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INTERPLAY OF SKETCHING & PROTOTYPING IN EARLY STAGE PRODUCT DESIGN

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Abstract: Research suggests that, for the design of simple mechanisms, sketching and prototyping are somewhat interchangeable in terms of their influence on design idea quantity and quality. This study explores whether this interchangeability holds true for a product design activity. Three conditions are compared: sketching only, prototyping only, and both prototyping & sketching. A design evaluation metric, idea distance, is proposed to evaluate the breadth of design space exploration. Results showed that individuals who sketched generated more ideas and had more creative final designs, while individuals who prototyped had designs that performed better functionally. Greater idea distance was found to correlate with more creative ideas. However, exploring too broad a design space reduced the depth of design idea exploration, and was negatively linked to the functional performance of the final design.

Keywords: *Sketching, Prototyping, Idea Generation, Creativity*

1. Introduction

Sketching is commonly used by designers during the early, idea generation stage of design. It is often followed by a phase in which physical prototypes are created for deeper investigation of a subset of ideas. One reason that physical prototyping typically follows sketching is the relative speed and cost of sketching compared to prototyping. This reflects a strategy of minimizing resources spent when design uncertainty is the highest and progressively increasing resources as uncertainty is reduced (Eppinger & Ulrich, 1995). However, there are cases when this strategy may not hold. Recent work of the authors (Faas, Bao, & Yang, 2014) suggests that, for a simple mechanical design task, sketching and prototyping are nearly interchangeable in terms of their influence on idea quantity and quality. In that study, the design goal and resulting mechanisms were simple enough that prototypes were often direct, 3-D instantiations of sketches, such as a fulcrum or pulley. This paper explores the interplay of sketching and prototyping in a different context, that of product design. The expectation is that consumer products will be user-oriented and potentially more complex, rather than strictly function-oriented, and concepts will be less obviously interchangeable between sketching and prototyping. This study investigates the following questions:

1. *In early stage design, how does sketching compare with prototyping in terms of creativity and functional performance for a product design activity?*

It is expected that sketching will be linked to a higher quantity of designs, and more creative designs, because it is generally a faster, lower overhead tool as demonstrated in related study (Neeley, Lim, Zhu, & Yang, 2013; Schütze, Sachse, & Römer, 2003). It is anticipated that prototyping will be linked to better functional performance since it allows participants to have more realistic, physical testing of their designs.

2. *How does the breadth of idea exploration influence design outcome? Does exploring narrower vs broader design space relate to design creativity and functional performance?*

An "idea distance" is proposed to measure the similarity between two design ideas. Ideas that are very different from each other with no commonalities or shared attributes are described as having large idea distance. The average distance among all ideas generated by a designer represents the breadth of design space explored. The expectation is that wider exploration will be linked to higher creativity, since wider exploration suggests designers are exploring different ideas at the same time. However, given limited time and resources, exploring too broad of a design space may harm design performance, since less effort will be put into developing ideas in depth and details.

2. Related Work

Sketching & Prototyping. Sketching is a design tool that is often used to drive the design process forward (Ullman, Wood, & Craig, 1990; Yang, 2005). Though it was found that sketching is not necessary for expert designers to develop ideas in the early phases of conceptual design (Bilda, Gero, & Purcell, 2006), it is usually believed that sketching facilitates individual designers as well as design teams in idea generation and development process (Song & Agogino, 2004), since it allows designers to capture and communicate ideas quickly while preserving design freedom (Goel, 1995).

Physical prototypes often uncover design issues that are not apparent from a 2D visualization (Gerber, 2009; Sass & Oxman, 2006; Viswanathan & Linsey, 2013). Early prototypes allow evaluation of specific aspects of a design and are often geared towards rapid iteration. Such preliminary prototypes are typically constructed with soft materials such as foam-core or paper and are referred to as "sketch models" because they are more specific than sketches yet not a full prototype. Studies have evaluated the effect of implementing prototypes during the ideation stage. Christensen and Schunn (2007) found that a high degree of design fixation when prototypes were implemented. Others have looked at the details of prototypes and their effect on cognition. One study found that prototypes with less detail was linked to higher quality final designs (Yang, 2005). Another study found that prototyping allowed designers to generate ideas more quickly than sketching or CAD in a product design task (Häggman, Tsai, Elsen, Honda, & Yang, 2015). Designs created by prototyping were perceived as more novel, more aesthetically pleasing, and more comfortable to use. However, Vidal et al. (2004) found no difference in idea generation between groups that build or don't build prototypes for a simple mechanical design task.

Design Creativity. Amabile et al. (1996) defined creativity as "the development of novel and useful concepts". Most ideation methods encourage designers to think blue sky and suspend judgement based on reality and plausibility (Pierce & Pausch, 2007). Creativity is often defined as an inherent ability to look at a problem in different ways so that new solutions are revealed. Oman et al. (2009) proposed using an "innovation equation" to develop more effective ways to determine if designs are creative.

Other metrics commonly used to evaluate idea generation efficacy include: novelty, variety, quality and quantity (Shah, Vargas-Hernandez, & Smith, 2003). Research suggests that higher quantities of ideas is linked to better quality ideas (Linsey et al., 2011; Yang, 2009). In the early stage of design process, many ideation methods employ divergent thinking to generate large quantities of novel ideas. TRIZ (Altshuller, Shulyak, & Rodman, 1999), synectics (Gordon, 1961), and design-by-analogy (Linsey, Markman, & Wood, 2012) are some well-known techniques for increasing idea generation. Previous work by the authors has examined the relationship between sketching and creativity, and found that the quantity of sketches produced over the life of project is positively linked with measures of creativity (Yang, 2009).

Idea Similarity Measurement. Dissimilarity among ideas can indicate idea novelty and variety. According to Shah et al. (2003), novelty measures how unusual an idea is, while variety measures the amount of exploration of the solution space. The less similar a new idea is to existing ideas, the more novel it is; the less similar ideas are in a group of ideas, the higher variety of ideas there is.

Shah et al. (2003) used a frequency method to evaluate the idea novelty and diversity. To measure the similarity between design ideas for the design-by-analogy method, McAdams and Wood (2002) created a quantitative metric by computing the inner product between vectors representing product functionality. In another study, latent semantic analysis was applied to a patent database to investigate the distance between existing solutions and new design problems (Fu et al., 2013). It was found that analogical stimuli that are neither too ‘near’ nor too ‘far’ are most likely to inspire creative design ideas.

Though substantial literature exists examining tools for design with creativity and outcome measurement in design, limited work links both topics. Our study attempts to fill this gap. It compares the performance of the two design tools, sketching and prototyping, in the early stage of a consumer product design challenge. The ideas generated with different tools were compared with the above mentioned metrics: creativity, quantity, similarity, and functionality.

3. Methods

3.1 Overview

Eighteen participants were recruited via emails or posters from various engineering departments of a US university to participate in an in-lab design experiment. Participants worked individually, and were randomly assigned to three groups. The three groups were given the same design task but different tools: a sketching only group, a prototyping only group, and a prototyping & sketching group that was permitted to use both tools as desired. Each participant received a token $5 amazon gift card as a courtesy. The resulting designs were compared and evaluated as discussed below.

3.2 Design task

Participants were asked to design a package that could hold both a sandwich and a cup of coffee so that a user could carry both of them with one free hand. They were provided a sandwich (7"x3"x1") and a lidded coffee cup (10-oz, filled with water) at the beginning of the experiment, and were told that their designs would be tested with these at the end of the experiment. This design task was chosen because: 1) all participants would likely be familiar with the experience of transporting a sandwich and a drink, 2) pilot testing suggested that participants would reasonably be able to sketch or prototype a design in the time allotted, and 3) the task was open enough that a wide variety of solutions was possible.

Figure 1. Left: coffee cup and sandwich provided. Right: experimental setup.

The design task was split into two 30-min phases. In the first phase, participants were asked to generate as many ideas as possible, with a minimum of three. The three conditions for the first design phase were:

1. Sketching only (S) - generate designs only by sketching, using pens, pencils and paper provided. Not allowed to build prototypes, but permitted to touch building material and tools.

2. Prototyping only (P) - generate and explore designs only by prototyping, not allowed to sketch. Materials provided: cardstock, foam-core, blue foam, wire, string, rubber bands, popsicle sticks; and tools provided: scissors, X-acto knife, ruler, cutting mat, glue gun, hotwire cutter, and tape.
3. Prototyping and sketching (P&S) - allowed to sketch and prototype as desired to generate their ideas.

In the second phase, all participants were instructed to create a final design by building a prototype. The prototypes would undergo a *reliability test* in which the participants would use their prototypes to carry the sandwich and the cup for at least 30 seconds while walking at least 20 feet. A design "passed" the reliability test if the prototype did not break and no food/drink was spilled. This second phase of the experiment forced participants to iterate on their designs. It also allowed fair comparison between the design outcomes of the different groups. If different design outcomes were observed, it could be concluded that the differences were introduced by sketching and prototyping during phase 1.

Prior to the experiment, participants completed demographic information such as design experience and familiarity with prototyping methods. If needed, brief training on prototyping was provided.

3.3 Data processing

3.3.1 Data pre-processing: re-sketching

The final designs from the second phase were all re-sketched by one of the researchers. Re-sketching ensured that the style and format of the designs would be consistent, and thus minimize potential evaluation bias caused by different prototyping materials and craftsmanship levels of the participants. The re-sketches included three views: one of the overall geometry of the package, one showing the design loaded with the sandwich and coffee, and one showing how users would carry the package (Figure 2).

Figure 2. Top row shows the phase 2 prototypes. Bottom shows re-sketched designs.

3.3.2 Design evaluation

All re-sketched designs were independently evaluated by five evaluators (faculty, grad and undergrad student researchers). Five key attributes were identified for all design ideas generated in both phases 1 and 2, each with three to five different configuration options:

- Package-Cup Relation: How does the package hold the cup?

- Cup-Sandwich Relation: What is the relative position between the cup and the sandwich?
- Sandwich Orientation: What is the orientation of the sandwich when in the package?
- Rigidity: Is the package rigid (made of hard materials) or flexible (made of soft materials)?
- User Interface: How should a user carry the package?

These objective evaluations were used to construct the distance between ideas.

All ideas were also evaluated on five subjective criteria: *Creativity*, *Ease of loading sandwich and coffee cup*, *Ease of transport*, *Stability*, and *Ease of storing the empty packages.* All ideas were evaluated on these criteria on a scale of 1-5, then averaged. The scores for the latter four criteria were averaged into a single number which was called the *Functional Performance* of the design. The design ideas were presented to evaluators via an online survey. Images of sketches and prototypes from the first phase and the re-sketches from the second phase were presented in random order. All evaluators looked at all of the designs and evaluated the subjective criteria. Three of them evaluated the objective criteria of all designs.

3.3.3 Idea distance

We formulated a metric, the *design idea distance*, to evaluate the diversity of a group of ideas and the uniqueness of one idea from others. The distance between a design idea i and another design idea j is:

$$D_{ij} = \sum_{c} d_{ij\_c} \tag{1}$$

where d_{ij_c} is a dummy variable that denotes whether idea i and idea j are the same or not based on the objective criteria c. If they are the same, $d_{ij\_c} = 1$. If not, $d_{ij\_c} = 0$. The distance is a measurement of the similarity between any two design ideas. Since there are five objective criteria, the idea distance between any two designs can vary from 0 to 5. For example, if two ideas have the same *Package-cup relation*, *Cup-sandwich relation* and *Sandwich orientation*, but have different *Rigidity* and *User interface*, then the distance between these two ideas is 2. This idea distance is similar to the metric developed by McAdams and Wood (2002) in that both compare the similarity of ideas in pairs. However, in this paper, the configurations of product features are directly compared, instead of comparing the importance of the product functions to the user needs.

Idea distance represents the similarity between any pair of designs by mapping them to a design space using the key attributes. By computing different combinations of the idea distance, different aspects of idea generation can be evaluated flexibly. In this paper, two measurements are calculated for each designer:

- Intrinsic idea distance: A diversity metric given by the average distance among the design ideas of an individual participant. Applies to Phase 1.
- Extrinsic idea distance: A metric of uniqueness represented by the average distance of a design idea from all other designers' ideas. Relevant to Phase 2.

Idea distance relates to variety and novelty metrics of Shah, et al. (2003), but is a departure due to its focus on the difference between idea pairs. This can be valuable when measuring evolution of design ideas.

4. Results

In total, 18 people (10 females and 8 males; 8 undergraduate students, 9 graduate students and a postdoc) participated in this study. Each experimental group had 6 participants. Participants with different design experience levels, from novice to expert, were evenly distributed among the group settings. One-third of the participants were trained on how to use the tools and materials.

In total, 90 design ideas were generated in phase 1. The sketching only group generated 38 ideas, sketching & prototyping group generated 30, and prototyping only group generated 22. Eighteen final designs were generated in phase 2. All final designs passed the reliability test.

For the five objective design evaluations, Krippendorff's Alpha among the three evaluators was 0.669 for the first phase ideas and 0.740 for the second, which is sufficient to draw tentative conclusions. For creativity and other subjective evaluations, rating differences among evaluators due to diverse personal taste were expected. The average ratings of the five evaluators were calculated for further analysis.

4.1 Design outcome evaluation

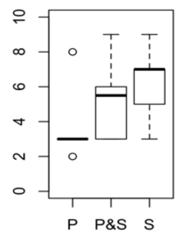
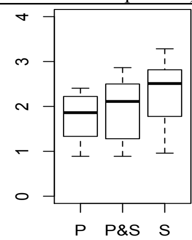
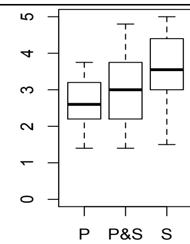
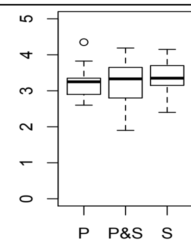
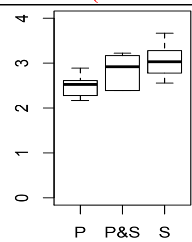
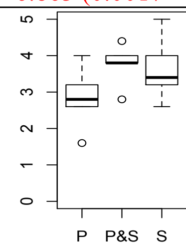
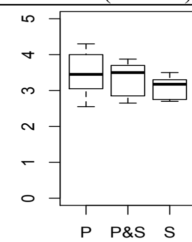
Figure 3 shows examples of phase 1 ideas. The ideas in the top two rows were generated by one participant. These were very different from each other and had the highest phase 1 intrinsic idea distance among all participants. The bottom row of ideas were generated by another participant and were very similar to each other, with only slight differences in configuration and sizing, and thus have the smallest idea distance. For the phase 2 idea examples shown in Figure 2, the left design received the lowest creativity score, the second lowest phase 2 extrinsic idea distance value, but the second highest functional performance value. The right design received the highest score on creativity, had a high phase 2 extrinsic idea distance value, and received an average score on functional performance.

Figure 3. Phase 1 ideas. Participant 1 developed 8 disparate ideas, Participant 2 developed 3 very similar ideas.

4.2 Comparison of design outcomes between groups

ANOVA was used to compare designs between experimental conditions. The design outcomes include the number of ideas generated and the intrinsic idea distance in phase 1, the extrinsic idea distance in phase 2, and creativity and functional performance for both design ideas in phase 1 and phase 2. The results are summarized in Table 1. Bartlett's tests were performed on unequal-sized design outcomes to validate the variance heterogeneity assumption of ANOVA. All samples passed the test except idea functional performance in Phase 1. However, even after applying squared transformation on the data to correct the unequal variance, there remained no significant differences on the phase 1 ideas' functional performance between groups.

Table 1. ANOVA F-ratio (p-value). P - prototyping, P&S - prototyping & sketching, S - sketching. (*significance level 0.1, ** significance level 0.05, significant values in RED)

	Number of Ideas	**Idea Distance** (Intrinsic for phase 1 and Extrinsic for phase 2)	**Idea Creativity**	**Idea Functional Performance**
Phase 1	 2.6021 (0.1094)	 4.0260 (0.0213**)	 6.863 (0.0017**)	 1.0814 (0.3436)
Phase 2		 3.9583 (0.0416**)	 2.8204 (0.0913*)	 0.8332 (0.4538)

Prototypers on average generated the fewest ideas in phase 1. With the exception of one participant who created 8 prototypes, all other prototypers created no more than 3 prototypes in phase 1, the minimum requested. On average, sketchers had the most ideas in phase 1, which is consistent with expectations.
In phase 1, average intrinsic idea distance and creativity were highest in the sketching group and the lowest in the prototyping group. The p-values showed that the differences between ideas was statistically significant.
In phase 2, the extrinsic idea distance was also on average the highest in sketching group and the lowest in prototyping group. However, creativity was highest in the prototyping & sketching group while the prototyping group still had the lowest creativity score. There was no significant difference in the functional performance of the designs between groups. However, the prototyping only group and the prototyping & sketching group had on average higher functional performance scores compared to the sketching only group.

4.3 Correlation between design outcomes

Pearson correlations were calculated between design outcomes to determine the relationships between phase 1 ideas and final designs (Table 2). The number of ideas in phase 1 was significantly correlated with idea distance and creativity in both phases. Idea distance and creativity tended to positively correlate with each other while idea functional performance tended to negatively correlate with the number of ideas, idea distance and creativity.
Design outcomes (except idea functional performance) in the first phase were significantly correlated with design outcomes in the second phase. This suggests that the higher the number of ideas generated and the broader the design space explored (larger intrinsic idea distance) in the first phase, the more unique (larger extrinsic idea distance) and more creative the final design would be in the second phase. However higher quantity and more diverse ideas exploration in the first phase did not necessarily guarantee the final design would have better functional performance.

Table 2. Pearson correlation (p-value) between Number of Ideas, Idea Distance, Idea Creativity and Idea Functional Performance (*significance level 0.1, ** significance level 0.05, significant values in RED)

		Phase 1 Average Evaluation				Phase 2 Evaluation		
		Number of Ideas	Intrinsic Idea Distance	Idea Creativity	Idea Functional Performance	Extrinsic Idea Distance	Idea Creativity	Idea Functional Performance
Phase 1 Average Evaluation	Number of Ideas	-	0.7354 (0.0005**)	0.8471 (<0.0001**)	-0.1711 (0.4972)	0.5008 (0.0342**)	0.4810 (0.0433**)	-0.1241 (0.6237)
	Intrinsic Idea Distance		-	0.8431 (<0.0001**)	-0.4423 (0.0661*)	0.5266 (0.0247**)	0.3770 (0.1230)	-0.3357 (0.1732)
	Idea Creativity			-	-0.2114 (0.3997)	0.5769 (0.0112**)	0.5362 (0.0218**)	-0.3458 (0.1599)
	Idea Functional Performance				-	-0.1308 (0.6050)	0.1898 (0.4507)	0.2968 (0.2317)
Phase 2 Evaluation	Extrinsic Idea Distance					-	0.4722 (0.0479**)	-0.5039 (0.0330**)
	Idea Creativity						-	-0.1600 (0.5261)
	Idea Functional Performance							-

5. Discussion

1. *In early stage design, how does sketching compare with prototyping in terms of creativity and functional performance for product design?*

In this study, the use of sketching vs. prototyping in the early stages of a product design oriented task was significantly linked with final design outcomes of the second phase. Almost all participants developed their final designs based on one or two ideas that were generated in the first phase. Even though the sketching and prototyping limitation only applied to the first 30 min of the experiment, this influence was observed in the final designs of phase 2. The prototyping & sketching group produced the best final design outcomes: on average the highest design creativity as well as functional performance.

Sketching only. The functional performance of the final designs for the sketching only group was lower compared to the other two groups. Not being able to build early appeared to limit the designer's ability to test design ideas and to explore what features would function better. In addition, even though the sketching only group's phase 1 ideas received the highest creativity scores on average, their final designs were not as high as those for the prototyping & sketching group. After examining each design, it was found that many 'creative' phase 1 ideas generated by the sketching only group could not be feasibly built in the context of the experiment, for example fabricating a drone to carry the sandwich and drink. These ideas were not chosen for the second phase. Instead, less creative but more buildable ideas were selected for phase 2. Even though the sketching only group generated on average more creative ideas in phase 1, their final designs had lower creativity scores compared to the prototyping & sketching group.

Prototyping only. As expected, the prototyping only group generated a much lower number of ideas in the first phase. This likely reduced their exploration of the design space as well as creativity. They had significantly less creative final designs compared to the other two groups. In contrast, the other two groups that were allowed to sketch generated more ideas in phase 1. This is consistent with existing literature: the higher the idea quantity, the higher the idea diversity and creativity (Osborn, 1963).

2. *How does the breadth of idea exploration influence design outcome? Does exploring narrower vs broader design space relate to design creativity and functional performance?*

The first phase intrinsic idea distance was used to evaluate the breadth of design space exploration of each participant. It was found that the phase 1 idea distance was significantly, positively correlated with the idea creativity and significantly, negatively correlated with the idea functional performance. This suggests that by generating ideas with fewer commonalities, participants were likely to have more creative ideas.

However, if the participants generated ideas with higher similarity, they were more likely to delve more deeply into details and improve the designs' functional performance.

6. Conclusion

A two-phase experiment was conducted to explore the role of sketching and prototyping in the early stage of designing a product. Results showed that sketching-only was linked to the generation of more ideas, and more diverse ideas, which likely contributed to the higher creativity of their final designs. Prototyping-only designers tended to test their ideas earlier through fabrication, which seemed to force the generation of more feasible ideas. Their final ideas tended to exhibit better overall functional performance. Being barred from sketching or prototyping in the early design stage was linked to poorer design outcome later on. Exploring broader design space appeared to help designers generate more creative ideas. However, given the constraint of time, exploring too broad a design space reduced designers' chance of exploring the design ideas in depth. This might harm the functional performance of the final design. In this study, intrinsic and extrinsic idea distances were used to evaluate the design space exploration and the uniqueness of design ideas.

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