CONFIDENTLY EXPLORING THE SOLUTION SPACE: THE WITHIN-SUBJECT EFFECTS OF PRODUCT DISSECTION ON DESIGN VARIETY (DETC2018- 85875)

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ABSTRACT
Product dissection is a popular educational tool in engineering design due to its ability to help students understand a product, provide inspiration for new design ideas, and aid in product redesign. While prior research has investigated how dissecting a product before idea generation impacts the creative output of the ideation session, these studies failed to look at the types of ideas generated before dissection or how the type of product

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dissected impacts this. Thus, the goal of the current study was to examine how product dissection impacts the solution space explored by students and understand their perceptions of the utility of the dissection activity in the design process. The results of the study highlight that students explored new types of ideas during the second ideation session for all conditions and at all levels, with students having the biggest increase in variety when they dissected analogically far products. Meanwhile, the working principle variety of students was increasing most in the control condition (no dissection). By performing content analysis on students' survey responses, we found that the vast majority of students felt the dissection activity was useful due to its ability to help them better understand the functionality of the product in addition to helping them consider design improvements.

Keywords: design education, creativity and concept generation, design courses and curricula, design theory

1.0 INTRODUCTION

To train the engineers of the future, engineering education has shifted towards a curriculum that focuses on creativity training [1, 2] due in part to a push from industry for creative engineers [3]. Creative ideas, or ideas that are both novel and useful [4-8], are desired by industry because in order for innovation to occur, a creative idea must first be produced. This push for creative ideas is focused towards the early stages of the design process, since the success of a product can be linked to this stage [9, 10]. As a result of this push for creativity, engineering undergraduate curricula has focused on creativity interventions during the early stages of the design process through activities such as product dissection.

Product dissection, or the systematic disassembly and analysis of a product and all of its parts, has been widely used in engineering education as a technique for encouraging learning [11-17] and creativity [18-23] in engineering design. Specifically, research has found that product dissection can help student designers map their knowledge to real world applications [11] and assists in benchmarking [24]. In addition to the learning benefits of product dissection, research has also found that product dissection can help student designers in redesign activities [18, 25]. Because of the inherent costs associated with performing dissection in the classroom [26-29], recent research has shifted to focusing attention on the impact of virtuality on engineering learning and creativity [13-17]. This work has shown that virtual dissection is as good as, if not better than, physical dissection for learning and creativity in an engineering classroom [15, 23, 30]. While these results support the use of product dissection in engineering education, prior work in this field has focused purely on between-subjects studies where different subjects are in different conditions and therefore have failed to consider how an idea set *changes* from pre- to post-dissection, as can be done with a within-subjects study. This leaves to question *how product dissection impacts the solution space explored in an individual's idea set.*

In addition to measuring creativity outcomes, students' engagement and motivation in any educational activity are essential components to student success in engineering education[31]. One method of assessing students' satisfaction of an in-class activity is assessing their perception, or value, of the activity. Indeed, task value is related to motivation and is a predictor of successful outcomes in education [32, 33].

2.0 RELATED WORK

In order to understand how dissection impacts the types of ideas generated and creative self-efficacy, relevant literature about idea generation, incubation, and ideation metrics was investigated.

2.1 Product Dissection and Idea Generation

Idea generation is one of the initial stages in the engineering design process and has been studied across various research domains [34, 35]. Spending sufficient time in the idea generation stage is crucial to drive desired design outcomes [36, 37] and generating a large number of ideas in the ideation sessions can stimulate the generation of novel ideas [38]. Researchers have found that factors such as visualization of ideas [39, 40], the environment (i.e. temperature, location, time allocated for ideation etc.) in which the ideation sessions happen, and providing examples [41] can impact the effectiveness of ideas generated [8, 42]. Specifically, providing examples has been found to help designers explore the solution space and drive design innovation [41] by providing jumping off points for designers [43]. For instance, far-field and less-common examples have been found to promote the generation of more novel ideas [44-46]. This may be due in part to the fact that far field analogies suggest new ways to characterize problems [47], while near field analogies allow for surface level connection [46, 48]. In contrast, other researchers have found that examples might decrease the variety of ideas explored in the concept generation stage [49]. This may be connected with other work that has found that certain types of examples might cause design fixation [44] or a “blind and sometimes counter-productive adherence to a set of ideas or concepts limiting the output of conceptual design,” ([50], p.4). For instance, Viswanathan and Linsey [51] found that physical examples caused a higher magnitude of fixation than pictorial examples, but that physical examples encouraged the creation of non-redundant ideas.

Product dissection is one way in which physical examples can be presented to designers in order to influence the idea generation process. Product dissection literature highlights the crucial impact dissection has on engineering student design learning [11-17, 23, 30] and creativity [20-22, 52, 53]. Specifically prior work has investigated the impact of dissection on the novelty and quality of the ideas generated, finding that students generated more novel ideas but of lower quality when dissecting products as opposed to looking at them [19]. In terms of design variety, prior work found that dissecting different types of products allowed for the exploration of a larger solution space in design teams [54]. In addition, when compared to a control of no design examples, dissection has been shown to enable students to focus on both form and function aspects of the design [18].

Unfortunately, physical product dissection, or taking apart a product that is physically in front of you, is sometimes overlooked as a viable classroom activity due to the inherent costs associated with performing physical dissection (i.e. cost, waste, classroom availability, etc.) [26-29]. Because of this, researchers have explored virtual product dissection that utilizes 3D models and allows users to view individual parts of a product by moving individual parts, using exploded views, and using animations [27, 55]. Recent research has focused on how the benefits of dissection differ in virtual vs. physical environments [13-17, 23, 30], finding that virtual dissection is as good, if not better than physical dissection for learning and creativity [15, 23, 30]. While these results support the use of product dissection in engineering education to increase the creativity of ideas, prior studies have been between subjects studies, and have not looked at how the types of ideas an individual is producing change after being exposed to product dissection as can be done through within-subjects studies. Therefore, this research aims to understand if and how an individual's idea set changes through an investigation of the solution space that the idea set covers.

2.2 The Role of Incubation Periods in Promoting Creativity

While creativity interventions, such as product dissection, have been found to be effective in engineering design, prior research supports the use of incubation periods to promote problem solving and creativity [56]. However, a meta-analytic review by Sio and Ormerod [57] found that the effectiveness of an incubation is dependent on the length of the incubation period, problem type, and whether or not solution-related cues are provided during that period. Interestingly, providing misleading cues have been found to show positive effects of incubation periods [58]. In terms of the length of the period, some scholars have argued that longer incubation periods would allow for a spreading of activation memory and hence a larger performance improvement [59, 60].

Wisberg [61] argues that the optimal length of the incubation period is dependent on the task provided and Kaplan [62] suggests comparing the preparation period (i.e. time spent on idea generation) with the incubation period to obtain an operationalization of the lengthiness of the incubation period using a ratio of the incubation time over the preparation time. One such low-demanding and short incubation task that has been implemented in prior work is completing a personality test [63]. Therefore, this work employed a control group that attempted to compare an incubation period (completing a personality test) with the effect of a *directed* creativity intervention (product dissection).

2.3 Ideation Effectiveness Metrics and Variety

In order to determine the effectiveness of ideation interventions, such as product dissection, four metrics for determining ideation effectiveness were established by Shah, Vargas-Hernandez, and Smith [8], with variety as a metric that assesses at the idea set level [8]. Variety is defined as a measure of the amount of solution space that is explored [8, 64] or "the degree to which the concepts from a single designer were dissimilar from other concepts from that designer" ([65] p. 738). Shah, Vargas-Hernandez, and Smith [8] assert that the expansion of one's solution space is critical in the concept generation phase to explore the highest number of solutions, and hence increase the probability of finding better solutions. In engineering design education, variety and number of ideas generated in the concept generation stage were highly correlated with students' performance on the design project [66]. In fact, researchers have found that the consideration of a variety of solutions is important to provide a cognitive restructuring of the design problem [67]. As a result, the variety of the solution space is highly correlated to the novelty of the idea set [68] and the quality of the final product [69] leading to more mature solutions to the design problem [70].

When measuring variety, there are two common methodological approaches taken: subjective and genealogy tree approaches. For subjective approaches, Linsey et. al. [71] developed an approach which bins ideas based on the similarity of the ideas. The metric is calculated by two raters and is based on the number of bins hit by an individual's idea space compared to the total number of bins from all ideas from all individuals [71]. Although efficient and computationally simple, the metric is subjective and would be difficult to compare across different idea sets [64].

For genealogy tree approaches, one of the more common measures to calculate the variety of a solution space is the Shah, Vargas-Hernandez, and Smith (SVS) metric [8]. Specifically, the metric utilizes a genealogy tree to categorize an idea based on its physical principle, working principle, embodiment and detail level attributes [8]. These levels are considered hierarchical, meaning that the physical principle is at the top of the tree and the detail level is at the bottom of the tree. Therefore, the most weight is given to physical principle, and weights decreasing for each remaining level: working principle, embodiment and detail. While the SVS metrics are the gold standard, Nelson and Wilson provided valuable criticism to this metric by balancing the weighting system and eliminating "double counting" of ideas [65].

While research in design variety has looked at the addition of new ideas at any level of the variety tree (physical principle, working principle, embodiment, and detail levels), no research has investigated where these changes exist. Therefore, this research will take a deeper look at each level of variety to understand not only if the solution space is changing between pre and post dissection idea generation, but at what level this solution space is changing.

3.0 RESEARCH OBJECTIVES

Based on this prior work, the purpose of the current study was to examine how product dissection impacts the solution space explored by students and understand their perceptions of the utility of the dissection activity. These questions are of interest because both creative output and student perceptions are important outcomes for educators. Specifically, we aimed to answer the following research questions:

1. ***Does product dissection impact variety of solutions explored by students? Is this relationship affected by the type of product dissected?*** We hypothesized that the solution space explored by students would increase after a product dissection activity since prior work has found that example solutions can provide a jumping off point for designers [43]. However, we also hypothesized that the impact of product dissection would be mediated by the analogical distance of the product dissected since prior work has suggested that subjects that are exposed to far field examples can produce more novel ideas [45, 46], and novelty and variety are highly correlated [68]. In addition, it was hypothesized that students dissecting the analogically far product would expand their solution space more at the physical principle and working principle levels while those dissecting the analogically near product would expand their solution space more at the embodiment level since far field analogies suggest new ways to characterize problems [47], while near field analogies allow for surface level connection [46, 48].
2. ***Is there a difference in the impact of the variety of solutions explored between students who dissected and those in the control condition?*** *We hypothesized that*

those in the dissection condition would have higher variety in their solution space explored since previous work has found that dissection increases creativity [19].

3. ***What were student's perceptions of the usefulness of the dissection activity?***

   We hypothesized that students would perceive the dissection activity to be useful and meaningful since prior work found that product dissection helped students learn about the products' functionalities [72] *and* aided them in redesigning activities [18, 25].

4.0 METHODOLOGY

To answer these research questions, an exploratory study was conducted with 24 undergraduate engineering students. This section serves to summarize the methodological approach taken in this study.

4.1 Participants

Participants were recruited from a first-year undergraduate engineering design course at a large northeastern university. The first-year course used in the study was an introductory course that encourages hands-on engagement of first-year students through two in-depth design projects throughout the semester. In all, 55 students (37 males and 18 females) participated in the study.

4.2 Procedure

At the start of the semester, a brief overview of the study was provided to participants and implied consent was obtained (the study was approved through the Institutional Review Board). Next, participants were provided with the following design prompt that they used for their first 8-week design project in the course:

"Upper management has put your team in charge of developing a concept for a new innovative product that froths milk in a short amount of time. Frothed milk is a pourable, virtually liquid foam that tastes rich and sweet. It is an ingredient in many coffee beverages, especially espresso-based coffee drinks (Lattes, Cappuccinos, Mochas). Frothed milk is made by incorporating very small air bubbles throughout the entire body of the milk through some form of vigorous motion. The design you develop should be able to be used by the consumer with minimal instruction. It will be up to the board of directors to determine if your project will be carried on into production."

It is important to note that prior to collecting the data of interest for the current study, students participated in a series of activities including a customer needs assessment, patent search, and a literature review which focused on the chemistry of frothed milk. The students also participated in a benchmarking activity where they interacted with and tested a hand-held milk frother, a milk steamer, a manual pump frother, and a mason jar as shown in Table 1.

During week 4 of the project and as part of the current study, students participated in a 2 hour ideation and dissection session. To start this session, students were asked to complete a 3-question Creative Self Efficacy (CSE) survey (described in the Metrics Section). Next, participants were given an introduction about what creativity is and why it's important to engineering design through the video developed by The

TABLE 1: PRODUCTS BENCHMARKED BY PARTICIPANTS BEFORE THE EXPERIMENT

			
Mind Reader Hand Held Milk Frother	Mr. Coffee Steam Espresso & Cappuccino Maker	Bialetti Manual Milk Frother	Mason Jar

Pennsylvania State University School of Engineering Design Technology and Professional programs (https://www.youtube.com/watch?v=fuaaXMp35NI). Following this, students completed a 20-minute brainstorming activity for the milk frother task where they were given sheets of paper and asked to sketch out one idea per paper and write a short description such that an outsider would understand the idea on isolated inspection, see Figure 1 for example. After the 20 minutes had expired, participants were instructed to complete a second CSE survey. Next, participants were randomly assigned to either a control group where they completed the Five Factor Model personality assessment [73], or one of four dissection conditions in the 2 (*analogical distance*) × 2 (*product complexity*) factorial design experiment (see *Experimental Design for details*). Participants were separated into different rooms based on whether or not they were assigned to the control condition or the dissection condition. Participants in the dissection conditions were then

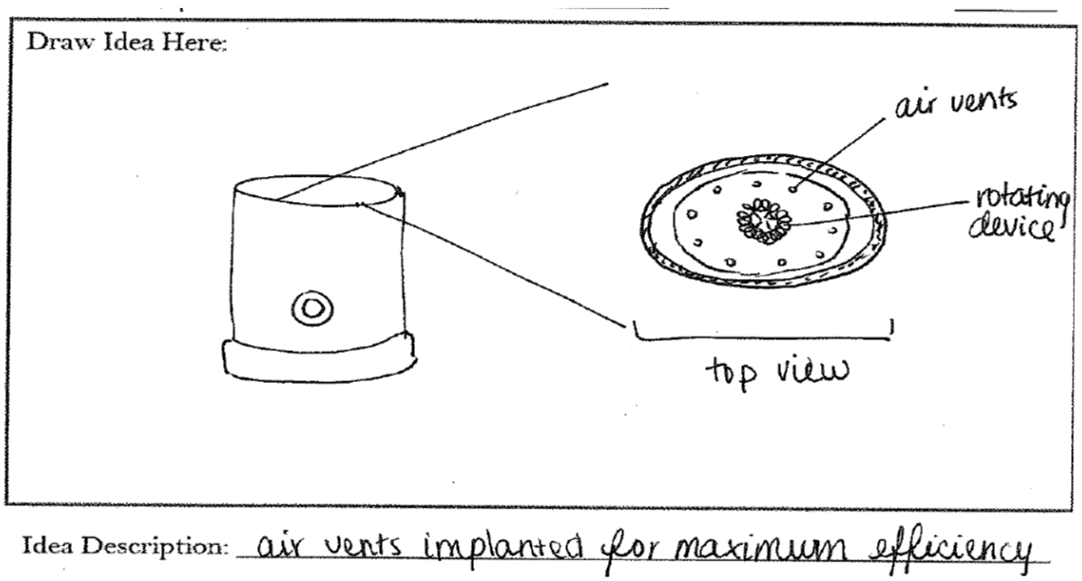


FIGURE 1: EXAMPLE IDEA GENERATED BY PARTICIPANT 23

introduced to the purpose and goals of product dissection. Specifically, participants were instructed that,

> *"Product dissection is often done in industry and academia to uncover opportunities for re-design. Designers take apart and analyze all components of a product to understand its structure and properties, and thus, find ways to improve the product. Therefore, the goal of dissection is to improve the functionality, maintainability, and reliability of a product through the examination, study, capture, and modification of existing products. During this activity, you will perform a product dissection on the provided product by taking it apart and analyzing the function of each component. Your goal is to understand strengths and weaknesses of the product in order to develop new innovative concepts that satisfy the design goal."*

Next, students were asked to complete their assigned virtual product dissection activity for 15 minutes using SolidWorks eDrawings x64 Edition version 17.3.0.0034. They were instructed to use the software to take apart their assigned product, analyze the function of each component, and complete the handout in Appendix A derived from [13]. Specifically, the handout asked students to identify the power source, primary form of motion, energy flow, and form and outer body of the product they were dissecting through both written descriptions and visual representations, and to identify any application opportunity for their milk frother design task. See Figure 2 for an example. Participants were instructed to use the full 15 minutes allotted for the dissection activity and to continue adding details to their handouts until the activity ended. While students were shown the full capabilities of eDrawings through a video developed by the research team (https://www.youtube.com/watch?v=mANf4dnBCno), they were not specifically instructed which tools to use during the dissection activity. Thus, each student used the tools they felt were most appropriate for the dissection task.

Students in the control condition were given instructions to complete the Five Factor Model personality assessment during the 15 minute break from ideation.

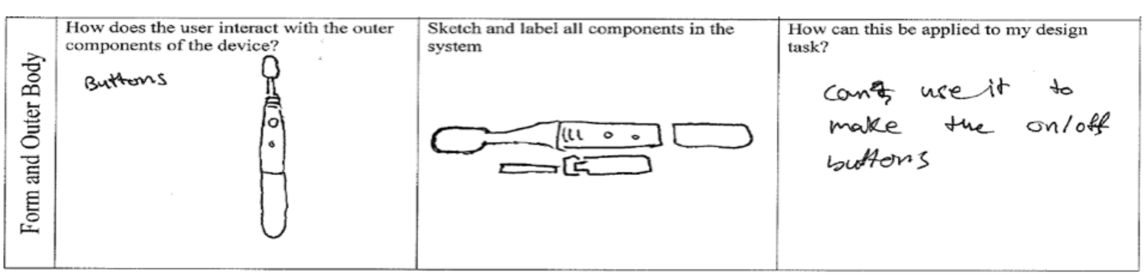


FIGURE 2: EXAMPLE FORM AND OUTER BODY RESPONSES TO DISSECTION HANDOUT BY PARTICIPANT 17

After completing the dissection or control activity, participants immediately participated in a second 20-minute brainstorming activity for the milk frother task, and then completed a third and final CSE survey. Finally, participants were instructed to answer the following survey questions: What did you like about the activity, what did you learn from the activity, what is still unclear, and was dissection useful, why or why not?

4.3 Experimental Design

In this study, students were randomly assigned to a condition where they were either asked to complete the Five Factor Model personality assessment as a control group or given one of four products to virtually dissect using SolidWorks eDrawings. The products dissected in this study were of a 2 (analogical distance) x 2 (complexity) factorial design where products ranged from analogically near to analogically far and relatively simple to relatively complex. The four products chosen for dissection were an electric toothbrush, an electric hand mixer, a correction tape dispenser, and a nerf gun. Table 2 shows where each of the products fell in the analogical distance and complexity measures (see [15] for a full description on how the products were chosen for these conditions).

In addition to the 2x2 factorial design for dissected products, a control group was introduced to understand the difference between dissection and no dissection. The control group completed the Five Factor Model personality assessment following similar studies that have used personality tests as a control condition in creativity studies [63]. This personality test was conducted in the same 15 minutes that were used for dissection.

In order to investigate how product dissection impacts the solution space explored by students and their confidence in their creative abilities, several metrics were used.

TABLE 2: PRODUCTS DISSECTED IN THE EXPERIMENTAL STUDY

		Analogical Distance	
		Near	Far
Complexity	Simple	Oral-B 3D white power Toothbrush (battery operated)  # parts – 16	Tombow Mono Correction Tape hybrid style  # parts - 9
	Complex	Proctor Silex Mixer (Model: 62509RY)  # parts – 43	Sharp Shot Nerf Gun (Model: 38123)  # parts – 31

There were 2 within subject factors that were investigated in this study: variety (at multiple levels) and Creative Self-Efficacy (CSE). Variety scores were taken after the first idea generation and after the second idea generation. CSE scores were taken at the beginning of the study, after the first idea generation, and after the second idea generation. This section provides detailed definitions and calculations for these metrics.

This section provides detailed definitions and calculations for these metrics.

Overall Variety: In order to understand the diversity of the solution space explored by participants, [8, 59], the idea set developed by each participant was measured using Nelson and Wilson's variety metric [60]. This approach uses weights 10, 5, 2, and 1 for physical principle, working principle, embodiment, and detail respectively. While these levels are not explicitly defined in this prior work, we define them for our design prompt as follows:

Physical Principle: the form of motion that creates the frothing (spinning, shaking, whisking, steaming, chemical reaction etc.);

Working Principle: the energy source that is used to create the frothing (batteries, AC wall power, human powered, etc.), and;

Embodiment: the physical representation of the idea (handheld like Mind Reader milk frother, looks like a blender, etc.). It should be noted that the ideas developed for the current study did not have enough details to produce a detail level measure, and therefore the detail level was not included in our variety tree, per recommendations of Shah, Vargas-Hernandez and Smith [8]. In addition, since all ideas were sketched, per the instructions of the brainstorming activity, there was an embodiment for every idea developed.

Using these categorizations, the variety metric was calculated as follows. In order to avoid double counting ideas, Nelson et. al.'s approach counts the number of differentiations in principles utilized rather than merely the branches [60]. These two changes to the Shah, Vargas-Hernandez and Smith metrics provide a variety score that is a better representation of the actual solution space that is explored, and therefore, this study utilizes Nelson et. al.'s [60] metric which is summarized in the below equation:

$$V = S_1(b_1 - 1) + \sum_{k=2}^{4} \left(S_k \sum_{l=1}^{b_{k-1}} d_l\right) \qquad (1)$$

where V is the variety score, S_k is the weight for level k, b_k is the number of branches for level k, and d_l indicates the number of differentiations, d, at a node l [60].

Physical Principle Variety: this metric was developed in order to determine how much participants expanded the solution space of their ideas at the physical principle level and was calculated using the above equation, assuming 0's at the working principle and embodiment levels.

Working Principle Variety: this metric was developed in order to determine how much participants expanded the solution space of their ideas at the working principle level and was calculated using the above equation, assuming 0's at the physical principle and embodiment levels.

Embodiment Variety: this metric was developed in order to determine how much participants expanded the solution space of their ideas at embodiment level and was calculated using the above equation, assuming 0's at the physical principle and working principle levels.

Content Analysis:

Students' qualitative responses on the open ended question "was dissection useful? Why or why not?" were analyzed using inductive content analysis [74]. Specifically, two researchers rated 68% overall of the qualitative data using Nvivo 12 Pro.

For the first part of the question, "Was dissection useful", the data was coded into the following nodes: *Yes and no*. For the second part of the question, "Why or why not?" the data was coded into the following nodes: "functionality", "idea generation", "software". "Functionality" is broken down into *inner parts*, *how parts fit together*, and *how the product functions*. Meanwhile, *idea generation was* broken down to *design improvements* and *didn't help generate ideas*. Software was not broken down any further. Coding the data in the nodes, or sub nodes, indicated what aspect of dissection the participants perceived to be useful.

5.0 Data Analysis and Results

During the study, participants developed an average of 7.24 (3.27) ideas in the first ideation session and an average of 4.46 (± 2.60) in the second ideation session, and an average total 11.7 (±5.30) ideas. The remainder of this section highlights the results with reference to our research questions. The data was analyzed using SPSS version 25 with a significance level of 0.05.

RQ1: Does product dissection impact variety of solutions explored by students? Is this relationship affected by the type of product dissected?

In order to test the first part of our hypothesis, a three-way Between, Between, Within (BBW) mixed Analysis of Variance (ANOVA) was computed with overall variety as the dependent variable, complexity and analogical distance as the between-subjects factors and pre- and post- dissection as the within-subjects factor. Prior to analysis, assumptions were checked. Since several outliers existed in the data, analysis was run both with and without the outliers. No differences were found in the outcomes of the analysis, thus the full results are reported here. Normality of overall variety was violated for the total overall variety scores ($p > 0.05$*) and the overall variety before the dissection activity (p > 0.05)* [75]. Since this test is robust to variations in normality, no transformations were made. Finally, Levine's Test for Equality of Variances revealed that the assumption of homogeneity of variances was met for overall variety scores. Thus, the analysis proceeded.

The results revealed a statistically significant main effect of **time for overall variety,** $F(1,35) = 94.165$, $p < 0.001$, $\eta = 0.729$. In total, participants had an overall mean variety score after the dissection of 53.36 ± 24.42, compared to an overall mean variety of 28.72 ± 14.418 before the dissection activity. These results indicate that individuals are able to come up with new ideas after their dissection regardless of which product they dissect. This confirms our hypothesis that students would develop ideas that expand their solution space in the ideation session after dissection. However, these results failed to identify any additional significant main effects or two- or three-way interactions effects ($p > 0.05$). This refutes our hypothesis that students would be able to expand their overall solution set more in the analogically far condition than those in the analogically near condition. These results are important because they indicate that students are able to come up with ideas that expand upon their original solution space during their second idea generation session, regardless of product dissected. This leads us to the next part of our research question, of which level is being impacted by these changes in solution space.

In order to test the second part of our hypothesis , 3 three-way BBW mixed ANOVAs were conducted to understand how variety was changed at each of the three levels investigated: physical, working and embodiment. Thus, the dependent variables of the analysis were physical principle variety, working principle variety, and embodiment variety respectively while the within subject factor were pre- and post- dissection and the between subject factors were complexity and analogical distance.

Prior to these analyses, the necessary assumptions were checked. Specifically analysis of box-and-whisker plots revealed that participants Billy and were outliers for physical principle and working principle levels [76]. There were no outliers at the embodiment level. Due to this analysis, our BBW ANOVAs were conducted both with and without the outliers to determine their impact on the results. Since there was no impact on the significance of results, analyses are presented with the full data set, including the outliers. Normality was violated for the variety scores at the physical principle, working principle and embodiment levels. ($p < 0.05$), as assessed using the Shapiro-Wilk test [75]. Since this test is robust to variations in normality, no transformations were made. Finally, Levine's Test for Equality of Variances revealed that the assumption of homogeneity of variances was met for variety scores at the physical principle, working principle and embodiment levels. Thus, the analysis proceeded.

The results of the first BBW ANOVA suggested a statistically significant main effect of product dissection of **physical principle variety** $F(1,35) = 38.010, p < .0001, \eta = 0.521$. The results indicate that student designers are coming up with new ways to froth milk at the physical principle level (e.g. shaking, stirring, steam) independent of the product that they dissect. There were no significant two-way or three-way interactions.

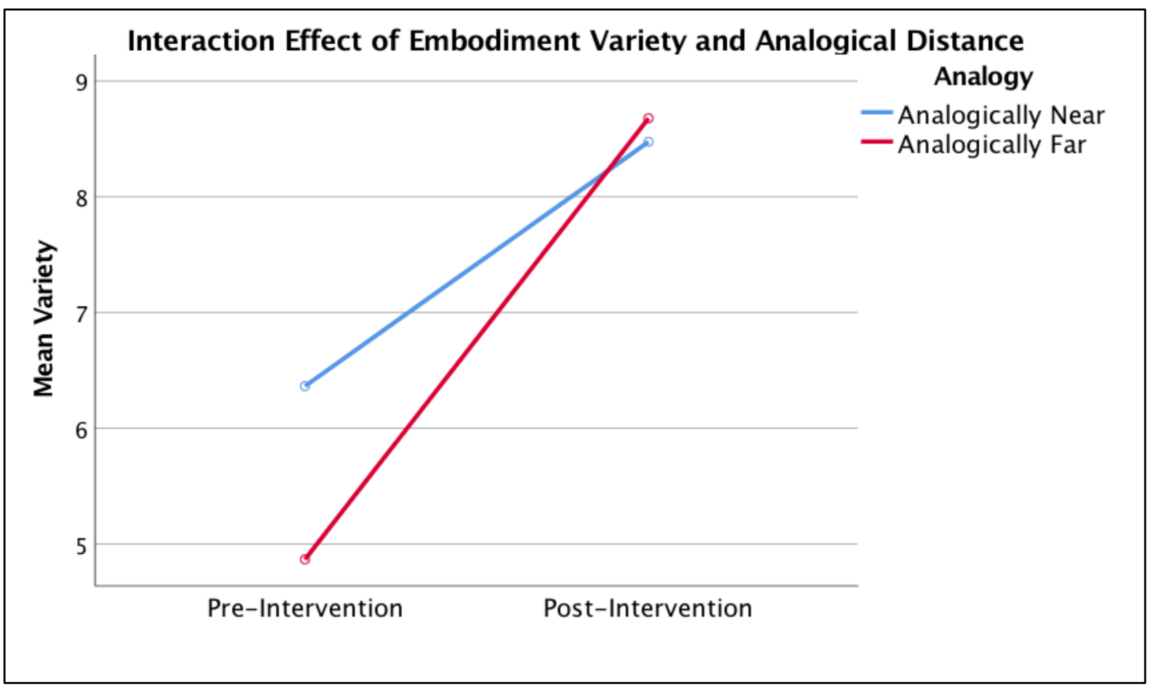
The results of the second BBW ANOVA also suggested a statistically significant main effect of product dissection on **working principle variety** $F(1,35) = 30.893, p < .0001, \eta = 0.469$, indicating that student designers are coming up with new ways to froth milk at the working principle level (e.g. power source) independent of the product that they dissect. There were no significant two-way or three-way interactions.

The results of the third BBW ANOVA analysis suggested a statistically significant main effect of dissection on **embodiment variety** $F(1,35) = 53.175, p < 0.001, \eta = 0.603$. More so, there was a statistically significant two-way interaction of **embodiment variety** and **analogical distance** of the product dissected, $F(1,35) = 4.382$, $p = 0.044, \eta = 0.111$. No other two-way or three-way interactions were found to be statistically significant ($p > 0.05$).

Therefore, pairwise comparisons were run where reported 95% confidence intervals and p-values are Bonferroni-adjusted. In the analogically far condition, participants in the second ideation session were associated with a mean variety score 3.81, 95% CI (2.633,4.990), p < 0.001, higher than the first ideation session. In the analogically near condition, participants in the second ideation session were associated with a mean variety score 2.1, 95% CI (0.958, 3.264), p < 0.001, higher than participants in the analogically near condition for the first ideation. However, pairwise comparisons have failed to show any significant differences between the overall and total variety of those in the analogically far and near conditions, $p > 0.05$. These results indicate that participants who dissected analogically far products had a higher change in their embodiment level variety after intervention than those who dissected analogically near products, as can be seen in figure 3 below.

These results indicate that student designers have explored the solution space more at the embodiment level (e.g. handheld, stand on table, like blender) after dissection and that the analogical distance of the product dissected is impacting the variety.

FIGURE 3. INTERACTION EFFECT OF EMBODIMENT VARIETY AND ANALOGICAL DISTANCE SHOWING THAT STUDENTS IN THE ANALOGICALLY FAR CONDITION WERE ABLE TO SHOW HIGHER INCREASES IN DESIGN VARIETY THAN STUDENTS IN THE ANALOGICALLY NEAR CONDITION



RQ2: Is there a difference in the impact of the variety of solutions explored between students who dissected and those in the control condition?

Our second research question sought to understand if the variety of solutions explored by students changed based on whether or not students dissected a product or were in the control condition (personality test). In order to answer this research question 4 mixed design ANOVAs were conducted with overall, physical principle, working principle, and embodiment level variety as the dependent variables and with dissection condition (4 different dissection conditions or the control group) as the independent between subjects variable, and pre- and post- intervention as the within-subjects repeated measures variable. The four dissection conditions are as follows: Nerf Gun (Complex and Analogically Far), Mixer (Complex and Analogically Near), Tape Dispenser (Simple and Analogically Far), and Toothbrush (Simple and Analogically Near). Before analysis, all assumptions were checked. Since several outliers existed in the data, analysis was run both with and without the outliers. No differences were found in the outcomes of the analysis, thus the full results are reported here. Normality was violated for the variety scores at the physical principle, working principle and embodiment levels. ($p < 0.05$), as assessed using the Shapiro-Wilk test [75]. Since this test is robust to variations in normality, no transformations were made. Finally, Levine's Test for Equality of Variances revealed that the assumption of homogeneity of variances was met for variety scores at the physical principle, working principle and embodiment levels. Thus, the analysis proceeded.

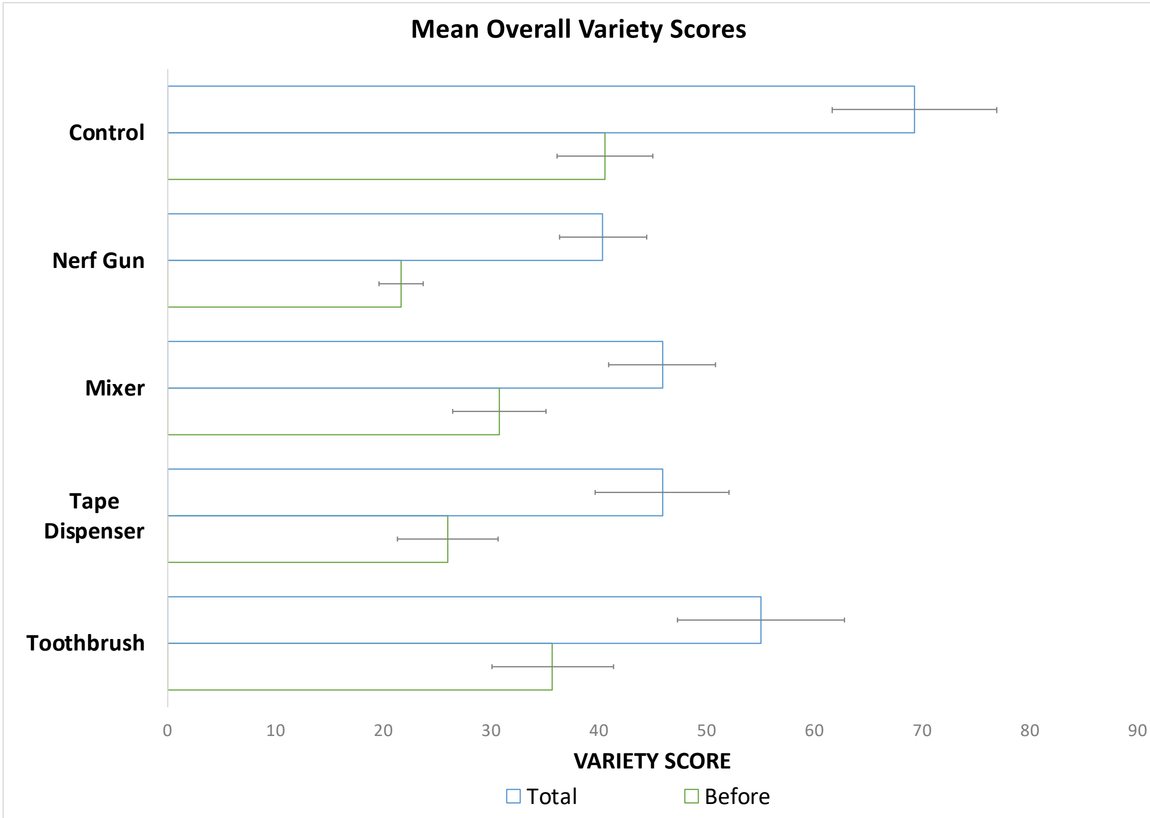


FIGURE 4. MEAN OVERALL VARIETY SCORES ACROSS THE DISSECTION CONDITIONS AND CONTROL GROUP (ERROR BARS REPRESENT ± STANDARD ERROR)

The results revealed that there was a statistically significant difference between pre- and post-intervention variety regardless of condition, including the control condition $F(1, 49) = 112.34$, $p< 0.001$, $\eta = 0.849$. Specifically, variety was higher post-intervention (53.26, SD 24.41) than pre-intervention (32.02, SD 16.04), see figure 4. In addition, there was a significant difference between types of dissection, with those in the control condition having significantly higher variety than those in the complex and analogically far condition. While there was a main effect for both dissection condition and time of variety measure, there was no significant interaction between the two, indicating that there was no difference in the increase in variety between those who dissected and those in the control group. This refutes our hypothesis that students who dissected a product would have higher gains in variety from first to second ideation session. This leads us to the next part of our research question, of which level is being impacted by these changes in solution space.

The results of the second ANOVA for physical principle revealed that there was a statistically significant difference between pre- and post-intervention variety regardless of condition, including the control condition $F(1, 49) = 56.07$, $p < 0.001$, $\eta = 0.534$. Specifically, variety was higher for post-intervention ideation (31.20, SD 16.14) than pre-intervention (19.07, SD 12.78), see figure 5. There was no significant interaction between

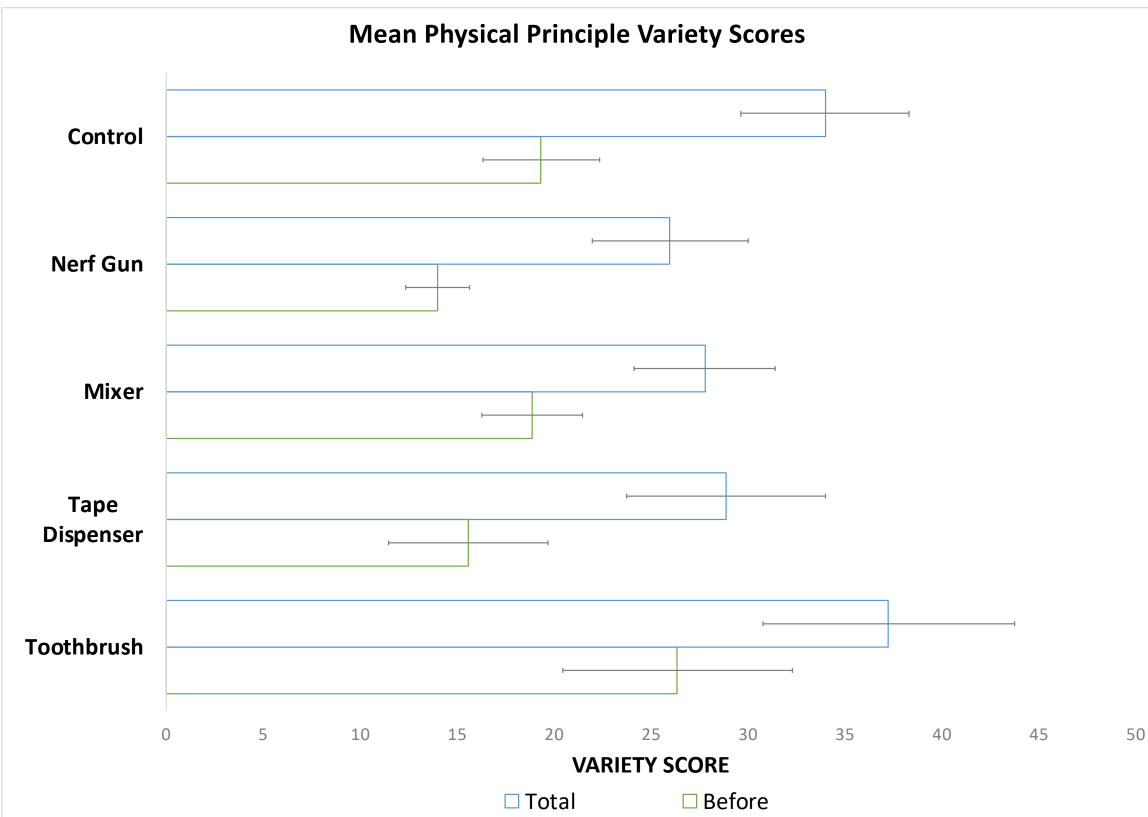


FIGURE 5. MEAN PHYSICAL PRINCIPLE VARIETY SCORES ACROSS THE DISSECTION CONDITIONS AND CONTROL GROUP (ERROR BARS REPRESENT ± STANDARD ERROR)

the two, indicating that there was no difference in the increase in variety between those who dissected and those in the control group. This refutes our hypothesis that there would be differences in physical principle variety based on the product that was dissected.

The results of the third ANOVA for working principle revealed that there was a statistically significant interaction between time of working principle variety and dissection condition $F(4, 49) = 5.116$, $p = 0.002$, $\eta = 0.295$. There was a statistically significant difference in working principle variety for pre-intervention ideation $F(4, 49) = 8.342$, $p < 0.001$, $\eta = 0.405$. Working principle variety was statistically significantly greater in the control condition than in any of the dissection conditions ($ps < 0.007$). There was no statistically significant difference between any of the other conditions see figure XXX. There was also a statistically significant difference in working principle variety after second ideation $F(4, 49) = 11.014$, $p < 0.001$, $\eta = 0.473$. Working principle variety was statistically significantly greater in the control condition than in any of the dissection conditions ($ps < 0.007$). There was no statistically significant difference between any of the other conditions, see figure 6. Lastly, there was a statistically significant effect of time on working principle variety for participants in dissection group 2 $F(1,8) = 7.200$, $p = 0.028$, $\eta = 0.474$, dissection group 3 $F(1, 9) = 15.783$, $p = 0.003$, $\eta = 0.637$, and the control group $F(4, 49) = 30.617$, $p < 0.001$, $\eta = 0.686$. These results reveal that there was a much greater gain in working principle variety for the control group than for the dissection groups indicating that those who are dissecting products might be fixating.

FIGURE 6. MEAN WORKING PRINCIPLE VARIETY SCORES ACROSS THE DISSECTION CONDITIONS AND CONTROL GROUP (ERROR BARS REPRESENT ± STANDARD ERROR)

The results of the forth ANOVA for embodiment level variety revealed that there was a statistically significant difference between pre- and post-intervention variety regardless of condition, including the control condition $F(1, 49) = 47.443$, $p < 0.001$, $\eta = 0.492$. Specifically, variety was higher for post-intervention ideation (10.59, SD 7.337) than for the pre-intervention ideation (6.85, SD 4.389), see figure 7. In addition, there was a significant difference between types of dissection, with those in the control condition having significantly higher variety than those in the complex and analogically far condition. While there was a main effect for both dissection condition and time of

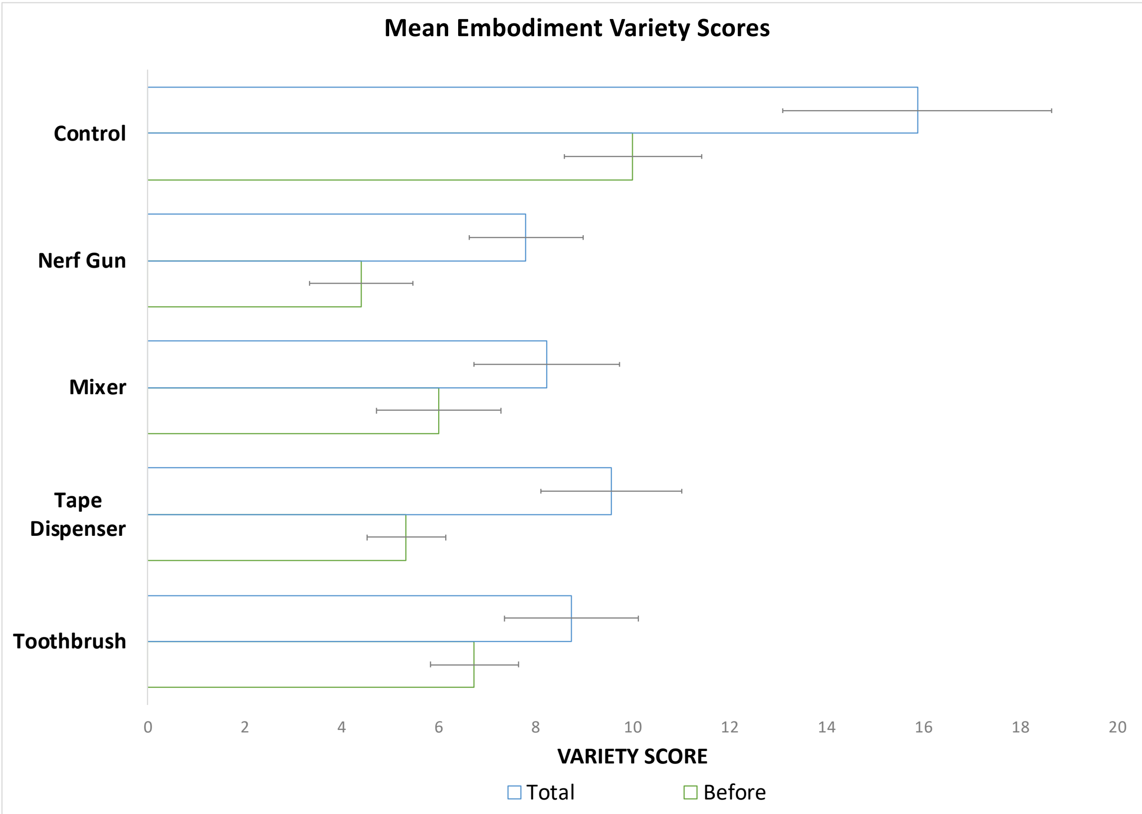


FIGURE 7. MEAN EMBODIMENT VARIETY SCORES ACROSS THE DISSECTION CONDITIONS AND CONTROL GROUP (ERROR BARS REPRESENT ± STANDARD ERROR)

embodiment level variety, There was no significant interaction between the two, indicating that there was no difference in the increase in embodiment level variety between those who dissected and those in the control group. This refutes our hypothesis that there would be differences in embodiment level variety based on the product that was dissected.

RQ3: What were student's perceptions of the usefulness of the dissection activity?

Our last research question sought to understand student perceptions of the dissection activity. Specifically, we aimed to understand if students recognized the value in the dissection activity through content analysis of the open ended question "was

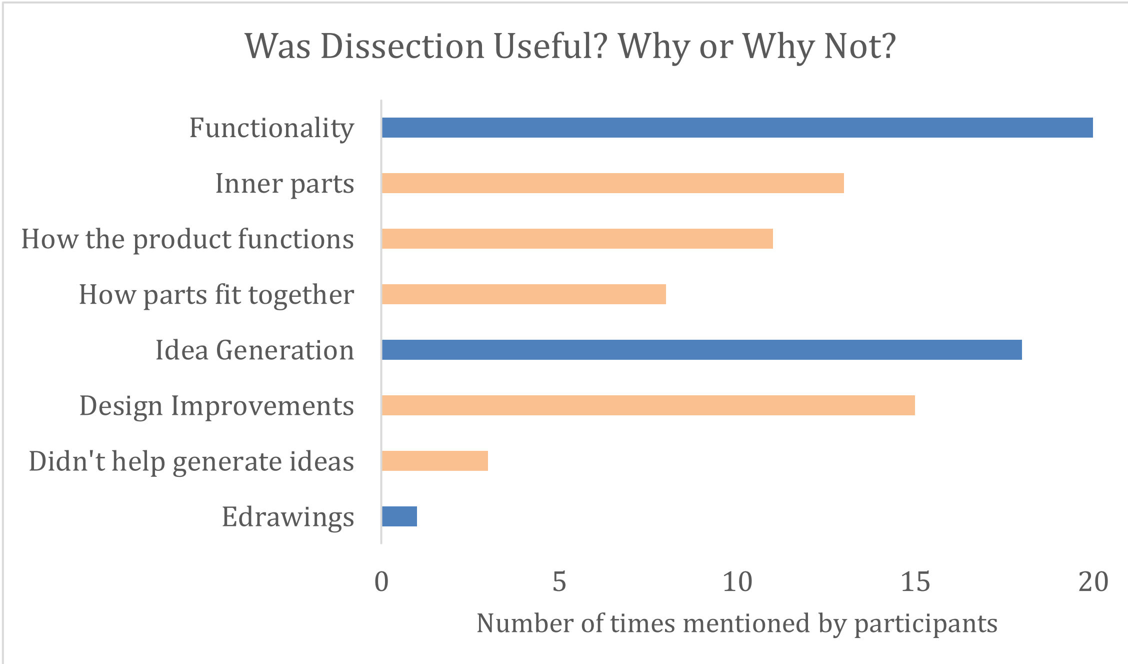


FIGURE 7. DETAILED CONTENT ANALYSIS RESULTS TO STUDENT RESPONSES

dissection useful? Why or why not?" that students answered at the end of the dissection activity. The two raters were found to be high in inter-rater reliability [77] (Cohen's Kappa=0.86), as assessed by rating 68% overlap of the data. There were 37 students who completed the open ended survey out of the 39 who completed the dissection activity (excluding those in the control group)

Through this content analysis, there was an overwhelmingly positive response to the question with 36 students saying that they thought dissection was useful. Further analysis of these questions revealed that 20 students discussed functionality and 18 students discussed idea generation. Of the students that discussed functionality, they talked about seeing how functionality through the inner parts (13), how parts fit together (8) and how the product functions (11). For example, participant 19 mentioned, "I was able to see products and how all the components fit in the product". Similarly, participant

6 quoted ”I got to see how things are put together instead of just looking at the outside”. For idea generation, students focused on design improvements (18), while 3 students felt that the dissection did not help them generate ideas. For instance, participant 21 mentioned “I was focused on different aspects of a design”. In contrast, some participants did not feel the activity allowed them to generate more ideas, as participant 24 quoted, “I didn’t really come up many new ideas after that”.

6.0 DISCUSSION

- Students explored new types of ideas during the second ideation session for all conditions and at all levels
- There was an interaction effect for time and analogical distance at the embodiment level with students having the biggest increase in variety when they dissected analogically far products
- There was an interaction effect for time and condition at the working principle level, with variety increasing most in the control condition.
- The vast majority of students felt the dissection activity was useful due to its ability to help them better understand the functionality of the product in addition to helping them consider design improvements.

The results in reference to their implications for engineering education are detailed in the following section.

The goal of the current study was to examine how product dissection impacts the solution space explored by students and understand their perceptions of the utility of the dissection activity in the design process. Our results showed that students explored more of the design solution space for overall variety and also at each level: the physical principle, working principle, and embodiment levels for all 4 of the dissection conditions. This is important because student designers were not just making superficial changes in their designs, but they are coming up with ideas that used new forms of motion to froth milk, new methods of powering their frothers, and new physical representations of their frothers.

In addition, there was an interaction between analogical distance and time with students having higher gains in variety over time when they dissected analogically far products. This indicated that student designers have explored the solution space more at the embodiment level (e.g. handheld, stand on table, like blender) after dissection and that the analogical distance of the product dissected is impacting the variety. Dissecting analogically far products might have given the students more room for transfer of ideas as interacting with analogically far examples can enable different characterizations of a problem [47]. It is confirms recent work by Starkey et. al. that found that dissecting analogically far products has shown greater increases in creative self-efficacy, or one's belief in their creative ability, which been related to creative success in the psychology literature [78, 79]. Therefore, design educators are encouraged to provide analogically far products to students in product dissection activities to allow students to increase their exploration of the solution space and hence generate more mature solutions to the design problem [70].

When compared to the control group, there was a main effect of time for overall variety, physical principle variety, and emboiment level variety. In addition, the control group had much higher variety than the other groups during ideation session 1, before the intervention, as well as in ideation session 2 after the intervention. Since there was not an interaction effect, the increases in the solution space explored in the control condition and in the dissection condition are of similar magnitude, even though there is a large difference in the starting point. We expected to see greater gains in variety from those who dissected products, since prior work has indicated that those who dissect produce more creative ideas [19]. We did not see these gains, refuting our hypothesis. These results are in line with previous research that has found that incubation periods can provide positive effects [58, 63],

While incubation may be allowing individuals to expand their solution space, since the control group had such a high starting variety, their gains may be due to individual differences, where those in the control group had more potential to develop a higher variety of ideas. Another potential cause for both of these groups to have increases in variety is that students may be looking at different types of solutions, but with similar breadth through. While not studied in the context of this paper, projects are typically done in a team setting, and therefore this difference in breadth may show up when students dissect different products, as prior work found that dissecting a variety of products helped design teams explore a wider solution space [54].

At the working principle level, an interaction effect was found between time and dissection condition when including the control group. The results showed that there was only a gain in variety over time for those dissecting the xx and the xx and those in the control condition, with the control condition having a much larger increase than the others. This finding indicates that students may be fixating on the power source after dissection of all products, and even more so for the simple products.

While the results from our first 2 research questions showed that the variety of solutions explored after dissection and incubation both increased, and in some cases variety increased more with incubation, the results of our last research question support the use of product dissection as a way to stimulate ideation. The results showed that 36 out of the 37 responders found that dissection was useful, with 15 participants indicating that it helped them with idea generation and 20 students indicating that it helped them with understanding the functionality of the product. Specifically Participant 20 said "it helped me diversify my ideas" and Participant 44 said "it gave me an idea including springs. While these participants focused solely on idea generation, others focused on both idea generation and functionality. For instance, Participant 3 who said dissection was useful "to see how other designs utilized common components most effectively", and Participant 7 said "it helped me understand how to make the battery powered components/how to incorporate them into the design". These participants clearly saw the potential in the product dissection for incorporating into their design, and generally for understanding how a product works. While product functionality was not always directly connected to the idea generation process, it was often implied from the students' responses.

7.0 CONCLUSIONS AND FUTURE WORK

The results of this study indicate that when students dissect a product they may not come up with more breadth in their idea set, but they are seeing the value of dissection as it applies to idea generation. While students see the value in dissection, they may be fixating on power sources when they dissect a product, as compared to the control group. While the results of this study support the use of product dissection for improving both surface and deep level design exploration in engineering education, it does have some limitations. First, our control condition had a much higher starting point than all of the dissection conditions for their variety of ideas. Due to these differences in starting points, there could be an effect of individual differences that is impacting gains after dissection and after incubation. Future work should include a larger sample size in order to mitigate these individual differences. In addition, we do not know how or if students are exploring different solution spaces based on their dissection condition. Future work should investigate how these solution spaces overlap in the different conditions to get a more clear picture of how dissection impacts ideation as compared to a control/incubation group.

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Figure Captions List

Table Captions List