fixation through other indirect avenues. Furthermore, the existing literature lacks results that link personality traits to creative achievement in engineering domains. Therefore, these results illustrate the complex interaction between individual factors and other design related parameters as well as relates personality traits to engineering-specific creativity metrics. The fact that no significant results were found for the direct relationship
between design fixation and personality traits suggests the possibility that existing approaches of examining personality-related creativity in engineering design settings may not be sufficient.

While this study successfully linked personality traits, product dissection, and design fixation, it is still exploratory in nature and differs from an experimental design where all factors can be controlled. In the current study, participants self-selected dissection categories to focus on and were allowed to freely interact within their teams, simulating the beneficial team environment that is often associated with product dissection [21]. While this allowed for a more realistic context for studying design fixation, this study does not explore the implications of product dissection on design fixation in more controlled environment. Future studies should address this research gap by exploring the impact of product dissection on design fixation in a more experimental setting, where confounding variables (e.g., gender, semester standing, self-selection) can be removed.

This study also adds to the existing literature on the utility of product dissection in engineering education [7, 16, 20-25, 54, 55] by establishing a relationship between product dissection and design fixation. Specifically, structured team-based product dissection activities where each student is given the opportunity to dissect parts of various complexities will help reduce fixation effects in the engineering classroom and thus, expose students to varied solutions. Future studies should examine the exact effect of participating in the dissection activity compared to not participating in the dissection activity at all. This would help understand the extent to which fixating effects are reduced by dissection activities and thus, help in determining methods that reduce fixation in the engineering classroom.

2.6 Conclusion

Overall, the results of this study show that design fixation effects are indeed related to the exposure to a dissection activity and individual personality traits of designers. This has important implications for engineering design research because it builds on our understanding of cognitive processes as it applies to idea generation and thus, the overall design process.

The results of this study have important implications for engineering education. The results agree with prior studies that illustrate the benefits of product dissection in engineering education [7, 16, 20-25, 54, 55] and also show that design fixation can be mitigated by
incorporating product dissection activities into the engineering curriculum. The fact that product dissection is immensely physical in nature [20] only adds to the positive influence it can have in increasing learning and retention in engineering education [55]. Given that familiarity with a concept can be increased through product dissection [54], it is recommended that students be encouraged to engage in the dissection of more complex aspects of the product to both reduce fixation in that domain, and to gain valuable understanding of the concept. From this study, it can be seen that each of the personality traits affect an individual’s involvement in the specific product dissection categories differently. Therefore, a more structured dissection activity may ensure more equal involvement among the team, and encourage the exploration of more complicated parts. Additionally, ensuring a more balanced involvement in the dissection activity can help maximize the performance of the team [35, 36] and reduce fixation effects. With more exposure to novel concepts and engineering solutions, students’ learning in the engineering classroom can be enhanced, and more creative approaches to engineering design can be fostered.

Future studies should explore the relationship between idea generation techniques of both the form and function of a product on design fixation. The use of a control group in future studies would also allow for an exploration of the exact impact of participating in a dissection activity on design fixation. Additionally, the complexity of each category being explored in the dissection activity should be examined for its effect on the design fixation apparent in the idea generation process. The effects of different personality traits on different idea generation techniques should also be examined for their impact on design fixation in order to provide a deeper understanding of how design activities impact design fixation.
2.7 References

[37] Costa, P., and McCrea, R., 1992, Revised NEO Personality Inventory (NEO PI-R) and NEO Five-Factor Inventory (NEO-FFI), Psychological Assessment Resources, Odessa, FL.


Chapter 3

The Impact of Team-Based Dissection Activities on Design Novelty

Christine Toh, Dr. Scarlett Miller, and Dr. Gül Okudan Kremer

Although design novelty is a critical area of research in engineering design, related research has focused on understanding and developing formal idea generation methods instead of focusing on the impact of current design practices. This is problematic because formal techniques are often not adopted in industry due to the burdensome steps often included in these methods, which limit the practicality and adoption of these methods. This study seeks to understand the impact of product dissection, a design method widely utilized in academia and industry, on design novelty in order to produce recommendations for the use or alterations of this method for supporting novelty in design. To investigate the impact of dissection, a study was conducted with 76 engineering students who completed a team-based dissection of an electric toothbrush and then individually generated ideas. The relationships between involvement in the dissection activity, the product dissected, the novelty and quantity of the ideas developed were investigated. The results reveal that team-members who were more involved in the dissection activity generated concepts that were more novel than those who did not. In addition, the type of the dissected product also had an influence on design novelty. Finally, a positive correlation between the number of ideas generated and the novelty of the design concepts was identified. The results from this study are used to provide recommendations for leveraging product dissection for enhancing novelty in engineering design education and practice.
3.1 Introduction

Researchers have long sought to identify and understand methods and mechanisms that support the generation of novel concepts in engineering design because novelty is considered the foundation of innovative work [1]. Novelty is often used as a metric for measuring idea creativity in conjunction with the quality, quantity, and variety metrics [1]. Design novelty refers to “how unusual or unexpected an idea is compared to other ideas” ([1], pg. 117). Thus, novel ideas expand the design space and help loosen the tight grip on the design goal that engineers often have. Novelty also offers opportunities to find better designs that do not yet exist [1], ultimately leading to better design outcomes [2]. As engineers, developing novel solutions is a vital step in moving the field forward and generating useful solutions for society. Therefore, understanding methods and tools that increase novelty in the design process is of fundamental importance.

Most research on improving novelty in engineering design has focused on understanding and creating formal idea generation techniques such as Brainstorming [3], C-Sketch [4], and TRIZ [5] as opposed to studying the impact of naturally occurring design practices. This is problematic because these formalized methods often require additional information to be provided at the start of the idea generation activity [6, 7], or they require the implementation of specific techniques during ideation [4, 5]. These factors significantly reduce the practicality and implementation of these methods in the broader-spectrum of design. In fact, many designers opt not to use formal ideation methods because the burdensome steps involved in these methods often bring about “doubt, ambiguity, and a lack of perseverance that can lead people to abandon the creative process ([8], p. 366).” Therefore, design research that focuses on studying isolated, formal techniques often do not bridge the gap between design practice and research [9]. For this reason, it is essential that we study methods currently utilized in engineering practice and understand the impact on design novelty.

Researchers have started to explore the implications of currently practiced design techniques, and have found that methods such as physical prototyping encourage designers to reuse less features from example concepts [10]. However, these studies focus on the effects of building and interacting with prototypes, rather than interacting with commercially-available products. This is important to study because designers are often exposed to existing products in the early stages of design in an effort to gain knowledge and insights into the solution space. One
such activity that involves examining and taking apart existing products is product dissection; it has not been studied extensively for its impact on design novelty, however.

Therefore, this study seeks to understand the impact of product dissection, a method commonly utilized in academia and industry [11] on engineering design novelty. This is important because the recommendations that are developed by understanding product dissection are more likely to be adopted by design practitioners and engineering educators since it is a method that is commonly used and taught. We also seek to understand the impact of the product selected for dissection and the number of ideas generated on design novelty. This is a vital area to investigate because it provides the engineering community with an understanding on how product dissection influences design novelty, allowing us to develop recommendations for how these practices should be altered or used to encourage or yield creative artifacts.

3.2 Background & Previous Work

The research hypotheses proposed in this paper are motivated by prior work on design novelty, the development of techniques that aim to improve design novelty, and research on the implementation of product dissection in academia and industry. These areas of research are explored in detail in the following sections.

3.2.1 Design Novelty

Researchers across many fields have emphasized the importance of studying novelty in idea generation because novelty is considered critical to gaining insights into the creative process [12]. In addition, understanding how novelty can be increased can positively impact productivity and innovation in various contexts. In particular, researchers in the field of psychology, education, advertising and engineering have all sought to understand the impact of activities and stimuli on creative reasoning.

Psychologists were the first to try and understand factors that influence novel thinking. Researchers in this field have primarily sought to characterize the novel thinking process [13] and understand the factors that affect the generation of novel ideas, such as personality traits [14], problem framing [15], creativity training [3, 16], and team participation [17]. Psychologists
have also studied the impact of presented stimuli on novelty and found that novel stimuli can lead to high-level or global thinking [18]. Building on the psychological research on design novelty, researchers in education have also studied novelty focusing primarily on creativity in problem-solving, and emphasizing the importance of originality and novelty in increasing learning in the science [19], mathematics [20], and entrepreneurship domains [21]. In contrast, work in the field of advertising has been focused on studying and identifying the creative aspects of advertisements. Importantly, research in this area often defines creative outcomes as both divergent and novel [22]. Hence, it can be seen that the notion of novelty, originality, or the ‘newness’ of an idea is an essential focus of many fields, in part because it helps enhance the performance of individuals in various contexts, and because it gives us insights into the creative process.

Early research in product design explored creativity in the design process and characterized novelty as one of the indicators of creativity in design [23]. In particular, researchers consider novelty to “take the form of something completely new, or it may be a combination of existing ideas or products” (p. 27) [24]. Some researchers consider the novelty of a generated concept to be indicative of the concept’s quality [25]. Thus, work done by Shah et al. [1] explored the notion of novelty as a measure of the effectiveness of idea generation techniques in engineering design. This work characterized an idea as novel if it addresses a function that is not addressed by others within a given sample. In other words, the novelty metric is “essentially a measure of whether the exploration occurred in areas of the design space that are well-travelled or little-travelled” (p. 742) [26]. In addition to the novelty metric, other metrics such as variety, quantity, and quality are used to characterize creativity in design and to evaluate the performance of an ideation process [1]. While these metrics were developed to assess the effectiveness of idea generation techniques, the novelty metric is by far the most relevant to the study of creativity in an engineering context. This is not only because novelty is often used synonymously with creativity [27, 28] but also because novelty captures the fundamental spirit of engineering- to create something new. Indeed, researchers have long acknowledged the importance of novelty in engineering design, emphasizing the generation of ideas that are new, unexpected [29], and valuable [30].

While studies have been conducted that support the importance of novelty in engineering design, its relation to product dissection has not been studied. In addition, only few studies have
explored the impact of commonly occurring design practices on engineering design novelty. This study seeks to fill these research gaps.

### 3.2.2 Methods and Techniques for Supporting Design Novelty

Since novelty is a central component of engineering design, researchers have focused on developing methods that increase design novelty. In fact, over 172 idea generation techniques have been identified in the literature as means to stimulate creative thought, generate more ideas, and expand on the solution space [31]. These methods consist of both artificial and formal techniques and the classifications of naturally occurring design practices [32]. However, the main thrust of this research thread focuses on developing and understanding the formalized ideation methods.

Formal idea generation techniques can range from highly structured to highly unstructured and can have a wide degree of impact on design novelty. For instance, TRIZ, or the Theory of Inventive Problem Solving, is a highly structured ideation method that involves utilizing specific algorithms built from principles of innovative technology [5]. A recent study found that this method encourages the generation of more novel ideas compared to other less structured methods [33]. On the other hand, SCAMPER [34], a less structured method which involves applying heuristics such as substitute, combine, adapt, and modify to the design problem has been found to increase the diversity and novelty of ideas during the design process [35]. Similarly, C-Sketch [4], a semi-structured method that involves designers collaboratively generating ideas through sketches, has been found to positively impact design novelty [36]. Finally, the brainstorming technique [37] has been shown to elicit the most novel design ideas compared to the TRIZ and SCAMPER methods [33], especially when combined with goal-specific instructions [38] or analogical operators [39, 40].

Although these findings highlight the possibility of increasing design novelty through formalized ideation techniques, they require additional information to be provided at the start of the idea generation activity, or the implementation of specific techniques during ideation. These factors reduce the practicality of these methods in design practice. Indeed, researchers have noted the specificity of certain formal ideation techniques (such as TRIZ), making it challenging to learn and apply these techniques in industry [41]. Others have concluded that design research
is focused on studying isolated, formal techniques that does not bridge the gap between design practice and research [9].

In addition to understanding the impact of currently utilized design practices on design novelty it is also important to study the relationship between the number of ideas generated and the novelty of the resulting concepts. Researchers in other domains have indeed identified a relationship between the number of ideas developed and the novelty of the generated concepts [42], but this effect has not been studied in detail in engineering design. For example, Linsey et al. [43] reported a relationship between the number of ideas generated in a team setting and design quality, but did not examine the role that design quantity may have on novelty. This is important because psychologists have regarded one’s fluency in generating ideas as an indicator of creativity [42], suggesting a relationship between the number of ideas one generates and design novelty. Therefore, studies are needed to explore the relationship between design quantity and novelty, and the impact of existing design practices on design novelty.

This study was developed to respond to these research gaps by understanding the relationship between the number of ideas generated and design novelty. In addition, the study sought to understand the impact of a commonly practiced design technique, product dissection, on design novelty that is discussed in the following section.

### 3.2.3 Product Dissection in Engineering Design

Product dissection is a design method commonly used in industry and academia as a means to systematically uncover opportunities for redesign [7]. During dissection, designers take apart and analyze all components and subcomponents of a system in order to study, capture and modify the existing components. Companies perform product dissection to provide competitive benchmarks and gain knowledge and insight of a particular product. In educational settings, product dissection provides students insight into industry practice [11] and ‘hands-on’ experience [44] and has been shown to improve the functionality of the generated designs [45]. As such, product dissection is widely implemented in engineering classrooms in order to teach benchmarking, manufacturing principles, and team-work, and serve to enhance the learning process [46]. In particular, product dissection of mechanical products is widely adopted in engineering education as a means of encouraging student involvement in learning [47].
Additionally, since product dissection occurs in the early phases of design [48], it has the potential to greatly influence the subsequent stages of the design process.

Engineering researchers have started to uncover the relationship between product dissection and idea generation. For instance, a recent study showed that students that performed dissection in a team environment generated more ideas, and explored both the form and function of a design compared to those that simply interacted with the product [49]. This suggests that product dissection encourages a deeper understanding of the product and larger exploration of the design space. Product dissection also combines the benefits of hands-on activities [48] with a greater ability to apply knowledge to the existing problem [50]. This is contrary to work on design fixation that argues that exposure to existing products, or examples, limits the originality of the generated ideas [51]. However, recent studies have found that interacting with 3-dimensional examples actually encouraged the generation of more ideas compared to picture-based examples [52]. In addition, research suggests that product dissection may have a constructive effect on design novelty because it provides a deeper understanding of the product and encourages designers to consider previously-ignored aspects of the product – a major goal of other ideation techniques that seek to increase design novelty [6, 7].

One aspect that may influence the effectiveness of product dissection on encouraging design novelty is the chosen product for dissection. Design fixation is an area of research that often parallels work on design novelty. Research in this area examines the impact of examples on design artifacts or, said another way, how often items from an example appear in designer generated concepts. Research has suggested that the complexity and originality of the design example utilized during a design task can impose attention constraints on the individual causing the designer to rely more on the elements in the example to provide a solution [53]. In addition, research has shown that designers who are exposed to examples that are common to the field or on the market often are more fixated than those exposed to novel examples [54]. This has been observed by researchers in product dissection who have shown that participants who dissect innovative products were less fixated than those that dissected products that were more common in the design domain [55]. Although these findings suggest that the types of product utilized for dissection can have a significant impact on the level of fixation encountered, no study to date has explored the impact of the type of product dissected on design novelty. This study was developed
to examine this relationship in order to provide recommendations on the use of the method in industry and academia.

### 3.2.4 Research Questions

The goal in this research is to examine the effect of a commonly practiced design method, namely, product dissection, on design novelty, and to develop practical recommendations for the use and modification of this method for influencing design novelty. We seek to answer three fundamental research questions:

**Question 1:** Does the type of product used for dissection affect the novelty and quantity of generated ideas? Our hypothesis is that the type of product dissected affects the novelty of the generated concepts, since different products provide different points of reference during the design process [56]. Additionally, the number of ideas generated is anticipated to be affected by the type of product dissected since psychologists and engineering designers consider fluency to be closely tied to novel idea generation [27, 57].

**Question 2:** Is there a relationship between the number of ideas generated and the novelty of the generated concepts? Our hypothesis is that generating more ideas increases design novelty since prior research has shown that generating more ideas increases the likelihood of developing better quality concepts [3]. However, the literature on the relationship between these two metrics in engineering design is inconclusive and few have explored the impact of the number of ideas generated on the resulting design novelty.

**Question 3:** Does involvement in product dissection impact design novelty? Our hypothesis is that individuals that participate in the dissection activity to a higher degree will develop more novel ideas as a result of better understanding of the product and a deeper exploration of the design space [48].
To address these research questions, an exploratory study was conducted with first-year engineering design students. The methods and results of this experiment are presented, and their implications for future research and the engineering design community are discussed in the following sections.

3.3 Methodology

3.3.1 Participants

Seventy-six (61 male, 15 female) students recruited from three-sections of a first-year engineering design course participated in this study. Each section consisted of 3 and 4-member design teams (20 teams in total, with 4 teams consisting of 3 members) that were assigned by the instructor based on prior expertise and knowledge of engineering design to balance the a priori advantage of the teams. This was accomplished through questionnaires given at the start of the semester that asked about student proficiencies in the following areas: 2D and 3D modeling, sketching and engineering design experience. The results of the questionnaire were used to randomly form teams of balanced design experience by the course instructor of each section.

3.3.2 Procedure

The design teams were tasked with redesigning an electric toothbrush for increased portability. Two of the three class sections (44 students) re-designed the Oral-B Advance Power 400 electric toothbrush while the other section (32 students) redesigned the Oral-B Cross Action Power electric toothbrush, both seen in Figure 3-1. Teams were balanced in terms of the team-members’ prior experience in design.
Each team was given 90 minutes to perform a product dissection of the electric toothbrush they were assigned to redesign. During this activity, participants were asked to complete a bill of materials (BOM) for each subcomponent and identify the team member that led each individual part dissection. For this study, the toothbrush was categorized into four general categories: brush head, body design, energy mechanism, and power supply/accessories. This distinction of product categories was made because of significant differences in the form vs. function aspects of the design that have been shown to play a role in the perceived quality of the final design [49]. Examples of the partially dissected toothbrushes are shown in Table 3-1.

Table 3-1. Partially dissected toothbrushes.
A week later, the participants attended a brainstorming session where each team member was given 30 minutes to generate as many ideas as possible for a novel electric toothbrush without consulting other participants. The participants were not informed of the brainstorming session prior to attending class. During the brainstorming session, participants were asked to sketch as many concepts as possible, writing notes on each sketch such that an outsider would be able to understand the concepts upon isolated inspection, see Figure 3-2. Each participant was provided with sheets of paper that had numbered boxes on it to clearly distinguish each idea. Each team was instructed to select two team members to develop ideas in each of the four categories. For example, team member 1 may have developed ideas for the brush head and power supply; team member 2, the brush head and energy mechanism; team member 3, the energy mechanism and body design; and team member 4, the body design and power supply. On average, participants generated 4.5 ideas for the toothbrush head, 3 ideas for the toothbrush body, 3.9 ideas for the energy mechanism, and 4.4 ideas for the power generation category.

![Figure 3-2. Sequential concepts generated for the body design by participant 45](image)

### 3.3.3 Metrics

A total of 678 concepts were developed by participants during the study. In order to quantify the degree of design novelty for the ideas developed, the metrics developed by Shah et al. [1] were utilized. While Shah et al.’s work on the novelty metric provides a method of studying creativity, researchers such as Nelson et al. [26] and Srivathsavai et al. [58] have discussed the original metric’s limitations, such as inaccurate representations and poor inter-rater reliability. Therefore, the novelty metric was considered in various ways (feature novelty, design novelty,
and participant novelty), and the raters (2) were trained prior to the rating to increase the inter-rater reliability.

Fifty-two questions were developed to assess the similarities of each design to the example toothbrush provided. Each question was categorized into one of four subcategories for analysis including: brush head, body, energy mechanism and power generation design, see Appendix 1. These questions were derived from features of the original design, as well as the solution space explored by all participants in their designs, as was done in previous studies [59, 60].

The two raters were asked to evaluate each design concept by completing the 52-question survey in order to identify the features that the idea focused on. Since participants often created simple drawings and described additional features in the written design description for complex ideas, see Figure 3-3, a 5-point rating system was developed through discussions and training sessions with the raters to aid in the evaluation of each concept. Since this study did not focus on how the participants presented their ideas (pictorial or written), ratings of 1 and 2 were grouped for analysis as the solution having a similar feature to the original design (not novel) and ratings of 3 and 4 were grouped and used to represent ideas that were not similar to the original design (novel). A rating of 5 was used when the participant did not address the feature in their design. Examples of concepts that were rated according to this scale are shown in Table 3-2. A
A design-benchmarking handbook was developed to assist the raters and provide a reference during the rating process. The inter-rater reliability was 85.2%, and a Cohen’s Kappa of 0.759 was achieved for the rating method. Disputes were settled in conference between the raters as was done previously by Chrysikou et al. [6].

Table 3-2. Example body design ideas rated using the questions discussed above. Assessments of 1 or 2 were rated as ‘agree’ whereas 3 or 4 were rated as ‘disagree’.

<table>
<thead>
<tr>
<th>Rating Questions</th>
<th>Feature Novelty, $f_i$</th>
<th>Similar/ Different from original design</th>
</tr>
</thead>
<tbody>
<tr>
<td>The idea has the same shape</td>
<td>0.94</td>
<td>Similar</td>
</tr>
<tr>
<td>The idea has the same method of providing grip</td>
<td>1.00</td>
<td>Different</td>
</tr>
<tr>
<td>The idea uses the same materials</td>
<td>0.97</td>
<td>Different</td>
</tr>
<tr>
<td>The idea has the same number of components</td>
<td>0.9</td>
<td>Similar</td>
</tr>
<tr>
<td>The idea has the same level of portability</td>
<td>0.86</td>
<td>Similar</td>
</tr>
<tr>
<td>The idea has the same power button location</td>
<td>0.58</td>
<td>Not Explicitly Stated</td>
</tr>
<tr>
<td>The idea has the same battery access location</td>
<td>0.48</td>
<td>Not Explicitly Stated</td>
</tr>
</tbody>
</table>

Novelty Calculation

- Sum of feature novelty for different features, $f_k$: $1.97$
- Total feature novelty of addressed features, $f_i$: $5.73$

Design Novelty

$$\frac{1.97}{5.73} = 0.34$$

$$\frac{3.38}{5.73} = 0.59$$
In order to quantify the amount of novelty in each generated design, several metrics based on the work by Shah et al. [1] were used:

**Feature Novelty, $f_i$:**

The novelty of each feature, $i$, as it compares to all other features addressed by the generated concepts for each category, adapted from Shah et al. [1]. Feature novelty, $f_i$, can then vary from 0 to 1, with 1 indicating that the feature is very novel compared to other features. The method of computing $f_i$ is shown in Eqn. 1, where $T$ is the total number of concepts generated for each category (brush head, body design), and $C$ is the total number of concepts that were rated 3 or 4 by the raters (different from original design) for each feature. An example calculation of feature novelty is shown in Table 3-3, where concepts 1 through 4 are example fictional concepts used to illustrate the calculation. The table indicates if the concept addressed a particular feature, and shows how the more addressed a feature is within the sample, the less novel it is considered.

$$f_i = \frac{T - C_i}{T}$$

(1)

**Table 3-3.** Example calculation of feature novelty for feature 1: number of brush heads, 2: brush head shape, and 3: bristle length, hardness, and/or direction. Feature 2 is the most novel.

<table>
<thead>
<tr>
<th>Concept #</th>
<th>Feature addressed?</th>
<th>Feature addressed?</th>
<th>Feature addressed?</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>2</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>3</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Instances of each feature</td>
<td>$C_1 = 3$</td>
<td>$C_2 = 1$</td>
<td>$C_3 = 2$</td>
</tr>
<tr>
<td>Feature Novelty</td>
<td>$f_1 = 0.25$</td>
<td>$f_2 = 0.75$</td>
<td>$f_3 = 0.5$</td>
</tr>
</tbody>
</table>
Design Novelty, $D_j$:

The novelty of each design, $j$, determined by the combined effect of the Feature Novelty, $f_i$, of all the features that the design addresses. Because $D$ is computed for all the features, the novelty per design is computed as a percentage out of the total possible design novelty, as seen in Eqn. 2. An example calculation of design novelty is shown in Table 3-2, and examples of concepts that scored high and low on novelty for each of the toothbrush categories are shown in Table 3-4.

$$D_j = \frac{\sum f_k}{\sum f_i} \tag{2}$$

Where $f_k$ is the feature novelty of a feature that was different from the original design (i.e., modified or changed in some manner). The sum of $f_i$ is the novelty of all the features that were addressed in the generated idea, identified as features not rated as ‘Not Explicitly Stated’ (i.e., the total possible novelty attainable by the design should all features differ from the original design). Therefore, design novelty is taken as a proportion of the total possible novelty that could be attained by the design, had all the features differed from the original design.
Table 3-4. Examples of highly novel concepts generated by participants for each of the 4 toothbrush categories.

<table>
<thead>
<tr>
<th>Category</th>
<th>Generated Concepts</th>
<th>Highly Novel</th>
<th>Not Novel</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brush Head</td>
<td><img src="image" alt="Sketch" /></td>
<td>$D_j = 0.68$</td>
<td>$D_j = 0.08$</td>
</tr>
<tr>
<td>Body Design</td>
<td><img src="image" alt="Sketch" /></td>
<td>$D_j = 0.85$</td>
<td>$D_j = 0.21$</td>
</tr>
<tr>
<td>Energy Mechanism</td>
<td><img src="image" alt="Sketch" /></td>
<td>$D_j = 0.72$</td>
<td>$D_j = 0.18$</td>
</tr>
<tr>
<td>Power Generation</td>
<td><img src="image" alt="Sketch" /></td>
<td>$D_j = 0.75$</td>
<td>$D_j = 0.02$</td>
</tr>
</tbody>
</table>

**Participant Novelty:**

The average design novelty, $D_j$, of all the concepts that each participant generated in each category. Average novelty has been used in prior research as a way to study design novelty [1, 61] because it captures how novel each participant was over all the concepts they generated.
Exposure Within Team

The rank of each team-member’s involvement (exposure) in the dissection activity for the four toothbrush categories. This metric was computed by comparing the number of parts each team-member dissected. Since each team had two members generate ideas for each category of the toothbrush, the team-member who participated the most in a specific dissection category received a rank of 1, and conversely, the team-member who participated the least received a rank of 0.

# Ideas:

The total number of ideas each participant generated for each individual toothbrush category (brush head, body design, energy mechanism, and power generation). As previously stated, participants were given idea generation sheets that had numbered boxes where they could sketch their concepts, and the number of ideas metric was computed by counting the number of concepts according to these numbered boxes.

3.4 Results

During this study, a total of 678 concepts were developed by participants. Table 3-5 identifies the mean and standard deviation for the number of ideas generated in each category.

Table 3-5. The means and standard deviations of the number of ideas generated for each toothbrush type and for all toothbrush types.

<table>
<thead>
<tr>
<th></th>
<th>Brush Head μ</th>
<th>Body Design μ</th>
<th>Energy Mech. μ</th>
<th>Power Gen. μ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Oral-B Advance Power 400</td>
<td>4.23 SD = 1.42</td>
<td>4.00 SD = 1.74</td>
<td>3.69 SD = 1.74</td>
<td>4.38 SD = 1.68</td>
</tr>
<tr>
<td>Oral-B Cross Action Power</td>
<td>4.71 SD = 1.27</td>
<td>4.21 SD = 1.67</td>
<td>4.79 SD = 1.42</td>
<td>4.43 SD = 1.45</td>
</tr>
<tr>
<td>Total</td>
<td>4.40 SD = 1.37</td>
<td>4.08 SD = 1.70</td>
<td>4.08 SD = 1.70</td>
<td>4.40 SD = 1.58</td>
</tr>
</tbody>
</table>
3.4.1 The Effect of Dissecting Different Products on Design Novelty and Quantity

In order to test our first hypothesis stating that the type of product dissected (2 different toothbrushes) affects design novelty and # of ideas (of each of the four toothbrush categories), two independent t-tests were performed. The first t-test that was performed with the dependent variable being average participant novelty, and the independent variable being the type of toothbrush revealed a significant difference in participant novelty between the brush head category (t(28) = -3.90, p < 0.00) and the body design category (t(38) = -3.26, p < 0.00) of the 2 toothbrush types. For both categories, individuals that dissected the Oral-B Cross Action Power toothbrush produced ideas that were more novel than those that dissected the Oral-B Advance Power 400 toothbrush (see Table 3-6). Although not significant, the same trend can be seen between the novelty of the energy and power generation categories. The second t-test conducted with the dependent variable being the # of ideas metric and the independent variable being the type of toothbrush revealed no significant differences in the # of ideas generated for all toothbrush categories (see Table 3-6). These results reveal that the type of product used in the dissection activity affects the amount of novelty in the generated concepts, but not the number of ideas generated. Based on these findings, the type of toothbrush dissected was included as a covariate in the remaining analyses.
Table 3-6. Summary of the independent t-tests between average novelty and # ideas of the two toothbrushes. Bolded cells indicate significant results.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Novelty</td>
<td>t (38)</td>
<td>-3.90</td>
<td>-3.26</td>
<td>-1.41</td>
</tr>
<tr>
<td>Significance</td>
<td>&lt; 0.00</td>
<td>&lt; 0.00</td>
<td>&gt; 0.17</td>
<td>&gt; 0.06</td>
</tr>
<tr>
<td># ideas</td>
<td>t (38)</td>
<td>-1.06</td>
<td>-0.38</td>
<td>-0.08</td>
</tr>
<tr>
<td>Significance</td>
<td>&gt; 0.29</td>
<td>&gt; 0.71</td>
<td>&gt; 0.93</td>
<td>&gt; 0.05</td>
</tr>
</tbody>
</table>

Oral-B Advance Power 400

<table>
<thead>
<tr>
<th></th>
<th>Average Novelty</th>
<th>Average # ideas</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μ =0.40 SD=0.19</td>
<td>μ = 4.23 SD=1.42</td>
<td>μ =0.31 SD=0.21</td>
<td>μ =0.42 SD=0.17</td>
</tr>
<tr>
<td>Oral-B Cross Action Power</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>Average Novelty</th>
<th>Average # ideas</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>μ =0.63 SD=0.16</td>
<td>μ = 4.71 SD=1.27</td>
<td>μ =0.52 SD=0.17</td>
<td>μ =0.55 SD=0.24</td>
</tr>
</tbody>
</table>

3.4.2 The Effect of Number of Ideas Generated on Novelty

Our next hypothesis was that the number of ideas generated would impact the novelty of the concepts generated after the dissection activity performed on the assigned toothbrush. In order to test this, a correlation test was conducted between the # of ideas and participant novelty, controlling for the type of toothbrush dissected since participants dissected two different toothbrushes. The results reveled a significant positive relationship for the body design (r = 0.38, p <0.02) and energy mechanism (r = 0.32, p <0.05) categories, see Table 3-7. These results suggest that producing more ideas can have a positive effect on the novelty of the design ideas created. Examples of highly novel ideas developed for the body design and energy mechanism category are shown in Figure 3-4. There were no significant findings for the brush head and power generation categories.
Table 3-7. Summary of the Pearson Correlation tests between participant novelty and # ideas. Bolded cells indicate significant results.

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Pearson coefficient</td>
<td>0.12</td>
<td><strong>0.38</strong></td>
<td><strong>0.32</strong></td>
<td>-0.093</td>
</tr>
<tr>
<td>Significance</td>
<td>0.46</td>
<td><strong>0.02</strong></td>
<td><strong>0.05</strong></td>
<td>0.57</td>
</tr>
</tbody>
</table>

Figure 3-4. Examples of highly novel ideas for the body design category generated by Participant 45 (left) and energy mechanism category generated by Participant 12 (right).

3.4.3 The Relationship between Exposure to Dissection and Design Novelty

Our final hypothesis was that exposure to the dissection activity would impact participant novelty. In order to evaluate this, ANCOVAs were conducted between participant novelty and the exposure within team metric for the four categories with the covariate of the type of toothbrush dissected. Bonferroni post-hoc tests were performed on significant effects.

The results revealed a significant effect for the body design (F (1,37)=13.94, p<0.00) and energy mechanism categories (F (1,37)=21.02, p<0.00). Post-hoc results indicate that participants that were more involved in the product dissection activity for the body design and energy mechanism categories produced ideas that were more novel than those that were less involved (see Figure 3-5). There were no significant effects for the brush head and power generation categories.
3.5 Discussion

This study sought to understand the impact of product dissection, a method commonly utilized in academia and industry, on engineering design novelty. We also sought to explore the relationship between design novelty, the product dissected and the number of ideas developed. The following discussion addresses each of the research hypotheses and provides further insights and implications of the results.

3.5.1 Hypothesis 1: The Type of Product Dissected Affects the Novelty of the Generated Concepts

Our first research question sought to understand the impact of the type of product dissected on design novelty since prior research has shown that the type of example presented to designers can impact ideation [54]. Our results revealed a significant difference in design novelty between participants that dissected different products. This indicates that the type of product dissected impacts the novelty of the generated concepts, supporting our hypothesis. This difference may be related to the participants’ familiarity with the underlying structures and

![Figure 3-5. The means and standard deviations of participant novelty for low and high levels of exposure within team for the body design and energy mechanism category.](image-url)
design of the toothbrushes used in this study. The Oral-B Advance Power toothbrush includes a single rotating/oscillating head that has been regarded by dentists for over a decade to be the most established and effective electric toothbrush head on the market [62]. As such, this type of brush head design is widely used in commercially available toothbrushes today. In contrast, the Oral-B Cross Action Power toothbrush is a relatively novel design that incorporates two brush heads, one rotating and the other oscillating, resulting in a design that is not as common in the market. Therefore participants that received the more innovative design (Cross Action Power) for product dissection produced concepts that were more novel than those that received the less innovative design (Advanced Power). These results support prior findings in the area of design fixation that reported that the originality of the examples used during the design process and the participants’ familiarity with the design impacted the amount of fixation encountered [54]. Our results also extend existing research on design novelty by studying the impact of physical interactions with products as opposed to studying the impact of 2D images.

Although there were significant findings for design novelty across the toothbrushes dissected, the results were only significant for the brush head and body design categories. This finding may be attributed to the participants’ lack of familiarity with the underlying principles of the energy mechanism and power generation categories. The participants in this study were recruited from a first-year engineering design course that had little or no exposure to alternative energy and mechanical designs. This is in contrast to the participants’ knowledge of the brush head and body design categories as most, if not all of the participants have used a toothbrush frequently prior to participation in the study. Thus, participants have been exposed to the form (brush head and body design) of toothbrushes on a regular basis, and are familiar with these aspects of the toothbrush’s design. This finding implies that there may be other factors that affect this relationship such as the designer’s familiarity with the domain in which they are designing or their level of expertise. As such, future studies are needed to explore the impact of dissection on design novelty with designers of various levels of expertise and with various design problems to further understand this relationship.
3.5.2 Hypothesis 2: The Number of Ideas Generated Affects the Novelty of the Generated Concepts

The second goal of this study was to understand the relationship between the number of ideas generated and the novelty of these ideas. Our results revealed a significant relationship between these areas for the body design and energy mechanism categories, partially supporting our hypothesis. The results from this study are significant because they imply that generating more ideas during the early phases of the design process is beneficial for encouraging novel thinking. However, we only found this significant effect for two of the four toothbrush categories tested and the Pearson correlation coefficients for these relationships were less than 0.40. Even though this relationship may not be very strong, it is still significant, and positive. As such, engineering educators and industrial leaders should encourage and support the production of a higher number of ideas in order to increase the likelihood of novel concept development. In addition, researchers should examine ways to increase idea production in education and industry through modifying existing practices rather than developing new, formalized methods in order to encourage widespread adoption. Our results add to the existing literature by providing insights into the relationship between idea production and novelty in engineering design.

3.5.3 Hypothesis 3: Exposure to the Dissection Activity Impacts Design Novelty

Our final hypothesis was that exposure to a product dissection activity would affect the amount of novelty of the generated concepts. Overall, our results support our hypothesis by revealing that participants who were more actively involved in the dissection activity produced concepts that were more novel than those that were less involved. This result supports prior research that shows that involvement in product dissection increases creativity [48-50]. However, this relationship was only significant for the body design and energy mechanism categories of the toothbrush. One possible rationale for this finding is that the body design and energy mechanism categories contain a large number of parts (Oral-B Advance Power 400: 33.3%, 25.9%; Oral-B Cross Action Power: 24.0%, 28.8%, respectively), and hence, had the most impact on the product dissection experience. In other words, this relationship may have only been significant for the body design and energy mechanism categories because there was a greater difference in exposure between actively and non-actively participating.
In short, the exposure to the dissection activity had, in general, a positive impact on the novelty of the generated concepts, supporting our hypothesis that product dissection can increase novelty in the idea generation process. However, the limitation of this result is recognized since dissection’s positive impact was only found for certain aspects of the idea generation activity. This result highlights the complexity of the relationship between currently practiced hands-on methods such as product dissection and design creativity in multi-faceted design tasks. Further research that explores the type of designer-product interaction and the focus on different aspects of the design can add to our understanding of how these interactions affect the design process. Nevertheless, this result indicates that an increased engagement in the dissection activity aids in generating more novel ideas, rather than simply participating in the activity at a reduced level of engagement. Therefore we recommend that product dissection be used to support novel thinking in engineering design, at least among novice designers. However, the activity may need to be structured in a team-environment to ensure active and equal participation by all members in order to see the benefits of dissection for encouraging design novelty.

3.6 Conclusion

The results of this study have important implications for engineering design research because it adds to our understanding of design cognition during idea generation. It demonstrates product dissection as a method of increasing the novelty of early-phase idea generation among novice designers and highlights other key factors that can impact design novelty, although care should be taken to select a novel example of the product being redesigned. The study also highlights the need for several key areas of research.

The current study sought to understand naturally occurring participation in a product dissection activity by allowing participants the freedom to interact within their teams as they normally would. This was done in an effort to simulate the beneficial team environment that is often associated with product dissection [63]. While this allowed for a more realistic context for studying product dissection and design novelty, this study does not address the implications of performing product dissection activities in a more controlled environment. Therefore, future studies should address this research gap by exploring the impact of dissection in a more controlled setting where confounding variables such as gender, semester standing, and team
interaction can be addressed. In addition, while the results of this study show that dissection can be used to encourage novelty in engineering education, the effects of dissection on engineering practice in industry is still unclear. Thus, future research that explores the impact of dissection beyond the engineering classroom is important for validating its positive effects on engineering design as it occurs in practice. Nevertheless, the results of this study can be used to better understand the process of creative idea generation in novice engineers, particularly as it relates to engineering education.

Future research is also needed to address the impact of product selection in dissection activities and understand methods for increasing design fluency. Our results highlight the fact that the novelty of the product selected for dissection influences the novelty of the generated designs in an educational setting. Therefore, special attention should be paid to product selection processes and aiding novice designers in choosing novel products. This recommendation is in line with research in psychology that states that novel stimuli presented to individuals can lead to high-level or global thinking [18]. In addition, the increased fluency of the novice designer in generating ideas can also be said to increase the novelty of the generated concepts. Therefore, future studies are needed to understand the impact of alterations of existing design practices outside of product dissection that better support the generation of more ideas.

Overall, the results from this study identify the utility of product dissection for improving the novelty of generated concepts by novice designers. Thus, our recommendation is that product dissection activities be performed during the early stages of the design process in order to gain a deeper understanding of products within that space as well as encourage the generation of novel ideas. This is particularly true for novice designers that have not yet gained relevant engineering experience, and who can greatly benefit from the hands-on nature of dissection. We also highlight the importance of product selection and the generation of multiple ideas. The results are used to provide recommendations for future research in this area and highlight the importance of studying naturally occurring design practices rather than developing formalized methods that are not widely adopted in design practice.
3.7 Acknowledgements

We would like to thank our undergraduate research assistants Kiley Coombe and Meagan Pandolfelli and our participants for their help in this project.

3.8 References


[27] Torrance, E., 1964, Role of Evaluation in Creative Thinking, Bureau of Educational Research, University of Minnesota, Minneapolis, MN.


[34] Eberle, B., 1996, Scamper: games for imagination development, Prufrock Press, Waco, TX.


Hands-on activities are a central component of engineering design, as they allow students to integrate theoretical and practical knowledge and increase student learning and enjoyment. One such beneficial activity is product dissection that involves the systematic disassembly of products in order to gain an understanding of its internal components and identify opportunities for improvements. However, due to the cost and time involved in conducting product dissection activities in the classroom, recent engineering educational efforts have sought to develop and utilize virtual dissection tools to help reduce and mitigate the costs of physical dissection activities. Yet, there exist little data on how these virtual product dissection environments impact student learning and understanding, leaving it unclear how and when to best use virtual dissection tools to enhance engineering instruction. Therefore, this study sought to explore the impact that virtual dissection tools can have on student learning in the engineering classroom through two studies conducted with first-year engineering students. The first study was an experimental study that sought to examine the learning, knowledge retention, and self-efficacy differences between students who performed virtual dissection and those who performed physical dissection. The second study was a qualitative study focused on identifying the impact of virtual dissection on student comprehension and self-mastery. These studies show that electro-mechanical self-efficacy is significantly impacted by the method of dissection with physical dissection resulting in a
higher self-efficacy gain. In addition, the results show that students desire more interactivity in the virtual dissection environment in order to make the interface more realistic and engaging. We use these findings to further understand the impact of using virtual dissection environments in lieu of physical dissection activities on student learning in the engineering classroom. In addition, the results from these studies allow us to develop a framework for virtual dissection learning tools and provide recommendations for engineering design education.

4.1 Introduction

“Experiences without words are difficult to integrate, describe, and retrieve. Yet, words without experience tend to have limited meaning. The two reinforce each other and are defined by one another” (p. 254) [1]. In fact, educational researchers have long acknowledged that interactive educational experiences provide students with a better means for blending theory with practice and allow students to see, raise, and seek out solutions to practical problems [2]. While the benefits of hands-on activities in engineering instruction are many (see discussion in [3]), the ever increasing class size [4], limitations in educational resources [5], and new educational paradigms like Massive Open Online Courses (MOOCs) [6] have impeded educators’ ability to use traditional hands-on activities as learning aids. Due to these developments, engineering education researchers have begun to explore the impact of virtual educational tools in an effort to reduce costs, time, and address practical and ethical issues [7].

One such hands-on activity that has received particular attention in the engineering literature is product dissection, which can be defined as taking apart or analyzing all components and subcomponents of a product in order to understand its structure and properties while uncovering opportunities for product improvement [8]. In the context of engineering education, product dissection has been recognized for its ability to help students relate classroom material to real-life engineering problems [9], increase the effectiveness of instruction [10], improve student’s practical knowledge [11], and increase student learning and enjoyment [12]. Despite its advantages, product dissection incurs significant costs such as the cost of the materials, space requirements, and instructional materials [13]. Therefore, educators have begun to rely on virtual
dissection tools as an alternative or supplement to physical dissection in the engineering classroom. The CIBER-U (Cyber-Infrastructure-Based Engineering Repositories for Undergraduates) project, is a virtual product dissection interface [14] that allows students to access 3D models of products stored in online databases and perform dissection virtually without having to purchase and dissect the product physically. The advantages of virtual engineering dissection tools are many, including increased sustainability and reduced time and effort required to dissect complex and challenging products physically. Earlier work done in engineering design that studied student learning between physical and virtual dissection activities has shown that while students gain knowledge about the dissected product regardless of the method of dissection, preliminary forms of virtual dissection may provide more detailed information to students that can help with learning [15]. However, this study investigated the use of less immersive virtual dissection environments that only involve an electronic parts and 3D model list and instructional dissection videos, and did not investigate the impact of individual exposure to virtual dissection tools on important educational constructs such as student knowledge retention and self-efficacy. Therefore, studies that explore the impact of exposure to more immersive virtual dissection environments on student learning, knowledge retention, and self-efficacy will provide more evidence for insights into the role that virtual dissection can play in the engineering classroom.

Research in other areas of education lend some insights into the impact that virtual dissection tools may have on student learning, such as improved knowledge retention of key concepts [16] and exposure to unique perspectives [17]. However, these research efforts also bring into question the effectiveness of existing virtual tools as alternatives to physical activities since the interactivity derived from the hands-on nature of these activities may not be sufficiently transferred over to the virtual environment [18]. Therefore, detailed investigations into the impact of virtual learning environments on student learning and knowledge retention in the engineering classroom are needed in order to gain a better understanding of how to best implement and improve these tools for effective use in engineering education.

The purpose of this paper is to provide empirical evidence supporting the use of virtual dissection environments in engineering education and to develop guidelines and recommendations for improving the effectiveness of these systems. The first study presented in this paper is a controlled experiment conducted with 20 first-year engineering students developed
to understand the impacts of virtual dissection on student learning, knowledge retention, and self-efficacy. The second study presented in this paper is an interview study conducted with 23 first-year engineering students who performed physical and virtual dissection tasks. The results of these studies contribute knowledge on the use of virtual learning environments in engineering education and provide insights into the impact that these environments can have on student learning. This work also contributes to the research community by examining the specific impact of product dissection modality (a form of hands-on activity) and product complexity on student learning, understanding, and self-efficacy in the engineering classroom.

4.2 Background & Motivation

4.2.1 Learning and Product Dissection

Before we can begin to uncover how to improve virtual learning environments in engineering education, we first must have the theoretical understanding of how students learn. There has been a wealth of research devoted to examining factors that encourage learning and knowledge retention of information in education [19, 20]. Researchers in educational theory have focused on the process of obtaining information, termed encoding, the process of storing that information in memory, called retention, and the process of recovering that information, often referred to as retrieval [21]. The process of encoding information is of particular interest to researchers and educators since without successful encoding, the likelihood of retrieving and applying information is non-existent.

Early work in cognitive psychology has identified the depth of processing as an important factor in determining successful encoding [22]. Physical interactions such as product dissection allow the user to experience the learning environment from a first-person perspective [23], providing more depth and information to the user during encoding. In addition, the diverse store of spatial information acquired by the individual when presented with detailed visual information is added to long-term memory [24] which can then be used for successful retrieval. These pieces of information are typically related semantically to form a representation of the knowledge regarding a particular domain, or as it is frequently referred to in the cognition literature, a
semantic network [25]. Therefore, the rich stimulation provided by product dissection can lead to more cognitive stimulation, activating nearby concepts in the semantic network, and hence, improving the encoding of this information [26]. These results suggest that product dissection is a highly beneficial educational tool that can be used to increase student learning in the engineering classroom, but little data exists on that investigates student learning after dissection activities using objective learning measures.

While research is needed that explores student learning of key engineering concepts after product dissection, the impact of different methods of dissection on student knowledge retention of these concepts after a longer time period is also important to study. Unsurprisingly, cognitive psychologists have shown that the amount of information stored decays with time, causing individuals to forget information at a later time. Specifically, researchers have studied the success of information retrieval over varying time periods and have found that individuals show diminishing retention loses with time [27] that can be affected by interfering information, the familiarity of the information [28], and pre-existing memories [29]. Since the successful recall of key engineering concepts after the information has long been imparted is of most practical concern to educators, it is important that we investigate the impact of dissection methods on student knowledge retention or decay of the information gained after product dissection activities.

Often studied in conjunction with student learning, self-efficacy is another measure of the effectiveness of instructional tools relevant to the study of virtual learning environments. Prior research in engineering education has identified self-efficacy as a crucial construct in influencing student learning behavior [30, 31]. In other words, learning outcomes are not limited to student knowledge of key concepts, but also the feelings of self-mastery and empowerment that are attained. Self-efficacy research in the field of science, technology, engineering, and mathematics (STEM) has shown that direct first-person experiences have the most influence over student self-efficacy [30]. On the other hand, other indirect and vicarious experiences, such as virtual dissection, may not positively impact student self-efficacy to the same extent [30].

While less direct interactions such as virtual dissection may not encourage active learning and self-mastery to the same extent as physical dissection, researchers have argued that virtual learning environments encourage knowledge acquisition and require less cognitive effort than
other third-person learning practices, making it a viable substitute for real-world first-person experiences [7]. Furthermore, since virtual learning environments allow for realistic and life-like representations of the world, it can encourage better learning by exposing students to knowledge in the context that it will be applied [32]. Since one of the main goals of implementing virtual product dissection is to preserve these learning gains while increasing practicality and accessibility, studies are needed that explore the differences in learning outcomes between students who perform physical and virtual dissection. In addition to student learning and knowledge retention, research suggests that the method of dissection may impact student perceptions of mastery and confidence. However, no study to date has explored the role that virtual dissection interfaces play on student self-efficacy. This research seeks to fill the knowledge gaps on virtual learning environments by exploring the impact of virtual dissection on student learning and self-efficacy in the engineering classroom.

4.2.2 Virtual Learning Advances in Education

While not studied in the area of virtual product dissection, research has been conducted on the use of virtual environments, or virtual interactions, to facilitate learning in the general education literature [23, 33, 34]. Specifically, virtual environments have been investigated as a method to enhance active learning [19, 35] because they allow students to experience the interactivity of a physical environment while allowing more freedom to “perform specific tasks that can be repeated as often as required in a safe environment” (p. 4) [7]. For example, researchers have developed a virtual tool for training students on industrial equipment (e.g., centrifugal pump, welding machine) [36]. They found that students that used the virtual environment performed equally high on an aptitude test as those who were trained traditionally. Other studies have explored the use of an immersive virtual environment program and found that participants who were allowed to virtually interact with three-dimensional models of various objects had a better memory of the objects compared to participants who only passively watched videos of the objects [35]. These studies are promising because they suggest that the interactivity in virtual learning environments may enhance student learning.

One of the biggest advantages of virtual learning environments is the fact that they can provide varied experiences to the user, some of which are impossible to experience in the real
world due to cost, danger, or practicality [7]. For example, one study tasked middle school students with the challenge of building a mousetrap car to optimize distance traveled. It was found that students who performed the task using physical materials and students who used a computer simulation were both equally able to learn about the functionality of the car and create an optimal final design [37]. Similarly, researchers in biology have developed and implemented virtual learning environments in classrooms in order to address concerns regarding ethics and resources surrounding the common practice of frog dissections. Studies conducted using these virtual interfaces in biology education have shown that virtual frog dissection environments increases student learning and knowledge retention when compared to traditional frog dissection [16]. Another way that virtual dissection provides varied experiences to the user is through the possibility of viewing and examining objects at different sizes or through different perspectives. For example, researchers developed a virtual training simulator for the treatment of trigeminal neuralgia that allows the user to view the procedure from outside the patient as well as from inside the patient [17]. The unique perspective of the procedure from the inside of the patient allows better understanding and training for such a fine-tuned and risky procedure. In the context of product dissection, different perspectives of the product can greatly aid in the understanding of its functionality by allowing the user to view the internal parts of a product while it is being operated. These studies suggest that virtual learning environments have the potential to replace or supplement physical learning environments without a loss of understanding or retention.

4.2.3 Research Objectives

While virtual product dissection environments carry many advantages and can address resource and instructional constraints, there still exists a gap in the research regarding the exact impact that these virtual interfaces will have on engineering student learning. This work fills the research void identified in the literature by examining the impact of dissection method and product complexity on student learning, understanding, and self-efficacy in the engineering classroom. Thus, two studies were conducted to understand the impact of these factors in engineering education. The first study was a controlled study that examined the impact of the dissection method and product complexity on student learning and engineering self-efficacy while the second study investigated the differences between virtual and physical dissection
activities through an exploratory qualitative study with engineering students. The experiment details, results, and discussion are presented individually in the following sections, followed by a joint exploration of their implications for engineering education.

4.3 Experiment 1: Impact of Virtual Dissection on Learning and Self-Efficacy

Our first experiment sought to examine the effects of the method of dissection and product complexity on student learning, knowledge retention, and self-efficacy. Specifically, the following research questions were addressed:

*Question 1:* Does the method of dissection or the complexity of the product dissected impact student learning and knowledge retention? Our hypothesis was that the method of dissection has little or no impact on student learning and knowledge retention since prior observational studies in engineering education have shown that there is limited difference in learning and performance between groups that utilize virtual dissection and those that performed physical dissection [38].

*Question 2:* Does the method of dissection or complexity of the product impact engineering self-efficacy? Our hypothesis is that there would be differences between the self-efficacy of students who dissected products virtually and physically since previous research has argued that virtual learning environments can make it easier to perform complex and time-consuming processes compared to physical environments [7].

*Question 3:* Does the complexity of the product dissected affect the relationship between the method of dissection and student learning, knowledge retention, and self-efficacy? Our hypothesis is that there would be a significant interaction effect between the method of dissection and product complexity due to the information content available to the student during dissection [17].
4.3.1 Participants

Participants were recruited from one section of a first-year undergraduate engineering design course at a large northeastern university. In all, 20 students (10 male, 10 female) participated in the study.

4.3.2 Procedure

At the start of the study, a brief overview of the study was provided to all participants, and informed consent was obtained. After all questions were answered, participants were randomly assigned to an experimental condition (described in Section 4.3.3). Participants were then asked to complete a pre-test Student Learning Assessment (SLA). The SLA sought to assess the participant’s knowledge and understanding of the mechanical and electronic components that can be found in their assigned product. Therefore, it included a set of questions where participants sketched and wrote brief descriptions of their assigned product according to four distinct categories: power supply, mechanism that provides primary motion, energy flow of the device, and the form and outer body. In addition to the SLA, participants were asked to complete a pre-test self-efficacy survey that assessed the individual’s perceived electrical and mechanical operative abilities. Students were informed that in addition to the pre-test SLA and self-efficacy survey, they will be asked to complete an identical post-test SLA and self-efficacy survey after the dissection activity in order to assess their learning before and after the dissection activity. The complete SLA and self-efficacy survey can be found in Appendix B.

Once all participants completed the pre-test SLA and self-efficacy survey, they were given instructions for the product dissection activity. Each participant was then asked to complete their assigned dissection activity. Participants completed the dissection activity using appropriate tools such as screwdrivers, pliers, and table clamps. All students were comfortable and familiar with the use of these tools during the dissection activity. During the dissection activity, participants were asked to identify each of the component parts of product they dissected and complete a bill of materials for each component, as it is typically done following dissection in engineering design [39], see Figure 4-1. After participants completed their assigned dissection activities, they were given a 3-hour break, and then the post-test SLA and self-efficacy survey were administered to the students. To measure the amount of knowledge retention of the
electro-mechanical aspects of the dissected product as well the change in self-efficacy after the dissection activity, participants were asked to complete a third SLA and self-efficacy survey 10 weeks after the study.

![Image of a bill of materials](image)

**Figure 4-1.** A bill of materials of the milk frother completed by participant 67. The Subtract and Operate Procedure (SOP) was used to encourage students to think about the purpose of a part and the consequences that may arise from the part being subtracted from the product.

### 4.3.3 Experimental Design

The study was a 2 (method of dissection) x 2 (product complexity) factorial design and participants were randomly assigned to a condition before the study began. The levels are described as follows:

**Method:** participants were instructed to dissect each product either *physically*, using tools like pliers and screwdrivers, or *virtually* using an animated exploded view of a detailed 3D model of the corresponding product, see Table 4-1 for example.

**Product Complexity:** participants were provided with either a milk frother (simple) or toothbrush (complex) to dissect, see Table 4-1. The milk frother was chosen as the simple product because it contained fewer components (12 components) than the electric toothbrush and had an internal structure that was easily accessible by hand. In contrast, the electric toothbrush contained more
components (17 components) and required the use of various tools and a significant amount of effort in order to fully dissect the product.

**Table 4-1**: Dissected milk frothers and toothbrushes in the physical and virtual dissection conditions.

<table>
<thead>
<tr>
<th></th>
<th>Milk Frother</th>
<th>Electric Toothbrush</th>
</tr>
</thead>
<tbody>
<tr>
<td>Physical</td>
<td><img src="image1" alt="Milk Frother" /></td>
<td><img src="image2" alt="Electric Toothbrush" /></td>
</tr>
<tr>
<td>Virtual</td>
<td><img src="image3" alt="Milk Frother" /></td>
<td><img src="image4" alt="Electric Toothbrush" /></td>
</tr>
</tbody>
</table>
4.3.4 Metrics

In order to investigate the differences in participants’ understanding of their assigned product before and after the dissection activity, several learning measures were developed and used in this study. In addition, the self-efficacy measures were used to analyze the participants’ pre-test, post-test, and knowledge retention dissection engineering self-efficacy.

The feature knowledge metric was developed as a measure of the participant’s understanding of the assigned product according to four aspects as discussed in the previous section: (1) power supply, (2) mechanism that provides primary motion, (3) energy flow of the device, and (4) the form and outer body. This metric was computed by counting the number of correct features identified by the participant in the SLA in each of the four categories by an expert rater, as was done in similar studies by Jee et al. [40]. These key features were defined as the individual components of the products that were taken from the bill of materials of the products and by identifying the energy flow steps. For example, participant S24RD’s pre-test sketch of power generation of an electric toothbrush scored a 0/3 (see Figure 4-2) because it did not include any of the following correct features: 2 AA batteries, a metal battery contact, 2 electrical contact clips. On the other hand, the both of the participant’s post-test and knowledge retention SLA sketch received a score of 3/3 since they included 3 of the correct features. The key for each of the four categories was provided to the experts by the authors, and the inter-rater reliability was calculated to be a Kappa of 0.859 for the pre and post-test questions.

![Feature Knowledge Sketches](image)

**Figure 4-2:** Student learning assessment (SLA) sketches of the power supply by participant S24RD that scored 0/3 for the (a) pre-test sketch and 3/3 for the (b) post-test sketch.
The students’ *engineering self-efficacy* was measured using the 10 self-efficacy questions that were administered before the dissection activity, 3 hours after, and 10 weeks after the dissection activity. The responses to these questions ranged from 0 (low self-efficacy) to 100 (high self-efficacy) and was used to compare changes in students’ self-efficacy between the different dissection conditions.

### 4.3.5 Data Analysis

To investigate differences in student learning between the two dissection conditions, a two-way repeated measures MANOVA was performed with the independent variables being the method of dissection and complexity of the product and the dependent variables being the pre- and post-test feature knowledge metrics which was used as a proxy for student learning. To examine student knowledge retention of the electro-mechanical features of the dissected product, a similar repeated measures MANOVA was performed with the same independent variables and the dependent variables being the post-test and knowledge retention feature knowledge metrics.

In order to examine the differences in electro-mechanical self-efficacy between the different dissection conditions, a two-way repeated measures MANCOVA was performed on the pre-test and post-test scores of the 10 electro-mechanical self-efficacy items using the method of dissection and product complexity as independent variables. Student gender and experience were used as covariates in this analysis since prior work has identified both gender and experience as important factors that affect self-efficacy [31]. Similarly, a repeated measures MANCOVA was conducted on the post-test and retention self-efficacy scores using the same independent variables and covariates. SPSS v.20 was used to analyze the findings and a significance level of 0.05 was used in all analyses.
4.4 Experiment 1: Results & Discussion

A summary of the results obtained from our statistical analysis is shown in Table 4-2. The following section presents the details and a discussion of these results with reference to our research questions.

Table 4-2. Summary of MANOVA and MANCOVA results conducted on pre-test, post-test, and retention student feature knowledge scores and electro-mechanical self-efficacy scores. Bolded rows indicate significant findings at the 0.05 significance level.

<table>
<thead>
<tr>
<th>Independent Variable</th>
<th>Factor</th>
<th>F-value</th>
<th>Sig.</th>
<th>Wilk’s Λ</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pre-test and Post-test Feature Knowledge Scores</td>
<td>Method of Dissection</td>
<td>2.45</td>
<td>0.11</td>
<td>0.58</td>
</tr>
<tr>
<td></td>
<td>Method of Dissection *</td>
<td>1.51</td>
<td>0.96</td>
<td>0.96</td>
</tr>
<tr>
<td>Post-test and Knowledge retention Feature Knowledge Scores</td>
<td>Method of Dissection</td>
<td>0.91</td>
<td>0.51</td>
<td>0.76</td>
</tr>
<tr>
<td></td>
<td>Method of Dissection *</td>
<td>1.03</td>
<td>0.42</td>
<td>1.03</td>
</tr>
<tr>
<td>Pre-test and Post-test Self-Efficacy Scores</td>
<td>Method of Dissection</td>
<td>5.91</td>
<td>0.03</td>
<td>0.08</td>
</tr>
<tr>
<td></td>
<td>Method of Dissection *</td>
<td>1.00</td>
<td>0.54</td>
<td>0.33</td>
</tr>
<tr>
<td>Post-test and Knowledge retention Self-Efficacy Scores</td>
<td>Method of Dissection</td>
<td>1.21</td>
<td>0.33</td>
<td>0.84</td>
</tr>
<tr>
<td></td>
<td>Method of Dissection *</td>
<td>0.18</td>
<td>0.83</td>
<td>0.97</td>
</tr>
</tbody>
</table>

4.4.1 Impact of Dissection Method on Student Learning and Knowledge Retention

Before testing our hypothesis, we wanted to confirm that students were indeed learning about the electro-mechanical concepts within their dissected products. Our repeated measures MANOVA results confirmed that student feature knowledge scores for all four categories of the post-test SLA were significantly higher than the pre-test SLA, $F(4,14) = 40.16, p < 0.00$; Wilk’s Λ = 0.08. However, student feature knowledge scores for the four categories of the knowledge retention SLA was significantly lower than the post-test SLA, $F(4,13) = 5.93, p < 0.01$; Wilk’s Λ = 0.35. These results show that all students, regardless of dissection condition, experienced an increase in feature knowledge scores after the dissection activity, but knowledge about the electro-mechanical aspects of the dissected product decayed with time (after 10 weeks). Figure
4-3 shows the average pre-test, post-test, and retention feature knowledge scores of students in all dissection conditions.

![Figure 4-3](image)

**Figure 4-3.** Pre and post-test feature knowledge scores for students across all conditions

Once we confirmed that learning was in fact occurring, we then tested our hypothesis that student learning and knowledge retention was not significantly impacted by the method of dissection. Our MANOVA results confirmed our hypothesis: there was no significant relationship between student learning (as measured from the pre-test and post-test SLA) and the method of dissection, $F(4, 13) = 2.35, p > 0.11$; Wilk's $\Lambda = 0.58$. Similarly, the repeated measures MANOVA revealed that there was no significant difference in student knowledge retention (as measured from the post-test and knowledge retention SLA) due to the method of dissection, $F(4, 13) = 1.12, p > 0.39$; Wilk's $\Lambda = 0.74$. The pre-test, post-test, and retention feature knowledge scores of all four SLA categories show a general trend of increase in knowledge after the dissection activity (after 3 hours), but a decay in this knowledge across time (after 10 weeks), regardless of the method of dissection.

These results indicate that student learning and knowledge retention was not affected by the use of the virtual dissection environment for all aspects of student learning tested (power supply, motion mechanism, energy flow, and form categories). This finding provides quantitative basis in support of virtual dissection and agrees with prior observational studies that report
limited differences in learning and performance between groups that utilize virtual dissection and those that performed physical dissection [38]. In addition to investigating the impacts of virtual dissection on the learning of key engineering concepts, this study goes one step further by examining the role that virtual dissection plays on the retention of these concepts. This result is promising because it supports the use of virtual dissection platforms in lieu of physical dissection activities. This is important because these virtual learning platforms increase the accessibility and efficiency of engineering instruction across the globe.

**4.4.2 Effect of Dissection Method on Electro-Mechanical Self-Efficacy**

Before investigating our second hypothesis, we ran a reliability analysis in order to determine the internal consistency of the self-efficacy survey. The Chronbach alpha for the 10-item pre-test electro-mechanical self-efficacy survey was 0.90, indicating a high level of reliability in this measure [41].

Our second hypothesis was that student electro-mechanical self-efficacy would be affected by the method of dissection. The repeated measures MANCOVA conducted on the pre-test and post-test self-efficacy measures showed that there was a significant relationship between changes in student self-efficacy and the method of dissection, $F(10,5) = 5.91, p > 0.03$; Wilk’s $\Lambda = 0.08$. Gender and semester standing were chosen as covariates for this analysis since prior work has shown that these factors significantly affect student self-efficacy [31]. Both gender, $F(10,5) = 14.90, p > 0.004$; Wilk’s $\Lambda = 0.03$, and semester standing, $F(10,5) = 16.21, p > 0.003$; Wilk’s $\Lambda = 0.03$, were significant factors in electro-mechanical self-efficacy improvements. In contrast, the repeated measures MANCOVA conducted on the post-test and knowledge retention self-efficacy measures with the same covariates showed that there was no statistically significant relationship between changes in student self-efficacy and the method of dissection, $F(10,5) = 3.73, p > 0.08$; Wilk’s $\Lambda = 0.12$.

These results indicate that students in the physical dissection condition experienced a larger increase in electro-mechanical self-efficacy after the dissection activity (after 3 hours) compared to students in the virtual dissection condition, see Figure 4-4. However, students in
both dissection conditions experienced similar changes in self-efficacy 10 weeks after the dissection activity, see Figure 4-4. This finding indicates that students who perform physical dissection experience more confidence and mastery gains from the activity compared to students who performed the virtual dissection. In addition, these self-efficacy gains are retained well after the dissection activity (10 weeks after), with no significant differences between the dissection conditions.

![Figure 4-4. The pre-test, post-test, and knowledge retention self-efficacy scores of students who performed physical and virtual dissection.](image)

### 4.4.3 Interaction Effects of Product Complexity

Our final hypothesis was that the complexity of the dissected product would impact the relationship between student learning, knowledge retention, and self-efficacy, and the method of dissection. Our repeated measures MANOVA results, however, showed that there was no significant interaction effect between product complexity and the method of dissection for the pre-test and post-test student feature knowledge scores, $F(4, 13) = 0.15, p > 0.07$; Wilk's $\Lambda = 0.96$, and for the post-test and retention student feature knowledge scores, $F(4, 13) = 0.95, p > 0.47$; Wilk's $\Lambda = 0.77$. Similarly, our MANOVA results revealed that product complexity does not significantly interact with the method of dissection for the pre-test and post-test electromechanical self-efficacy scores, $F(10,5) = 1.00, p > 0.54$; Wilk’s $\Lambda = 0.33$, as well as for the
post-test and retention electro-mechanical self-efficacy scores, $F(10,5) = 4.24$, $p > 0.06$; Wilk’s $\Lambda = 0.11$.

These results indicate that product complexity does not affect the relationship between the method of dissection and student learning, knowledge retention, and self-efficacy. Our findings contrast prior work that has shown that virtual tools allow for unique perspectives of complex artifacts [17], resulting in better understanding and comprehension of complex products. This result indicates that the use of complex products neither improves nor reduces student learning and self-efficacy gains in the virtual dissection environment. This could be attributed to the insufficient difference in complexity between the two products chosen for this study. In addition, this result could be caused by the lack of interactivity in the virtual dissection interface used in this study that could have leveraged the advantages of virtual learning environments touted by prior research.

4.5 Experiment 2: Exploring Virtual Dissection in the Engineering Classroom

The second experiment was conducted to build upon the findings of the first experiment by exploring the differences between physical and virtual dissection activities for its effects on student comprehension of the dissected product through an exploratory qualitative study. In this study, student comprehension was investigated since it contributes to students’ feelings of self-mastery of the product that has been shown to be the strongest influence on self-efficacy [31]. In addition, this study probed users of the virtual dissection interface for improvements and modifications that would be most helpful for increasing the utility of virtual dissection environments. Therefore, the following research questions were investigated.

Question 1: Does the method of dissection impact student comprehension and self-mastery of the dissected product? Our hypothesis was that physical dissection encourages better comprehension and self-mastery of the product’s functionality and structures since prior research on education has shown that direct first-person interactions play a crucial role in the learning process [23].
Question 2: What improvements and modifications to the virtual dissection interface would be most helpful for increasing student comprehension and self-mastery of the dissected product? Our hypothesis was that users of the virtual dissection interface would suggest interface improvements that increase the interactivity and detail of the virtual dissection interface.

4.5.1 Participants

Participants were 23 students (14 male, 9 female) in a product dissection class between the ages of 18 – 23 (mean 20). Participants were recruited from the same class section, but were engineering students of various disciplines (mechanical, electrical, chemical, etc.).

4.5.2 Procedure

Participants formed two-member teams and completed a physical dissection of either a Swingline PowerEase stapler, or a Staples Mini Magnetic stapler. Participants inspected the stapler and completed a Bill of Materials, for each component, as it is typically done following dissection in engineering design [39].

After the first stapler was physically dissected, participants virtually dissected the Accentra PaperPro stapler using an animated exploded view of a detailed 3D model of the stapler, see Figure 4-5.

Figure 4-5. A screen capture of the virtual dissection interface where participants virtually dissected the Accentra PaperPro stapler.
Once participants completed the dissection activities for both staplers (physical and virtual), they were asked to complete an online survey on their experiences with the physical and virtual dissection activities. The survey included questions such as “What features would you change or add to the virtual dissection activity on the computer in order to enhance its utility?” and “Are there any additional feedback methods you would like to add or change in the current virtual dissection platform (e.g., the current platform responds to mouse movements by rotating, panning, and zooming)?” Additionally, participants were asked to indicate the extent to which a type of dissection was preferred over the other (virtual versus physical dissection) with regards to understanding and ease of use. A 5-point verbally anchored scale was used to elicit responses, with a value of 1 indicating a strong preference for physical dissection, a value of 5 indicating a strong preference for virtual dissection, and a value of 3 indicating no preference between the two dissection techniques. Participants were then asked to give an explanation for their answer, and all survey questions can be found in Appendix B.

Following the online survey, focus groups and semi-structured interviews were conducted. There were 3 focus groups (10 participants, 9 participants, 14 participants), and 2 individual interviews. Participants were asked to answer questions such as “Can you describe how virtual dissection compared to physical dissection? Was one easier to perform than the other? Why or why not?” and “What features were most useful in the virtual dissection tool? Why?” All interview questions can be found in Appendix B.

4.5.3 Data Analysis

The results from the survey were analyzed in order to determine which aspects of virtual dissection could be improved. Thus, a Wilcoxon Signed-Rank Test was conducted on all survey results. In addition, the focus groups and interviews were transcribed and analyzed using the principles of content analysis [42] and were used to provide rationale and insights into the quantitative findings.
4.6 Experiment 2: Results and Discussion

The results of the survey and interviews are presented in the following sections and are grouped according to three major themes: (1) advantages of physical dissection, (2) advantages of virtual dissection, and (3) improvements to the virtual dissection environment. The qualitative results from the interviews are used to provide rationale for the quantitative results obtained from the survey.

4.6.1 Advantages of Physical Dissection

From the survey results, we found a significant preference for the type of dissection method (Z = -2.49, p < 0.01), indicating a preference for physical dissection in allowing easier manipulation of the product and its parts during dissection (median score of 2 out of 5). In addition, there was a significant preference for a type of dissection method (physical) in adding to the understanding of the product’s functionality (Z = -3.30, p < 0.01). The median score for this question was found to be a 1 out of 5, indicating a strong preference for physical dissection in increasing participants’ understanding of the product’s functionality. It was also found that participants preferred physical dissection over virtual dissection when dissecting simple products (Z = -2.60, p < 0.01), with the median response of this question being a 2 out of 5.

From the focus groups and interviews, participants found that physical dissection had several key advantages that aid in their understanding of the product’s functionality. The most common observation provided by participants’ was that physical dissection allowed for an easier understanding of the product’s materials and physical properties. For example, Participant 7 commented that they “couldn’t tell what material it [the part] was, looking on the computer”, while Participant 35 observed that “you can’t distinguish between aluminum, brass, things like that.” In addition, the knowledge of the type of fit between parts could be obtained through physical dissection. As Participant 34 explained, “On the computer, everything happens quickly, but going step by step and physically moving the parts and feeling them, how rigid they are and how things snap or fit together I think is very valuable.” As a result, participants felt that physical dissection encouraged a deeper understanding of the function of the device, as explained by Participant 18, “being able to take it apart to a point and then move stuff by your hands,
physically move it with your hands, it’s a lot easier to tell how things work. As opposed to just dragging it on a screen.”

4.6.2 Advantages of Virtual Dissection

While participants indicated that physical product dissection had several advantages over virtual dissection, the survey results revealed that virtual dissection may be advantageous in certain situations. It was found that there was no significant preference ($Z = -1.38, p < 0.17$) for virtual dissection with complex products (indicated by more components). This result, while not statistically significant, echoes the qualitative findings from the focus groups and interviews.

From the results of the focus groups and interviews, it was found that participants felt that virtual dissection was easier and quicker to perform compared to physical dissection. For example, as Participant 11 explained: “It [virtual dissection] was quicker. I thought it was cleaner. Taking apart other things, I got grease on my hands, like the drill we were using. And having parts fall, trying to look for those things, the ball bearings.” Similarly, Participant 23 commented that, “[virtual dissection] takes it apart faster and you don’t have the parts flying off and the springs going everywhere, losing parts.” In addition, participants noted that virtual dissection allowed for a better understanding of part connectivity when dissecting complex products with many parts. For example, Participant 29 commented that, “it’s hard to get an idea [of how the product works] when you’re taking something apart; especially when it’s a complicated system and you have no idea- you can’t watch it until you put it back together and you have to guess based on the parts.”

Participants also showed a preference for virtual dissection in adding to their understanding of the internal mechanisms of the product. Since the external structures of a product can be viewed in different modes (i.e., transparent, wireframe, hidden), participants were better able to understand the structure of the product’s internal parts through virtual dissection compared to physical dissection. For example, Participant 32 commented that, “you could see the see-through version of how it was. You could see all the parts together, but on the other stapler [physical dissection], it was a solid piece and you had to look underneath and try to get a good look at all the parts working together.” Similarly, Participant 34 observed that, “you could rotate
everything and kind of visualize everything at once. When you do it physically, you have different pieces lying on the table and you have to do it step by step, but with this, you could easily see how every piece had its own role in the assembly.”

4.6.3 Improvements to the Virtual Learning Environment

These results not only provide insights into the impact of virtual learning environments in engineering education, but also provide insights into methods for improving the virtual dissection interface. Through interacting with the virtual dissection interface, participants were able to provide recommendations and suggestions for future improvements to the virtual dissection interface. The most common suggestion was for a step-by-step, interactive variant of the exploded view animation. In other words, participants suggested that the dissection animation involve the different parts of the product being removed individually, instead of simultaneously, as is currently done in the virtual dissection interface. In addition, participants expressed a desire to interact with the individual components through clicking or dragging to more closely simulate a physical dissection experience. For example, Participant 27 in the second study suggested “Being able to drag the parts out rather than them going their own way and understand where they are and how they’re getting there.” Similarly, Participant 34 in the second study explained: “You could do piece-by-piece instead of taking it apart all at once. And then you could also have an alternate view of the exploded thing coming out because I think there is something to be said for piece by piece- the natural way of taking it apart.” These suggestions mirror the results of the engineering education literature that encourages the engagement of students in meaningful tasks in order to increase learning and retention [7].

Through interacting with the virtual dissection interface, participants suggested implementing more feedback and interactivity into the virtual dissection interface to provide a more realistic product dissection experience. For example, Participant 34 explains that “if you were doing it piece-by-piece, then the piece would come apart more similarly to how they would come apart in real life. So say, you had to bend something back, you had to physically do that. If it were tighter, it would provide more resistance, you would have to drag mouse farther or something to get less of a rotation or something like that. Some sort of feedback would definitely
help.” Participants also suggested including more information on each component in the virtual dissection interface. For example, Participant 15 suggested “within the actual animation exploded views, it would say its name and material when you click on it, if that’s possible.” This feature would enable participants to identify the exact material of each component. Other attributes, such as manufacturing process, dimensions, and weight could also be embedded into the virtual dissection interface to provide a richer source of information on each product. These improvements would not only bring the virtual dissection interface one step closer to providing the same depth of information as physical dissection, but also increase student comprehension and self-mastery of key engineering concepts through these additional interactive elements.

Other suggested improvements included animations of the product’s internal mechanisms during operation. Since the external structures of the 3D model can be made transparent, moving parts within the product can be animated to provide users with a better understanding of the product’s functionality in a way that would be challenging to accomplish through physical dissection. Participant 16 suggested implementing “3D animation where you can see it working it and coming on, and changing see-through [transparency] so we can see inside the internal components working.” By implementing this feature in the virtual dissection interface, the advantage of providing different perspectives through virtual learning environments can be successfully leveraged in engineering education.

4.7 Implications of Experiments

The main goal in this research was to examine the impact of virtual dissection on student learning, understanding, and self-efficacy and develop recommendations and guidelines for improving the utility of virtual dissection interfaces in the engineering classroom. Our results revealed the following:

- Student learning does not appear to be impacted by the method of dissection.
- Students that performed virtual dissection did not experience the same amount of self-efficacy improvements as the students who performed physical dissection.
• Feedback and interactivity are important to student comprehension, and hence, self-mastery of the dissected product.

The details and implications of these findings in engineering education are discussed in the following sections.

4.7.1 Virtual and Physical Dissection Environments Have the Same Effect on Student Learning and Knowledge retention but Different Effects on Self-Efficacy

One of the main findings of this study is that there was no difference in student learning and knowledge retention of the product’s internal structures and mechanisms between the physical and virtual dissection conditions. This finding is supported by prior observational results that showed limited differences in student learning between those that performed a dissection activity physically and those that performed dissection virtually [38]. While the results of the second study indicate that students preferred physical dissection over virtual dissection for understanding the internal structures of the product, the results of the first study suggest that students in both physical and virtual dissection conditions had the same depth of processing and amount of relevant cues that allowed them to encode and retrieve information with success after the dissection activity [22, 43]. This study furthers our understanding of the impacts of virtual environments on student learning and knowledge retention by comparing student knowledge of key concepts before and after the use of an instructional tool. In addition, the objective measures of student learning in this study provide a precedent for measuring student knowledge of key engineering concepts for use in future research investigating the impacts of other hands-on educational activities.

While this study showed that student learning and knowledge retention was unaffected by the method of dissection, the results of our first study also revealed that physical dissection led to greater changes in electro-mechanical self-efficacy compared to students who performed the virtual dissection. This finding is echoed by the results of the second study that showed that students preferred physical dissection for adding to their understanding of the product’s
functionality. Reduced changes in self-efficacy for participants who virtually dissected the product may be attributed to the fact that students are less able to identify the relationship and fit between parts when using a virtual dissection tool compared to physical dissection [18]. Additionally, physical interactions tend to be more interactive, which has been shown to be crucial to the learning process [7]. These factors may result in a greater increase in self-mastery of the product’s internal structures and mechanisms in students who performed the physical dissection compared to students who performed the virtual dissection. One of the major advantages of product dissection is its ability to empower first-year students and increase self-confidence with regards to engineering concepts. Prior work in the education literature has shown that a student’s sense of first-person or direct mastery of a task is the strongest predictor of self-efficacy [30]. On the other hand, third person or vicarious experiences, such as virtual dissection, are less influential on task-specific self-efficacy.

The results from these findings provide empirical evidence of the advantage of hands-on activities in education and also extends our knowledge of the impact of virtual learning environments on student learning and self-mastery in engineering more generally. Specifically, the result that the virtual analog of a hands-on activity was found to result in the same amount of student learning suggests that virtual learning environments have the potential to replace or supplement physical activities in situations where cost, resources, or time may be prohibitive. As is the case with product dissection and other hands-on activities in engineering education, the adoption of virtual learning environments can make these activities accessible to larger groups of individuals on the web and increase the sustainability of these activities. However, reduced self-efficacy gains in students who used the virtual learning environment in this study indicate that the indirect nature of virtual learning environments does not encourage feelings of self-mastery and empowerment that is a crucial component of the learning process [30, 31]. Therefore, more work is needed to improve virtual learning interfaces in order to reduce these self-efficacy gaps and create effective and well-rounded virtual learning environments.

In addition to exploring the impacts of virtual learning environments on student learning and self-efficacy, this study also provided an empirical basis for the direction of future research efforts in the area of virtual learning environments in engineering design. The results of this study show that the 10 self-efficacy questions used was a reliable measure of student mastery with regards to electro-mechanical self-efficacy. However, future work should investigate the
effects of virtual dissection tools on broader domains of student self-efficacy since this study only investigated electro-mechanical self-efficacy. In addition, further work should focus on the development of virtual dissection environments that leverage the unique computational abilities of virtual dissection environments as well as the hands-on and interactive nature of physical dissection. For example, techniques such as visible feedback and exploded views can lead to effective instructional virtual dissection tools that provide sufficient levels of understanding and self-efficacy to engineering students. These improvements to virtual dissection environments should be further tested for their impact on student self-efficacy in order to help develop effective virtual dissection tools that can replace physical dissection activities.

Our results also provide a starting point for further research on the use of virtual learning environments in engineering education. Specifically, future studies should investigate the impacts of both virtual and physical dissection with a larger sample of students in order to further generalize the findings. In addition, more work should be conducted that explores the virtual dissection of products from other domains, such as engines and bicycles. This research adds to our understanding of the utility of virtual dissection in a wide range of engineering disciplines and expertise, and will allow for a broader adoption of virtual dissection tools in education. In addition, research is needed that explores other methods of input control and feedback, such as gesture-based control in order to leverage new technologies and further enhance virtual dissection environments. Lastly, this movement toward virtual dissection practices can open up opportunities for the development and adoption of other virtual learning environments in engineering education that leverage 3-D modeling to enhance engineering instruction.

4.7.2 Virtual Dissection in Engineering Education and a Framework for Improvements

One of the main goals of virtual dissection environments in education is to encourage student learning of key engineering concepts while increasing practicality, accessibility, and sustainability. While the results of this study show that overall, student learning and knowledge retention is equally increased by both physical and virtual dissection, students experience smaller self-efficacy gains when dissecting a product virtually compared to physically. This finding is
contrasted by prior work that has argued that virtual environments can make it easier to perform complex and time-consuming processes compared to physical environments [7], suggesting that students should feel more mastery over the dissection elements in a virtual environment that can lead to increased self-efficacy. However, as was shown in this study, students who performed the physical dissection activity experienced a greater increase in self-efficacy that can be attributed to the more hands-on nature of physical dissection. This is problematic since one of the key advantages of product dissection over other traditional forms of instruction such as lectures and reading is that it serves as a powerful and empowering tool for engineering students. Therefore, it is clear that more work is needed to improve virtual dissection interfaces in order to increase its effectiveness in the engineering classroom.

The results of our second study provide an empirical basis for the strengths and weaknesses of virtual dissection interactions. From these results, a summary of the strengths, weaknesses, and implications are presented in terms of a Strength, Weaknesses, Opportunities, and Threats (SWOT) matrix [44] in Table 4-3. This summary shows that while virtual dissection may lack interactivity and detail compared to physical dissection, it holds many advantages over physical dissection that can encourage the adoption of virtual dissection in education. In addition, there exist several key areas that virtual dissection can exploit in increasing student learning, such as the use of a variety of open-source 3D models available online, as well as the ability to view 3D animations of products in operation. Lastly, future work on improving upon virtual dissection interfaces will need to contend with several threats that plague virtual dissection environments such as unstandardized interface and 3D model standards, as well as challenges in encouraging the adoption of virtual dissection tools in place of traditional physical dissection activities.
Table 4-3. The SWOT matrix for virtual dissection interface for increasing student learning, knowledge retention, and self-efficacy.

<table>
<thead>
<tr>
<th>Internal Origin</th>
<th>Helpful</th>
<th>Detrimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>STRENGTHS</td>
<td>Time saving</td>
<td>WEAKNESSES</td>
</tr>
<tr>
<td></td>
<td>Resource saving</td>
<td>Less hands-on</td>
</tr>
<tr>
<td></td>
<td>Accessible to more students</td>
<td>Less interactive</td>
</tr>
<tr>
<td></td>
<td>Safe</td>
<td>Limited detail</td>
</tr>
<tr>
<td></td>
<td>Sustainable</td>
<td>Dependent on 3D model proficiency</td>
</tr>
<tr>
<td></td>
<td>Unique perspectives of products</td>
<td>Limited by scope of 3D models available</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Dependent on effectiveness of interface</td>
</tr>
<tr>
<td>External Origin</td>
<td>OPPORTUNITIES</td>
<td>THREATS</td>
</tr>
<tr>
<td></td>
<td>Established computer infrastructure</td>
<td>Changing interface standards</td>
</tr>
<tr>
<td></td>
<td>Wealth of open-source 3D models</td>
<td>Differing 3D model formats</td>
</tr>
<tr>
<td></td>
<td>Visualizations of working products</td>
<td>Adoption challenges</td>
</tr>
</tbody>
</table>

This SWOT matrix provides directions for the improvement of future virtual dissection iterations. Specifically, the following guidelines and recommendations are proposed for leveraging the strengths, weaknesses, opportunities, and threats facing virtual dissection interfaces:

- Develop virtual dissection interfaces that emphasize interactivity. A step-by-step disassembly of the system will allow students to better understand the internal structures of the product.
- Consider incorporating the use of hand-tools such as screwdrivers and pliers in order to emphasize the hands-on nature of product dissection.
- Include crucial details such as material texture in order to provide cues to students regarding the product’s functionality and properties.
- Provide additional information such as material properties, dimensions, and manufacturing process of the components in order to leverage the advantages of virtual earning environments and provide students with a more complete picture of the product.
Develop virtual dissection interfaces that allow the student to view the product while it is being operated (e.g., working motor, levers, springs) to take advantage of the unique perspectives available in virtual dissection environments.

Source 3D models that are available for free online in order to expand the library of products available to students to dissect.

Standardize the 3D model format and importing procedure in order to facilitate the development and availability of products that are compatible with virtual dissection.

These guidelines provide a foundation for future work on virtual dissection interfaces and can increase student learning, knowledge retention, and self-efficacy in order to enhance engineering instruction. These improvements also help increase the effectiveness of virtual dissection environments and encourage the adoption of more sustainable and accessible dissection practices.

4.8 Conclusion

The purpose in this research was to understand the impact of virtual dissection on engineering student learning, knowledge retention, and self-efficacy of the dissected product. Our results showed that student learning and knowledge retention was not diminished through the use of virtual dissection environments, but increases in electro-mechanical self-efficacy was reduced in students who performed virtual dissection compared to students who performed physical dissection. These results indicate that virtual learning environments can be used as a replacement for costly and impractical physical activities without reducing learning and understanding of key engineering concepts, but improvements to the virtual interfaces are necessary in order to encourage equal amounts of self-efficacy improvements. In addition, the results of the qualitative exploratory study allowed us to identify the strengths and weaknesses of virtual learning environments for its ability to encourage student learning. From these results, we provide guidelines and recommendations for future virtual dissection iterations that aim to increase the efficacy and adoption of virtual dissection in engineering education.
While this study showed that virtual dissection environments can be used as a replacement for physical dissection activities without affecting student learning, there exist several limitations that are important to note. First, future work should explore the use of virtual dissection environments with practicing engineers is needed in order to better understand the role that virtual dissection plays in the industrial setting. In addition, the measures of student learning used in this study were specific to the dissected product and other more general forms of student learning should be explored. For example, student performance on the dissection of future products should be investigated as another proxy of student learning. Lastly, the use of other more complex products in virtual dissection environments should be explored for its impact on student learning and self-efficacy in order to further refine and enhance virtual dissection environments in engineering education.
4.9 References


Chapter 5

Summary, Contributions, & Future Work

The use and exposure to examples is an inescapable part of engineering practice and education. The research presented in this thesis was developed to explore the implications of exposure to existing examples on design creativity and learning of engineering students. The first manuscript of this thesis, presented in Chapter 2, investigates individual factors such as personality traits and student involvement in team-based dissection practices for its impact on design fixation during ideation. The second manuscript, found in Chapter 3, examines the impact of dissection practices on design novelty as well as the influence of exposure to different products on the ideation process. The third and final manuscript, found in Chapter 4, examines the utility of virtual dissection interfaces on student learning, knowledge retention, and self-efficacy and presents a framework for improving the effectiveness of these virtual learning environments in engineering education. In addition, a summary of these studies is explored in Chapter 1.

The findings in this thesis provide empirical evidence for the impact that personality traits, involvement in dissection activities, and the type of product dissected have on design fixation and novelty. In addition, the use of virtual dissection tools is investigated for their impact on student learning and self-efficacy. This research contributes new knowledge regarding the use of examples in design, and provides the following contributions to work in this area:

1. This research adds to our understanding of the impact of product dissection activities on design fixation and novelty during early-phase ideation activities. The results of the studies conducted in this thesis indicate that product dissection can mitigate fixation effects and enhance design novelty in engineering design education. These results can be used to enhance our understanding of the design process, and help encourage creativity in the engineering classroom.

2. This research provides empirical evidence for the influence of individual attributes such as personality traits on involvement in team-based dissection activities. The studies
conducted in this thesis demonstrate a relationship between personality and exposure to the product dissection activity, adding to our knowledge of the different factors that influence the design process.

3. This research provides further insights into the influence of exposure to different products on design novelty during subsequent concept generation. It was found that participants that were exposed to a more innovative design for product dissection produced concepts that were more novel than those that received a less innovative design. This result is used to drive recommendations for leveraging product dissection for enhancing novelty in engineering design education and practice.

4. The results of this research provide insights into the impact of virtual dissection environments on student learning, knowledge retention, and self-efficacy compared to physical dissection practices. The results of this research show that student learning and knowledge retention is not affected by the use of the virtual dissection interface, but increases in electro-mechanical self-efficacy is reduced in students who performed virtual dissection compared to students who performed physical dissection. These results add to our knowledge of the impact that virtual dissection tools can have on student learning and self-efficacy.

5. The results of this research provide an empirical basis for developing guidelines for improving the effectiveness of virtual dissection interfaces and a framework for leveraging the strengths and weaknesses of virtual learning environments in the engineering design context. The results of the studies conducted in this thesis allow us to recommend improvements to help increase the effectiveness of virtual dissection environments and encourage the adoption of more sustainable and accessible dissection practices.

This research also provides important evidence for the careful selection and implementation of example usage practices in engineering design. It also examines the use of virtual learning environments in engineering education and highlights the need for refining and
enhancing these interfaces to increase student learning and self-mastery of hands-on activities. The results from these studies are used to develop recommendations and guidelines for enhancing example usage in engineering practice and education and increasing adoption rates for sustainable virtual dissection practice. While this research focuses on the use of product dissection activities in engineering design, the results may be generalizable to other hands-on techniques found in practice and education. Future work should examine the use of larger-scale and more complex examples for their impact on design creativity. In addition, while the results of the studies conducted in this thesis show that dissection can be used to encourage novelty in engineering education, the effects of dissection on engineering practice in industry is still unclear. Thus, future research that explores the impact of dissection beyond the engineering classroom is important for validating its positive effects on engineering design as it occurs in practice. Lastly, research is needed that focuses on the development of effective next-generation virtual learning environments and explores the implications of other forms of hands-on interactions in engineering design in order to enhance the design process.
## Appendix A

### Toothbrush Rating Statements

<table>
<thead>
<tr>
<th>No.</th>
<th>Rating Statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>The idea has the same location and number of brush heads.</td>
</tr>
<tr>
<td>2</td>
<td>The idea has the same shaped brush head.</td>
</tr>
<tr>
<td>3</td>
<td>The idea has the same bristle length, hardness, and/or direction on the brush head.</td>
</tr>
<tr>
<td>4</td>
<td>The idea generates the same number of movement types (only rotation, rotation AND vibration, etc...)</td>
</tr>
<tr>
<td>5</td>
<td>The idea has the same type and/or range of brush head movement (rotational/ translational/ vibrational/ angle of rotation).</td>
</tr>
<tr>
<td>6</td>
<td>The idea has the same operating speed. **</td>
</tr>
<tr>
<td>7</td>
<td>The idea's brush head is similar to the original design.</td>
</tr>
<tr>
<td>8</td>
<td>The idea has a neck that is the same shape and size.</td>
</tr>
<tr>
<td>9</td>
<td>The idea has a neck that has the same rigidity and flexibility.</td>
</tr>
<tr>
<td>10</td>
<td>The idea has a neck that has the same appearance (solid, single piece).</td>
</tr>
<tr>
<td>11</td>
<td>The idea's neck design is similar to the original design.</td>
</tr>
<tr>
<td>12</td>
<td>The idea has the same overall size.</td>
</tr>
<tr>
<td>13</td>
<td>The idea uses the same materials.</td>
</tr>
<tr>
<td>14</td>
<td>The idea performs the same functions (no toothpaste, no tongue scraper, no flosser).</td>
</tr>
<tr>
<td>15</td>
<td>The idea connects with the rest of the toothbrush in the same way.</td>
</tr>
<tr>
<td>16</td>
<td>The idea's general characteristics are similar to the original design.</td>
</tr>
<tr>
<td>1</td>
<td>The idea uses the same method to remove and access the battery(ies). **</td>
</tr>
<tr>
<td>2</td>
<td>The idea has the same battery access location.</td>
</tr>
<tr>
<td>3</td>
<td>The idea's battery access design is similar to the original design.</td>
</tr>
<tr>
<td>4</td>
<td>The idea uses the same type of power button.</td>
</tr>
<tr>
<td>5</td>
<td>The idea has the same power button location.</td>
</tr>
<tr>
<td>6</td>
<td>The idea's power activation design is similar to the original design.</td>
</tr>
<tr>
<td>7</td>
<td>The idea has the same shape.</td>
</tr>
<tr>
<td>8</td>
<td>The idea uses the same method of providing grip.</td>
</tr>
<tr>
<td>9</td>
<td>The idea uses the same materials.</td>
</tr>
<tr>
<td>10</td>
<td>The idea has the same number of components.</td>
</tr>
<tr>
<td>11</td>
<td>The idea has the same functional features. (no power indicator, no tongue scrubber, no flashlight)</td>
</tr>
<tr>
<td>12</td>
<td>The idea has the same size and weight.</td>
</tr>
<tr>
<td>13</td>
<td>The idea has the same color.</td>
</tr>
<tr>
<td>14</td>
<td>The idea has the same level of portability.</td>
</tr>
<tr>
<td>15</td>
<td>The idea's general characteristics are similar to the original design.</td>
</tr>
<tr>
<td>No.</td>
<td>Rating Statement</td>
</tr>
<tr>
<td>------</td>
<td>----------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>1</td>
<td>The idea uses the same energy source (ie: batteries)</td>
</tr>
<tr>
<td>2</td>
<td>The idea operates independently of other external sources (no AC cord, water, etc…)</td>
</tr>
<tr>
<td>3</td>
<td>The idea has no power accessories. (dock, charging mat, etc…)</td>
</tr>
<tr>
<td>4</td>
<td>The idea has the same operating speed. **</td>
</tr>
<tr>
<td>5</td>
<td>The idea uses batteries.</td>
</tr>
<tr>
<td>6</td>
<td>The idea uses the same type of battery (not AAA, not rechargeable, Li-ion)</td>
</tr>
<tr>
<td>7</td>
<td>The idea uses the same number of batteries.</td>
</tr>
<tr>
<td>8</td>
<td>The idea has batteries that are placed in the same location and configuration (side-by-side, vertically, etc…)</td>
</tr>
<tr>
<td>9</td>
<td>The idea uses a serial electrical connection for the batteries.</td>
</tr>
<tr>
<td>10</td>
<td>The idea uses the same method to remove and access the battery(ies). **</td>
</tr>
<tr>
<td>11</td>
<td>The idea has the same number of batteries provided at the time of purchase.</td>
</tr>
<tr>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>The idea does not add or omit any significant parts in the energy mechanism (no extra gears, cogs, pistons, etc…)</td>
</tr>
<tr>
<td>2</td>
<td>The idea places the motor and moving parts in the same place within the body.</td>
</tr>
<tr>
<td>3</td>
<td>The idea has the same size.</td>
</tr>
<tr>
<td>4</td>
<td>The idea powers only one function.</td>
</tr>
<tr>
<td>5</td>
<td>The idea has no damping mechanisms (ie: no rubber wells to absorb vibration and reduce noise).</td>
</tr>
<tr>
<td>6</td>
<td>The idea uses the same number of shafts.</td>
</tr>
<tr>
<td>7</td>
<td>The idea uses components that are made of the same materials.</td>
</tr>
<tr>
<td>8</td>
<td>The idea connects the main shaft with the brush head in the same way (press-fitted into brush head, no cogs)</td>
</tr>
<tr>
<td>9</td>
<td>The idea generates only one type of movement (only rotation).</td>
</tr>
<tr>
<td>10</td>
<td>The idea generates the same type and range of movement (rotational/ translational/ vibrational). **</td>
</tr>
<tr>
<td>11</td>
<td>The idea uses the same type of motor (PMDC).</td>
</tr>
<tr>
<td>12</td>
<td>The idea uses the same number of motors.</td>
</tr>
</tbody>
</table>
Appendix B

Student Learning Assessment (SLA) Questionnaire

Name: ________________________

Mechanical and Electrical Device Learning Quiz EDSGN100

PART I: Functional Classification and Analysis

Describe and sketch the function of the different parts of your assigned product in the table provided below. Provide as much detail as you can on how you think the product works with respect to the following categories:

<table>
<thead>
<tr>
<th>Category</th>
<th>Visual Representation</th>
<th>Functional Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power supply</td>
<td>Sketch and label all components in the system</td>
<td>How is power supplied to the device?</td>
</tr>
<tr>
<td>Mechanism that provides primary motion</td>
<td>Sketch and label all components in the system</td>
<td>How is mechanical motion (rotation, translation, etc.) achieved in the device?</td>
</tr>
<tr>
<td>Energy flow of the device</td>
<td>Sketch and label all components in the system</td>
<td>How is power transferred to create motion in the device?</td>
</tr>
<tr>
<td>Form and outer body</td>
<td>Sketch and label all components in the system</td>
<td>How does the user interact with the outer components of the device?</td>
</tr>
</tbody>
</table>
**Student Self-Efficacy Questionnaire**

Name: ___________________________________

**Mechanical and Electrical Device Learning Quiz**

**EDSGN100**

**PART II: Engineering Self-Efficacy for Electromechanical Devices.**

Using the provided scale, rate how confident you are that you can perform the following engineering related activities on an electromechanical device. An electromechanical device is one that has physical moving parts in addition to electrical parts that require electrical power to function. An example of an electromechanical device is an electric drill.

Judge your operative capabilities as of now, not your potential capabilities or your expected future capabilities.

<table>
<thead>
<tr>
<th>Cannot do at all</th>
<th>Highly certain can do</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>10</td>
</tr>
</tbody>
</table>

1. Take apart an electromechanical device without damaging the internal structures.
2. Identify the physical connections and structures of an electromechanical device (i.e., how the internal components are laid out).
3. Identify exactly how the mechanical components of an electromechanical device provide motion to the device.
4. Identify the flow of power (electrical connectivity) through an electromechanical device.
5. Identify if an electromechanical device is functioning properly or optimally.
6. Troubleshoot a malfunctioning electromechanical device (i.e., identify malfunctioning areas or components).
7. Repair a malfunctioning electromechanical device of (i.e., completely restore to working condition).
8. Communicate the details of an electromechanical device’s internals and components through sketches.
9. Identify the strengths and weaknesses of a particular electromechanical device.
10. Redesign an electromechanical device for increased efficiency and usability.
Virtual Dissection Survey Questions
Answer the following questions using this scale:

1. You were more satisfied with this activity:
2. This activity required more effort to perform:
3. This activity provided you with more information regarding the individual parts (easier to identify and recognize):
4. This activity allowed for easier manipulation of the dissected product:
5. In your opinion, this activity is most appropriate for dissecting products that have few parts:
6. In your opinion, this activity is most appropriate for dissecting products that have many parts:

Answer the following questions in your own words:

7. Describe your experience using the computer to perform the virtual dissection of the product (include features that were helpful, and features that were problematic):
8. What features (if at all) would you like to see added to the virtual dissection on the computer?
9. What (if at all) do you think could be enhanced about virtual dissection by using a tablet or touch-based device instead of a mouse-and-keyboard computer?
10. List any other methods of performing virtual dissection that you think could improve the experience:
11. What methods of providing feedback do you think could help improve virtual dissection?
12. What other improvements would you recommend for improving the overall virtual dissection experience?
Virtual Dissection Interview Questions

1. Please describe your educational background (degree, concentration, year).

2. Describe your experience performing the virtual dissection activity. Did you run into any problems during the task? What were they?

3. Can you describe how virtual dissection compared to physical dissection? Was one easier to perform than the other? Why or why not?

4. Was it easier to more difficult to sketch the exploded view of the product after virtual dissection compared to physical dissection? Why?

5. Do you think having a collapsing animation in addition to the exploding animation would have improved virtual dissection? (or both?)

6. Did you feel that the animation of the exploded view of the product helped you understand the internals of the product? If not, what other methods of virtually dissecting a product would you rather have used (point and click, drag)?

7. Describe your overall level of engagement with the virtual dissection interface. What improvements would you recommend to make it more engaging or intuitive?