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EXPLORING THE UTILITY OF PRODUCT DISSECTION FOR EARLY-PHASE IDEA GENERATION

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ABSTRACT

Product dissection is a tool widely used in industry and academia as a means to understand components of existing products and identify opportunities for design. Dissection activities have the potential to impact design creativity because dissection is performed in the early phases of design, which is arguably the most influential phase of the design process. However, researchers have only just begun to explore the relationship between dissection and creativity, and thus little research to date has identified how variations in dissection activities impact creativity. Therefore, in this paper we respond to this research gap by presenting the results of a controlled experiment developed to understand how the type and number of products dissected and the structure and medium of the dissection task (electronic versus physical) impacts creativity. Our quantitative findings (from ANOVAs) are paired with qualitative analysis (interview results) to provide rationale for our results and insights into their cognitive underpinnings. The results from this study indicate that the structure of the dissection activity, the medium of dissection, and the number of products dissected impacts the variety of the generated concepts while the analogical distance and number of products impacts design novelty. These findings are used to develop recommendations for the alteration of dissection methods for inspiring creative thought in engineering design.

Keywords: design creativity; product dissection; variations in dissection activities; virtual dissection.

INTRODUCTION

In the words of Pablo Picasso, "The urge to destroy is also a creative urge" [1]. Undeniably, it is in the nature of engineers to take apart artifacts in order to satisfy their inherent curiosity of the world. Discovering the inner workings of products can serve to teach and inspire, and engineers often practice this "dissection" in order to gain design insights and identify opportunities for redesign [2]. In fact, product dissection is widely practiced throughout industry and academia as a way to understand core concepts, and gain insights into competitors' practices before conceptual design begins. Although product dissection is widely used, there are many variations of dissection activities used. However, little is known about the utility of these variations for encouraging creativity. This is problematic because without this knowledge we do not know if product dissection promotes or inhibits creativity in the conceptual stages of design, or which implementation methods are best used for these purposes. Thus, it is unclear how or when to effectively implement product dissection activities in order to encourage creative thinking. This is an important area of research because dissection occurs in the early stages of design and thus has the potential to significant impact design outcomes [3].

Recently, researchers have started to explore the impact of product dissection on engineering creativity. For example, studies have shown that individuals who perform dissection in a team setting are more novel and produce more ideas than those that do not perform dissection [2, 4]. While these studies identify the potential for dissection to encourage creative thought, the findings are limited in their generalizability for engineering practice. For example, most research in this space has studied the impact of dissecting a single product, when it is standard practice to dissect and benchmark *multiple* products in the early phases of design in order to understand the broad solution space. In addition, existing studies on dissection are often conducted in a team environment, which limits our understanding of the impact of dissection at the individual level. Finally, while factors such as the structure of the dissection activity (visual vs. non-visual) varies greatly in engineering practice, no research to date has studied how variations in these practices impact creativity. This is problematic because without this knowledge the exact impact of these product dissection variations on creativity is unknown. This is particularly important to study because the literature has shown that the type of example used in the early phases of design can have a large influence on the quality and originality of the design solution [5]. Thus, the effects of different forms of product dissection activities need to be researched in order to develop recommendations for improving the utility of dissection activities for inspiring creative thought.

The current study was developed to respond to these research gaps and examine the effect of variations in product dissection activities on engineering creativity. The results from this study add to our understanding of design creativity and direct researchers in this field to focus on understanding modifications of existing design practices for enhancing the design process.

Product Dissection: Physical and Virtual

Product dissection is a tool frequently used in engineering industry and academia as a method to systematically uncover opportunities for product improvement prior to concept generation [7]. Dissection involves taking apart and analyzing all components and subcomponents of a system or product in order to study, capture, and modify the existing components. In both engineering education and industry, product dissection allows individuals to understand core concepts, benchmark products, and gain insights into competitor's practices [6]. Due to the nature of product dissection, it is often performed at the early stages of the design and thus has the potential to greatly influence the subsequent stages of the process, and ultimately, the design outcomes.

In order to examine product dissection's role in the design process, researchers have started to explore its impact on inspiring creativity during ideation. Recent research has linked product dissection with aspects of creativity, showing that students that perform 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 [2]. Other studies have also found a relationship between involvement in team-based product dissection activities and the novelty of the generated designs [4]. While these studies demonstrate a connection between product dissection activities and creative outcomes, they did not consider other aspects of creativity, such as variety, quality, and quantity. Nevertheless, these studies suggest that product dissection encourages a deeper understanding of the product and exploration of the design space. These benefits are illustrated by product dissection's ability to combine the benefits of hands-on activities [7] with a greater ability to apply knowledge to the existing problem [8]. These factors direct researchers in this area to focus on identifying the factors of product dissection that impact ideation as well as to develop methods to increase the effectiveness of product dissection activities.

Although dissection has proven to be a useful component of the design process, one of the main issues with implementing dissection is the cost involved, namely the cost of the materials, space requirements, preparation and instructional materials, and costs of products [9]. There is also an inherent cost associated with the amount of time and effort it takes a designer to perform physical dissection. Because of these factors, researchers have begun to uncover alternate forms of dissection such as virtual, or electronic, dissection.

In virtual dissection, designers access 3D models of products stored in online databases and perform dissection virtually without having to purchase and dissect the product physically. Using this technique, designers are able to perform a dissection on the 3D model of the product by viewing animations of an exploded view of the model that can be rotated and manipulated in the interface [9-12]. The advantages of this method are many, but the most compelling of them is the sustainability of dissecting products virtually. In addition, virtual dissection indirectly expedites the dissection process by reducing the time and effort required to dissect complex and challenging products physically. This may be an added benefit of virtual dissection since research regarding the role of the Sunk Cost Effect suggests that reduced effort and time invested into performing a design activity could reduce a designer's fixation on the existing design solutions during idea generation [13]. Since design fixation has been shown to be a barrier to design creativity [5, 14], the reduced effort and time invested in the dissection process may serve to increase the creativity of design outcomes. However, no study to date has explored differences between virtual and physical dissection practices and their impact on design creativity. Therefore, this study seeks to respond to this research gap by examining physical and virtual dissection in a controlled setting.

Variations in Product Dissection Activities

In addition to exploring the effects of virtual and physical dissection, it is also important to study the impact of variations in product dissection activities since a large variety of methods are used in industrial and academic practices. These methods can vary based on the type of product dissected, the number of products dissected and the structure of the post-dissection task. However, little research to date has focused on how variations in dissection activities influence the utility of dissection during the design process and specifically how these variations impact design creativity. Thus, the current study was developed to respond to this research void.

One of the largest variations in dissection activities is the type of product selected for dissection. Because designers utilize dissection in part to provide benchmarks of competing products [6], designers often dissect products in the domain for which they are designing. However, because new ideas are often recombination's or reconfigurations of previous ideas, designers may select to dissect products outside of the domain for which they are designing in an effort to gain inspiration for new ideas [2]. Because research in the area design fixation suggests a relationship between the type of product (example) the designer is exposed to, and the amount of features reused from the original design [5, 15], it is important that the type of product dissected be explored for its impact on design creativity. In particular, research has suggested that using analogous products may serve to increase creativity in design.

Analogical reasoning in engineering design involves comparing two products that share core working principles or structures, but differ based on surface-level attributes. During analogical reasoning, the individual first *encodes* the source information and relevant attributes of the source in working memory [16, 17]. When a new problem is encountered, the individual searches for and retrieves the appropriate source analog from memory with the help of specific retrieval cues, through the process of *inference.* This process of retrieving relevant information in order to solve a new design problem has been considered to be the most challenging aspect of designing by analogy [18, 19]. In analogical reasoning, the source and target are termed "analogically far" if they share little superficial similarities, but rather share deeper structures and working principles, and are termed "analogically near" if they share more superficial similarities [20]. Thus, the analogical distance between two products can be defined as the extent to which the source and target share surface similarities or belong to similar domains of knowledge [20, 21].

This discussion on analogical reasoning is highly relevant in product dissection because the top-down approach of dissection has the potential to facilitate the analogical transfer of underlying concepts and structures of surface-dissimilar products. However, the success of analogical examples in stimulating creative thought is largely dependent on the background and expertise of the designer [22] and thus, novice designers may not find this approach as useful as more experienced designers. However, the literature lacks information on how the analogical distance of products selected for dissection can impact the creativity of design outcomes. Therefore the current study seeks to understand how dissecting analogous products influences design creativity,

In addition to the type of product dissected, the number of products dissected may also influence creativity. However, research on design cognition has been largely focused on the impact of isolated examples on design creativity (e.g., analogous product [23]), reducing the practicality and realistic implications of these results. This is important because engineers typically dissect multiple products in the early stages of design in order to obtain a clearer picture of the solution space and provide benchmarks of competing products [6]. Research in the cognitive science literature seems to refute these findings by showing that the more examples individuals received the more they conformed (less creative) to the examples presented [24]. However, this study did not consider the number of examples in a product dissection task, reducing its generalizability to engineering design. Therefore, additional research is needed that explores the number of products used in a dissection task to understand the relationship between these variables.

Finally, the structure of the post-dissection activity also has the potential to significantly impact creativity due to the widely employed post-dissection activities often utilized in industry. These activities range from non-visual to highly visual in nature. Non-visual tasks include activities such as the completion of a Bill of Materials (BoM) [7] and benchmarking [25], while visual tasks include activities like fishbone diagrams [26] and exploded views [7]. Although these variations may impact the creative process, most research on dissection and creativity have focused on non-visual post-dissection activities such as the completion of a BoM [4, 28], which limits our understanding of the impact of these activities on creativity. This is problematic because research has identified visualization as an important element of cognition. In particular, prior research on visual representation has shown that highly visual design activities tend to focus the designer on the details of the product, reducing the scope of the solution space explored and thus, reducing design creativity in the conceptual design stage. [27].

Therefore, the current study was developed to understand the impact of variations of dissection activities in engineering design by conducting a controlled laboratory study. Our work fills the research voids identified in this literature by identifying the utility of commonly used variations of dissection activities and develops recommendations for alterations of dissection practices.

Research Objectives

The goal of product dissection, much like other design practices in engineering design, is to aid the designer in solving the design problem and to improve design outcomes. Therefore, factors that affect design creativity in product dissection need to be identified in order to understand how product dissection can be altered to improve design creativity. In order to investigate these factors, several research questions were posed:

Question 1: Does the analogical distance of the product chosen for dissection affect the creativity of the generated concepts? Our hypothesis is that dissecting analogically far products increases design creativity since prior research has shown that carefully selected analogies has the potential to encourage creativity in design [29]. This, paired with product dissection's ability to uncover the structural elements of the problem may serve to increase the creativity of design outcomes.

Question 2: Does dissecting multiple products impact the creativity of design outcomes? Our hypothesis is that dissecting multiple products will increase the creativity of the generated designs since providing more examples has been shown to encourage successful analogical transfer and thus, has the potential to increase design creativity [30].

Question 3: Does the method of dissection impact the creativity of design outcomes? Our hypothesis is that the method of dissection has little or no impact on design creativity since prior research on engineering education and learning has shown that there was no significant differences in creativity between groups that utilize virtual dissection and those that performed physical dissection [31].

Question 4: Does the visual representation of the dissection activity affect the creativity of the generated concepts? Our hypothesis is that performing the visually based dissection activities will reduce design creativity. This is based on prior research [27] that states that highly visual design activities tend to focus the designer on the details of the product, reducing the scope of the solution space explored and thus, reducing design creativity.

METHODOLOGY

The main goal of this study was to understand the impact of variations of dissection activities in engineering design by conducting a controlled laboratory study. In order to test our hypotheses, a factorial study was conducted with 8 engineering students who were asked to complete a dissection activity and an idea generation session. A semi-structured interview was also conducted immediately following the study. Although our study utilized only 8 participants, the results revealed several significant differences highlighting the impact and contribution of our findings. In addition, we used the semi-structured interview data to provide rationale for our quantitative findings and produce recommendations for the alterations of product dissection practices for improving creativity in engineering design. The details of the study are provided below.

Participants

Eight students (7 males, 1 female) between the ages of 21-31 (mean 25) participated in the study. We limited study participation to upperclassman engineering students to minimize individual differences that could arise from varying educational backgrounds and design training. The participants were recruited by emails sent to engineering list-serves at a large northeastern university.

Procedure

At the start of the study, participants were given a brief overview of the study and any questions were answered. Once completed, an IRB consent document was signed and participants were provided with the following problem description:

> "Your task is to develop concepts for a new, innovative, product that can froth milk in a short amount of time. This product should be able to be used by the consumer with minimal instruction. Focus on developing ideas relating to the form and function of the product."

After participants had read the problem description, they were given instructions for the product dissection activity. Each participant was randomly assigned to an experimental dissection condition (described below) before the study began and asked to complete the corresponding dissection activity. Once the participants completed the dissection activity, they were given 20 minutes to brainstorm and sketch as many concepts as possible for an innovative frothing device. They were asked to write notes on each sketch such that an outsider would be able to understand the concepts upon isolated inspection, see Figure 3. After the brainstorming session, the participants were asked to complete a 10-question semi-structured interview on the utility of the dissection activity including the following questions: How did you feel about dissecting the product virtually/ physically? Did dissecting the product help you in generating ideas to address the design goal? Did you feel that the product you dissected was relevant to the design task?

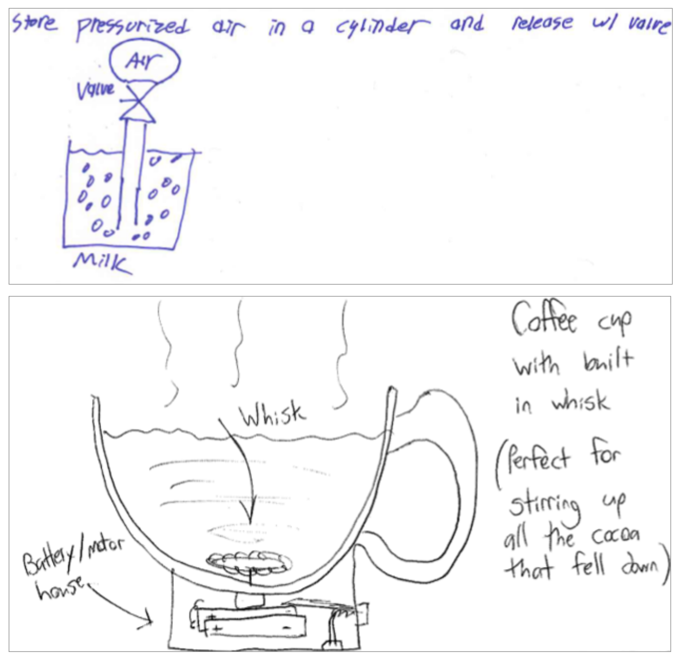


Figure 3: EXAMPLES OF MILK FROTHER SKETCHES BY PARTICIPANTS 7 AND 8, RESPECTIVELY.

Experimental Design

The study was a 2 (*analogical distance*) x 2 (*number of products dissected*) x 2 (*method of dissection*) x 2 (*visual representation*) factorial design and participants were randomly assigned to a condition before the study began. The levels are described below:

Analogical distance: participants were either provided with a milk frother (analogically near) or toothbrush (analogically far) to dissect. An electric toothbrush was selected as the analogically far product because it does not share surface similarities with milk frothers (did not serve the same purpose), but it does share underlying structural elements (fast rotating motion).

Number of products: participants were provided with either *1* or *2* products to dissect. Participants who dissected two products dissected either two that were analogically close or two that were analogically far.

Method: participants were instructed to dissect each product either *physically*, using tools like rotary tools and screwdrivers, or *virtually* using an animated exploded view of a detailed 3D model of the corresponding product.

Visual representation: participants were asked to either complete only a *bill of materials* (non-visual) for the dissected product or complete a *functional layout diagram* (visual) in addition to the bill of materials, which involved laying out each of the product components and describing how the components connected together, see Table 1.

Table 1: EXAMPLES OF PRODUCTS USED FOR THE DISSECTION AND THE ACTIVITIES PERFORMED DURING DISSECTION.

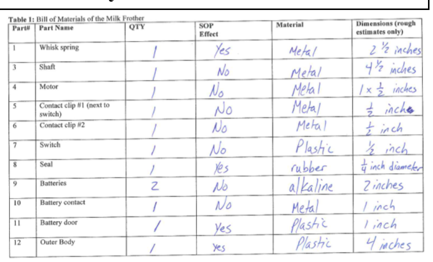
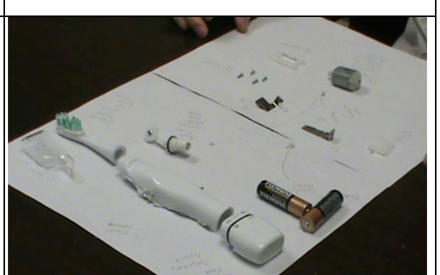
Product		**Dissection Activity**	
Analogically Near		Non-visual	
Analogically Far		Visual	

Table 1: Bill of Materials of the Milk Frother

Part#	Part Name	QTY	SOP Effect	Material	Dimensions (rough estimates only)
1	Whisk spring	1	Yes	Metal	2 ½ inches
3	Shaft	1	No	Metal	4½ inches
4	Motor	1	No	Metal	1 x ½ inches
5	Contact clip #1 (next to switch)	1	No	Metal	½ inch
6	Contact clip #2	1	No	Metal	½ inch
7	Switch	1	No	Plastic	½ inch
8	Seal	1	Yes	rubber	¼ inch diameter
9	Batteries	2	No	alkaline	2 inches
10	Battery contact	1	No	Metal	1 inch
11	Battery door	1	Yes	Plastic	1 inch
12	Outer Body	1	Yes	Plastic	4 inches

Metrics

The creativity metrics developed by Shah et al. [32] were utilized in this study to assess the participants' concepts, including the novelty, quantity, variety, and quality of the designs. This multi-faceted approach to assessing creativity was chosen over other single-metric approaches, such as those proposed by Nelson et al. [33], in order to examine the specific effect of each factor on creativity.

To assess design creativity, the following process was used: First, twenty coding questions were developed to classify each concept based on the features that it addressed. These classifications were then used to calculate the *novelty* and *variety* of the design concepts, see example in Figure 5. 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 [4, 28]. Next, three additional questions were developed to assess the *quality* of each design, as was similarly done in [34].

Once all the coding questions were developed, two independent raters were asked to classify and rate each concept according to the 23-question survey. Each rater received training prior to rating the ideas from the study in an effort to improve inter-rater reliability, which is often low for the Shah et al. metrics (see Nelson et al. [33] and Srivathsavai et al. [35] for discussion). The training sessions were conducted to instruct each rater on the intent behind each of the 23 questions on the survey and to provide raters with practice rating example designs. Once the training was completed, the raters then answered the 23-question survey for each generated design. A Cohen's Kappa of 0.813 was achieved for this rating process and any disputes were settled in conference until consensus was reached.

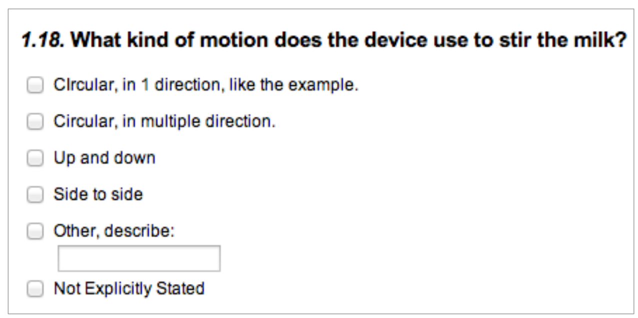


Figure 5: EXAMPLE RATING QUESTION USED TO IDENTIFY FEATURES OF THE GENERATED DESIGNS.

Once the ratings were complete, the creativity metrics were calculated using Shah et al's 2003 metrics as follows:

Novelty

In order to assess the novelty of the designs generated by each participant, the novelty of each feature must first be calculated. Feature novelty is the novelty of each feature, *i*, as it compares to all other features addressed by all the generated designs. Feature novelty, f_i, varies from 0 to 1, with 1 indicating that the feature is very novel compared to other features. The method of computing *f* is shown in Equation 1, where T is the total number of designs generated for each category (brush head, body design), and C is the total number of designs that were rated as being addressed by the design, see Table 2 for an example calculation.

$$f_i = \frac{T - C_i}{T} \quad (1)$$

Table 2: EXAMPLE CALCULATION OF FEATURE NOVELTY FOR FEATURE 1: HANDHELD BODY, 2: ROD WITH ATTACHMENT, AND 3: OPERATED BY BATTERIES. FEATURE 2 IS THE MOST NOVEL.

Concept #	Feature addressed?		
	1	2	3
1	No	Yes	Yes
2	Yes	No	No
3	Yes	No	No
4	Yes	No	Yes
Instances of each feature	$C_1 = 3$	$C_2 = 1$	$C_3 = 2$
Feature Novelty	$f_1 = 0.25$	$f_2 = 0.75$	$f_3 = 0.5$

The novelty of each design, j, is then 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 Equation 2.

$$D_j = \frac{\sum f_k}{\sum f_i} \quad (2)$$

Where f_k is the feature novelty of a feature that was different from the original design, and f_i is the feature novelty of a feature that was addressed in the generated idea.

The novelty of each participant for the idea generation activity is then determined as the average design novelty, D_j of all the designs each participant generated, as is commonly done in the design novelty literature [32, 36]. Thus, 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.782) [33]. This metric is relevant to the study of design creativity because researchers have often used novelty synonymously with creativity [37], and is an important aspect in generating ideas that are unique and unexpected [38], and thus, valuable [39].

Quantity

During the brainstorming session each participant was provided with paper with numbered boxes on it for each new idea. Therefore, the quantity metric was calculated as the number of boxes completed by each participant during the study. This metric is important in the study of creativity because it follows the reasoning that generating more ideas increases the chances of generating better ideas [40]. In fact, researchers in classical psychology have regarded one's fluency in idea generation to be an indication of creativity [37].

Variety

The variety metric was calculated by first computing the variety of each question that was addressed by the participant. This was done using Equation 3, where b_q is the number of options addressed for question q by ALL of the participant's ideas, and N is the total number of ideas generated by Participant 1.

$$V_q = \frac{b_q}{N} \quad (3)$$

The amount of variety produced by each participant's generated designs is then computed as the total variety of all questions, as seen in Equation 4, where Q is the total number of questions addressed by all designs generated by a participant.

$$V_T = \sum_{q=1}^{Q} V_q \Big/ Q \quad (4)$$

The variety metric has been considered to be a "measure of the explored solution space" (p.117) [32] during idea generation. Researchers have regarded variety as an important aspect of creativity because it increases the probability of generating innovating ideas by restructuring the problem and exploring a wider space of solutions [32].

Quality

The final creativity metric was assessed for each design using 3 questions at the end of the rating questionnaire. The first of these questions evaluated the degree to which the design addressed the design goal (i.e., to design a device that froths milk). The remaining questions evaluated the feasibility of the generated design. Specifically, the technical feasibility of the design (is it *possible* to make it) and the ease of execution (is it *plausible* to make it) were evaluated. The quality of each design was then computed using Equation 5, where q_k is the answer to each of the quality questions. $q_k = 1$ when the quality question is answered with a 'yes', and $q_k = 0$ when the quality question is answered with a 'no'. The quality score for each participant is then obtained by computing the average quality scores of all designs that the participant generated.

$$Q_j = \frac{\sum q_k}{3} \quad (5)$$

Quality is important for assessing the feasibility and competitiveness of the generated design. This is important for counterbalancing the other creativity metrics and evaluates the *effectiveness* of a particular design idea [32], which is an important aspect of creative idea generation.

Data Analysis

In order to test our hypotheses, ANOVAs were computed with the independent variables of analogical distance, number of products dissected, method of dissection, and visual representation and the dependent variables of novelty, quantity, quality and variety. SPSS v.20 was used to analyze the findings and a significance level of 0.05 was used in all analyses.

In addition to the quantitative analysis, the post-study interview results were analyzed using principles of content analysis [41]. These results provide rationale for the quantitative findings of the study and help us gain a better understanding of the cognitive processes that underlie the findings.

RESULTS AND DISCUSSION

Table 4 shows the ANOVA results for each of the creativity metrics studied, and Table 5 provides a summary of the significant differences in creativity metrics for all factors. The following sections present the results of the analysis in order of our research hypotheses, and also provide rationale for the results by exploring the interview data in detail.

Table 4: RESULTS OF THE ANOVAS PERFORMED ON THE FOUR CREATIVITY METRICS.

Source	Dependent Variable	SS	DOF	MS	F_0	P-value
Distance	quantity	10.13	1	10.13	0.70	0.46
	quality	0.01	1	0.01	1.47	0.31
	variety	0.00	1	0.00	0.22	0.67
	novelty	**0.00**	**1**	**0.00**	**19.92**	**0.02**
Number of products	quantity	10.13	1	10.13	0.70	0.46
	quality	0.00	1	0.00	0.11	0.76
	variety	**0.01**	**1**	**0.01**	**23.49**	**0.02**
	novelty	**0.06**	**1**	**0.06**	**284.26**	**0.00**
Method	quantity	3.13	1	3.13	0.22	0.67
	quality	0.00	1	0.00	0.00	0.10
	variety	**0.07**	**1**	**0.07**	**150.14**	**0.00**
	novelty	0.00	1	0.00	8.13	0.07
Visual represen-tation	quantity	21.13	1	21.13	1.46	0.31
	quality	0.00	1	0.00	0.04	0.86
	variety	**0.01**	**1**	**0.01**	**23.54**	**0.02**
	novelty	0.00	1	0.00	3.11	0.18

Table 5: SUMMARY OF SIGNIFICANT DIFFERENCES IN CREATIVITY METRICS ACROSS THE FOUR DISSECTION FACTORS (ARROW REPRESENTS POSITIVE / NEGATIVE EFFECT)

		Creativity Metrics	
		Novelty	**Variety**
Factors	Analogical Distance	↑ Near ↓ Far	
	Number of products	↑ Multiple ↓ Single	↑ Multiple ↓ Single
	Method		↑ Virtual ↓ Physical
	Visual representation		↑ Non-visual ↓ Visual

Effect of Analogical Distance

Our first hypothesis was that participants who dissected analogically far products would be more creative than those that dissected analogically near products. The ANOVA results showed significant effects for the analogical distance of the product dissected and the novelty of the generated concepts ($F_0 = 19.92$, $p < 0.02$). More specifically, participants that dissected analogically near products ($M=0.66$, $SD=0.01$) produced concepts that were more novel than those that dissected analogically far products ($M=0.61$, $SD=0.01$). There were no significant effects for variety, quantity or quality. These results refute our hypothesis and show that individuals who dissected analogically near products produced concepts that were more creative. Our qualitative results provide insights into these findings.

Novice designers often have difficulties drawing analogies between analogically far products [42]. Although the analogically far product in our study had similar functional features as the milk frother, our participants had difficulty using the knowledge of the functional elements of the toothbrush in the design of a novel milk frother. For instance, participant 5 who dissected the toothbrush explained, "I was trying to build on those ideas, but I had no idea how a sonic toothbrush can be used for the milk frother." On the other hand, participants who dissected analogically near example(s) were able to anchor their ideas and generate concepts that were significantly different from the provided example. For example, participant 7 who dissected the milk frother explained, "I had to try to come up with the most innovative ideas, I kind of felt like I had in mind what was *not* an innovative idea, I did not write that down on the paper. So if we had done an electric toothbrush, I'd be like-- I'm coming up with ideas for a milk frother, I would have come up with more things similar to what I guess is the kind of milk frother today." Similarly, since participant 3 dissected the analogically far product, they noted that they "would have at least have had more realistic and better results because I then would have more of an idea of what could be improved" if they dissected an analogically near product compared to an analogically far product. This result is unsurprising as prior research that has shown that novices have difficulties drawing abstract problem-relevant representations of analogically far products, reducing their ability to make successful analogical transfer [42].

Despite the fact that dissecting analogically far products reduced design novelty in this study, it is important to note that the difference in novelty scores was relatively small (difference of 0.05). Therefore, it may be that novice designers need tools or support systems that aid in drawing analogies between analogically far products. Prior research has noted the differences in cognition between novice and expert designers [22, 42], further justifying the need for analogy-inducing support tools. Even through participants were less able to generate novel designs after dissecting analogically far products, most participants felt that analogically far examples could play an important role in enhancing the design process. In particular, analogically far products could be used in the early stages of the design process in order to "open up" the solution space and "branch away" from preexisting assumptions about the design goal. For example, one participant noted that "it might be good in stage one to try and get some basic ideas, but after you think about the feasibility, if it looks like the handheld milk frother is really the feasible one, then you should be benchmarking those and take those apart and try to be better than what you have." Thus, the timing of dissecting analogically far products can be said to be crucial in developing well-rounded ideas, agreeing with prior research that has shown that the timing and analogical similarity of examples impact design outcomes [43].

Effect of Dissecting Multiple Products

Our second hypothesis was that participants who dissected multiple products would produce concepts that were more creative than those that dissected only one. Our ANOVA results showed significant effects for the number of products dissected for the novelty ($F_0 = 284.26$, $p < 0.00$) and variety ($F_0 = 23.49$, $p < 0.02$) of the generated ideas. More specifically, individuals that dissected multiple products developed ideas that were more novel (M=0.76, SD=0.007) than those that dissected only one (M=0.54, SD=0.007). Similarly, participants that dissected multiple products developed a larger variety of ideas (M=0.35, SD=0.01) than those that dissected a single product (M=0.27, SD=0.01). There were no significant effects for quantity or quality. These results support our hypothesis and show that dissecting multiple products can have a positive impact on design creativity.

The use of multiple examples in the dissection activity was met with an overwhelmingly positive response from the participants in the study. Even participants that dissected a single product expressed interest in dissecting multiple products. For example, participant 2 who dissected only one product stated that they would "be able to see two different ideas behind a product (what it's supposed to do) but you'd have 2 different takes on it, so it might get thinking in two different ways, coming from two different angles" if they had dissected multiple products. Thus, providing multiple examples helped to add divergence to participants' ideation process, adding variety and novelty to their generated ideas. Multiple examples also increased the number of design cues and information flow that participants used to generate ideas. For example, participant 2 noted that dissecting multiple products "pushed them to be more creative", while another participant (participant 6) who dissected multiple products as well, had "a better idea of what innovative was".

While participants favored dissecting more than one product, most participants expressed a desire to dissect multiple *distinctly different* products. In other words, instead of dissecting multiple analogically near products, or multiple analogically far products, participants felt that dissecting one analogically near product and one analogically far product would have helped them be more creative in idea generation. For example, participant 6 noted: "if you could find something completely different, that could really help because I think that helps with the creative process. You could say like "oh, here's a completely different design and we could use *both* of them and use them together. To me that's creative and innovative." This finding is unsurprising because prior research in the field of cognitive psychology have long since identified multiple examples as a factor for increasing category breadth and understanding [30].

Effect of Dissection Method

Our third hypothesis was that the method of dissection (physical or virtual) would have little or no effect on participants' creativity. Our ANOVA results showed significant effects for the method of dissection and the variety of the generated concepts ($F_0 = 150.14$, $p < 0.00$). More specifically, participants that dissected products virtually (M=0.41, SD=0.01) produced a larger variety of concepts than those that dissected the products physically (M=0.22, SD=0.01). There were no significant effects for novelty, quantity or quality. These results support our hypothesis and show that individuals that perform dissection virtually produce concepts that are as creative (quality, quantity and novelty) as those who perform dissection physically, but they have more flexibility in their design concepts (variety).

One of the main findings revealed from our qualitative analysis was that participants perceived that the virtual dissection consumed less time than dissecting products physically. Participants in the virtual dissection condition were able to complete the activity in a shorter amount of time (M = 20.3min, SD = 9.4s) compared to participants that dissected the product(s) physically (M = 25.0s, SD = 9.9s). Although there was no statistically significant difference in the time to perform the two activities, participants perceived virtual dissection as consuming less effort than physical dissection. For instance, participant 1 commented after performing virtual dissection that "(virtual dissection) shows me all the parts, and it dissects for me, so that would be much easier for me to comprehend". Similarly, participant 3 who performed the dissection virtually explained, " you would see it exploded you know very simply, easy to understand, so you would pick up on how they connected to each other pretty easily. Because if you have all these pieces scattered around if you're taking it apart you could put it together, but it wouldn't be as simple as the diagram." This perception of time and effort spent on dissection may have impacted design variety in two ways. First, by performing the dissection virtually, participants were able to complete the activity in a shorter amount of time compared to participants that dissected the product(s) physically, leaving the details of the example product 'fresh' in their minds. This agrees with research in the field of cognitive science regarding the recency effect that states that information that is processed temporally closer to recall is more successfully retrieved [43]. Second, because dissecting the product virtually was perceived as easier than dissecting the product physically, the amount of perceived effort invested into the dissection activity was reduced. According to the Sunk Cost Effect [44, 45] the more effort or time invested into a particular path, the less likely it is that the individual will pursue an alternate path. Thus, participants that dissected the products physically can be said to have invested more time and effort into the dissection activity (cutting, pulling apart, etc.), potentially making them less likely to explore alternatives in ideation.

While participants generally did not encounter major problems during the virtual product dissection, several participants expressed concern that the virtual dissection interface lacked any real-time feedback. For example, a participant that performed virtual dissection noted, "on the computer screen, the parts just magically separate. So you see the order, but the function is still a little obscure because you're not really sure why piece A slides over piece B. Is it like a loose fit? Is it a bearing? Or is it a coupler that has a friction fit from the motor shaft to the head of the mixer? Whereas if I took it apart, there would be no doubt." Similarly, another participant in the virtual dissection condition explained: "there were plates stabilizing the motor in the first toothbrush, and if I was on a computer, I just pull those plates off- but here, I pull them off, and the motor clearly shifts and I'm like, "oh okay, that's what that plate is doing there, it's what's stopping the motor from shifting". So I guess maybe if you're trying to do it you would have to put in some physics or something to make sure that when you are pulling things apart, it behaves the way it should." Thus, while virtual dissection proved to beneficial to the design process as was found in previous studies [46], and in fact, encouraged more variety in the generated designs, certain improvements should be made to future iterations in order to maximize the benefits that can be gained from the activity.

Effect of Visual Representation

Our final hypothesis was that individuals who had a more visually oriented dissection activity (functional layout diagram) would produce concepts that were less creative than those who had a non-visual activity (bill of materials). Our ANOVA results showed significant effects for the structure of the dissection activity and the variety of the generated concepts ($F_0 = 23.54$, $p < 0.02$). More specifically, participants that only completed the bill of materials (M=0.35, SD=0.01) produced a larger variety of concepts than those that also visualized the dissection through a functional layout diagram (M=0.28, SD=0.01). There were no significant effects for novelty, quantity or quality. These results support our hypothesis and show that individuals that were exposed to a more visual form of dissection activity were less creative in their ideation.

One possible explanation for these findings is that the more visual layout activity encouraged participants to focus on the internal mechanisms of the product and how they connected together in more detail. While this activity increased their understanding of the example product, it also limited their thinking in the idea generation phase, supporting prior research that showed that visual representation limits variety in problem solving tasks [27]. As participant 2 who performed the functional layout activity explained: "I got a better understanding of how (the milk frother) worked but I don't know if it helped me create (ideas)." Participant 2 also commented that the structured layout activity, "would have been more helpful if I was supposed to generate ideas and very specific parts for milk frothers, but then to just jump in and come up with a basic machine-- this will do this-- doesn't help that much." Thus, participants were more constrained by the example when doing the layout activity because they were encouraged to think at a more detailed level, as opposed to a more conceptual, "higher-level".

While the structured layout activity reduced design variety, most participants felt that the activity could be utilized in a setting where the design goal was more specialized or detailed. Importantly, the design goal largely determines the effectiveness of the activities performed during dissection. As one participant in the visual condition explains: "you gave me a design statement before I started dissecting, so personally I don't really care how to it all fit together, I didn't really care about taking inventory. I fixated on a couple of parts, I played with them and saw how they moved and that was enough because that's what I was here for. So you might take or leave that second part. I don't think it did anything for me." Thus, the activities performed during dissection should be selected carefully in order to increase their effectiveness. This is important because product dissection is being practiced and studied in a multitude of ways, and factors that support the inspiration of creative ideas need to be identified.

Implications for Product Dissection

Our research findings identify several key factors for supporting creativity in engineering design through product dissection activities. These implications and their details are discussed in the following sections.

Support the Dissection of Multiple Products

The results of our study indicate that dissecting multiple products helps designers expand the solution space by providing them with multiple design cues in the early phases of design. This finding supports prior research which found that multiple examples can increase the breadth of mental representations, allowing for easier retrieval and problem solving [30]. While this result appears supportive, these previous studies on example usage and product dissection in engineering design typically study examples in isolation, leaving questions unanswered regarding the impact of multiple examples on design creativity. Practically, the results of this study suggest that ideation techniques aimed at improving design creativity should focus on the use multiple examples in an effort to encourage creativity, as well as emulate industrial practices. Interestingly, the use of multiple products in dissection may be able to encourage better analogical transfer in novices, as more design cues are available for retrieval. Dissecting multiple products is also more sustainable in virtual environments.

Support Novice Designers in the Identification of Analogical Relationships

The results of the study indicate that novice designers have difficulties drawing analogies between distantly related products during dissection. From prior research, it becomes clear that this is due to novices' difficulties in drawing abstract problem-relevant representations of analogically far products, reducing their ability to make successful analogical transfer [42]. In other words, the novice designers in our study were unable to make a clear connection between the analogically far products, negating the positive effects of dissecting them. However, our results show that the difference in novelty scores between dissecting analogically near and far products, while significant, was relatively small (0.61 vs. 0.66). This suggests that the novelty of designs can be improved if effective techniques are developed that aid novices in analogical transfer. In addition, understanding what analogical products (far or near) designers themselves would select for dissection would add to our understanding of this selection process as the current study utilized carefully selected analogical products in its design. Finally, structures that help novice designers draw analogies between analogically far products could be implemented in a virtual dissection interface, allowing researchers to explore the implication of analogy-inducing tools on the success of analogical transfer.

Develop Realistic Virtual Dissection Environments

The results of this study provide evidence for the benefits of performing product dissection in a virtual environment. By virtually dissecting a product, participants were able to complete the dissection with less perceived time and effort. This served to encourage the exploration of alternative paths in idea generation, and left the details of the dissected product 'fresh' in participants' minds. Additionally, virtual dissection reduces the costs and resources associated with dissecting products physically, increasing the sustainability and accessibility of dissection. Future studies should consider the human factors elements of virtual product dissection in an effort to develop virtual dissection tools that are more realistic and effective. For example, implementing haptic or other types of feedback systems may greatly enhance virtual dissection by creating a richer dissection experience.

CONCLUSION

The results of this study identify aspects of dissection activities that have a significant impact on design creativity. In particular, the analogical distance, number of products, method of dissection, and visual representation of the dissection activity was found to impact specific facets of creativity. The results from this study also provide significant contributions to the engineering design community by identifying key factors that influence design creativity, and demonstrate methods of altering existing design practices in order to enhance the design process.

Future studies should examine the role of the factors discussed in an experimental setting involving a larger number of participants. In addition, the creativity of design outcomes when designers are allowed to self-select products for dissection should be explored. Research is also needed to improve virtual product dissection experiences to maximize the 'buy-in' factor and benefits of performing virtual dissection. Lastly, the effect of various visual representations on the feasibility and level of detail of design outcomes need to be studied in conjunction with product dissection in order to add to our understanding of design cognition.

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