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Examining Design Fixation in Engineering Idea Generation: The Role of Example Modality

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Design fixation is a major concern in engineering idea generation because it restricts the solution space in which designers search for their ideas. For designers to be more creative, it is essential to mitigate their fixation. The majority of studies in the literature investigate the role of pictorial stimuli in design fixation; however, the role of examples presented in other formats, including physical prototypes, is largely unknown. This paper presents a study that compares design fixation, in novice designers, caused by pictorial and physical representations. The effects of defixating materials proposed by Linsey et al (2010) are also investigated. The results show that physical formats cause a higher magnitude of fixation compared to pictorial form; however, participants utilizing physical examples produce a greater quantity of non-redundant ideas. Consistent with prior studies, the results also indicate that the defixation materials may not facilitate mitigation of novice designers' fixation.

Keywords: Design Fixation, Example Modality, Idea Generation, Physical Representations, Pictorial Representations

1. Introduction

Engineering idea generation is a crucial and relatively difficult stage of new product development. At this stage, a wide variety of novel ideas for solving a design problem are sought. However, generating creative and novel ideas for design problems is a very challenging task. This difficulty can be mainly attributed to the inherent ill-structured nature of design problems (Simon, 1973). While solving such problems, designers need to first clarify their task before attempting to find solutions from a relatively undefined solution space (Ho, 2001). Hence it is important to understand the various factors affecting the process and develop tools and tactics to assist designers in their idea generation.

Design fixation has been a major subject of concern in the engineering idea generation research. It can be defined as a blind and often counter-productive adherence to a designer's own initial ideas and example solution features (Jansson & Smith, 1991). This confines the solution space where designers look for their ideas, decreasing creativity. Most of the fixation research in the engineering design and psychology literature investigate the effects of pictorial solution examples on the extent of fixation (Jansson & Smith, 1991; Purcell & Gero, 1996; Chrysikou & Weisberg, 2005; Linsey et al., 2010). These investigations show that both design experts and novices can fixate in the presence of pictorial examples of solutions. The effects of solution examples presented in other formats, especially three-dimensional physical models, are not well understood. In more realistic design situations, the examples from the physical world can influence idea generation. In fact, most of the physical systems around us are three-dimensional and can act as physical solution examples for idea generation. The fixation aspects of such solution examples need to be studied in detail. The study presented in this paper aims to clarify this issue.

This study seeks to compare design fixation caused by pictorial and physical solution examples. The authors hypothesize that physical example solutions can cause the same level of design fixation as pictorial example solutions. A controlled, between-subject experiment evaluates this claim. The subsequent sections in this paper present a brief background, the experimental method, relevant results, further discussion and finally, the conclusions.

2. Background

The study presented in this paper investigates the differential effects of pictorial and physical examples on design fixation. The subsections below provide a brief summary of the existing literature about the use of examples in engineering idea generation and

design fixation.

2.1 Examples in Engineering Idea Generation

Examples are useful in engineering idea generation because they help designers identify new solutions via analogical reasoning. Analogical reasoning is considered as a very powerful tool to invoke designer creativity (Pahl & Beitz, 2003). In analogical reasoning, the most challenging task is the identification of a relevant source analogy (Alterman, 1988; Markman, 1997). Numerous research efforts in the literature attempt to simplify the identification of source analogies (Chakrabarti, Sarkar, Leelavathamma & Nataraju, 2005; Nagel et al., 2008; Sarkar, Phaneendra & Chakrabarti, 2008; Linsey, Markman & Wood, 2012). When designers receive examples, the examples act as source analogies, eliminating the difficult step of analogy identification. Thus, examples can facilitate idea generation. Unfortunately, analogies from domains very close to that of the design problem can fixate designers (Dugosh & Paulus, 2005; Perttula & Sipilä, 2007).

2.2 Design Fixation

A number of studies show that, when designers are given example solutions to design problems, they fixate to those (Jansson & Smith, 1991; Purcell & Gero, 1996; Chrysikou & Weisberg, 2005; Linsey et al., 2010). Jansson and Smith show that when designers receive examples, they blindly copy features even if those features violate the problem requirements. In a follow-up study, Purcell and Gero (1996) show that industrial designers fixate less to examples compared to mechanical engineers. Linsey et al. (2010) find that even experts with years of experience solving open-ended design problems fixate to examples. Interestingly, these experts can successfully mitigate their fixation via the use of alternate representations of the design problem.

Psychology literature explains design fixation with the help of network models of memory (Matlin, 2005). According to this theory, information is stored in the long term memory in the form of inter-connected network of related concepts. When a concept is retrieved from this network, it activates the connected nodes, making it easier to retrieve those (Collins & Loftus, 1975). Since the newly retrieved concept is closely connected to the first one, the resulting ideas possess less variety. This process happens unconsciously, explaining the unintentional nature of design fixation. The concepts at farther nodes in the network represent higher variety concepts and they are not activated and hence are not retrieved easily. Thus, design fixation hinders the generation of a variety of novel ideas. According to the theory of biased retrieval, when a solution example is present during idea generation, the probability of retrieving the concepts related to that example increases (Raaijmakers & Shiffrin, 1981). Thus, cuing of concepts related to the example solution further activates the related concepts in the associative network, leading to more solutions that are related to the example solution. In this way, example solutions may be providing a blocking effect for the generation of novel ideas (Smith, 2003).

Some other researchers attribute the phenomena of design fixation to the cognitive strategy adopted by the designers. Generally the design problems are ill-structured and do not convey the full set of requirements to the designers. When designers solve ill-structured problem, they form the constraints based on the information derived from their initial solution or an example available (Restrepo & Christiaans, 2004). This is called a “working-backwards” strategy. This strategy leads designers to develop a cognitive commitment towards those initial solutions or the example, which in turn leads them to fixate (Cross, 2008).

2.3 Role of Example Representation in Design Fixation

A majority of the studies on design fixation from design and psychology literature use hand sketches to present their examples. Jansson and Smith's study (1991) is the first one to explore the presence of design fixation in engineering idea generation. For their various design problems, they use pictorial stimuli to fixate designers. Many researchers replicate this study under various conditions (Purcell & Gero, 1992; Purcell & Gero, 1996; Chrysikou & Weisberg, 2005), again using pictorial representations of examples. Providing further support to these efforts, Cardoso and Badke-Schaub (2011) use richer pictorial stimuli, in the form of photographs, in their study. Ultimately, they observe that the photographic format fixates designers to the same extent as hand sketches. Essentially, all these studies investigate the design fixation effects of comparatively low-fidelity example representations.

A few researchers have studied the effects of example modality on the extent of fixation caused by the same. A recent study by Chan, et.al (2011) investigates the effects of examples presented in the form of text or pictures. They observe that when the examples are presented in the form of texts, the quantity of ideas is negatively influenced. In another study, McKoy et al. (2001) study the difference in the idea generation with the help of two different representations: textual and pictorial. They show that pictorial representations lead to the generation of better ideas. In a similar manner, a recent study by Viswanathan and Linsey (2012) has shown that physical representations of generated ideas can lead to ideas with better functionality. Overall, these studies indicate that modality of examples and the generated ideas is a very important factor in engineering idea generation.

Efforts to replicate the design fixation results with higher fidelity representations, including three-dimensional virtual models and physical models, are

scarce. A recent study by Youmans (2011) explores how student designers fixate to a physical model of the example given to them. The participants are asked to design tools to pick up two objects inside a box without touching the sides of the box. They are also shown a physical example with a few negative and neutral features. They are asked to replicate the same tool before generating more ideas to solve the problem. It is observed that the participants do not fixate to the physical example presented to them.

The study described in this paper differs from Youmans' study (2011) in a few aspects. Firstly, this study is conducted in a controlled laboratory environment, where only the modality of the example provided to the participants varies. Secondly, in addition to investigating the effect of physical models of examples on design fixation, this study also compares the extent of fixation caused by pictorial and by physical representations of the same example. In addition, any potential effects of defixation materials proposed by Linsey et al. (2010) on the group of participants receiving the physical example are also investigated.

The studies available in the current literature mainly study the fixation effects of a specific modality of one or more solution example(s). Few efforts have been made to explore the role that example modality plays in design fixation. As described in the literature presented above, studies involving pictorial solution examples show that designers fixate (Jansson & Smith, 1991; Purcell & Gero, 1992; Purcell & Gero, 1996; Chrysikou & Weisberg, 2005), whereas a recent study with physical solution example (Youmans, 2011) fails to show fixation. Based on these, it can be suspected that the representation used to present the example to the designer is an important factor to consider in fixation research. The study described in this paper aims to explore this argument by investigating the following hypothesis:

Hypothesis: Designers fixate to both pictorial and physical solution examples to the

same extent.

A between-subject controlled experiment investigates the design fixation caused by two different representations of a solution example: pictorial form and physical form. The experiment explores the extent of fixation caused by each of these with respect to a control condition and between each other. The effectiveness of certain defixation materials in mitigating the fixation effects of physical representations is also investigated. The following sections present the method followed, along with the key results and a discussion of these results.

3. Method

A between-subject experiment with novice participants was conducted to investigate the hypothesis. This experiment was designed based upon the prior experiments by the authors (Linsey et al., 2010; Viswanathan & Linsey, 2012). Participants generated ideas to solve a design problem in four different groups: No Example (Control) Group, Pictorial Example Group, Physical Example Group and Physical Example Defixation Group. In each group, the participants solved the same design problem. The occurrence of example ideas in their concepts was studied to identify the extent of their fixation to the given solution example. The following subsections outline the details of the method followed for this study.

3.1 Participants

Senior undergraduate and graduate students from the Mechanical Engineering Department at Texas A&M University participated in this study. There were a total of 44 participants (36 undergraduate students and 8 graduate students). All the four experiment conditions had 11 participants each. The graduate students were equally distributed across the conditions, to avoid any bias. Ten participants were female, and

the average age of the participants was 23. None of the participants possessed more than six months of industrial design experience. The participants were recruited from the senior and graduate level design courses offered at Texas A&M University. They received either money or extra course credit as a compensation for their participation in the study.

3.2 Design Problem

All the participants solved a “peanut sheller” design problem, which was employed successfully in many prior studies (for example: (Linsey et al., 2011; Linsey et al., 2012)). This problem asked participants to generate as many ideas as possible for a device that could quickly and efficiently shell peanuts without the use of electricity and with a minimum damage to the peanuts. They were also informed that this device was to be used in places like Haiti and certain West African countries. None of the participants were familiar with the design problem before the experiment; but they all had experienced the routine task of shelling peanuts. The participants were also given a list of customer requirements associated with the problem. Figure 1 shows the exact problem statement provided to the participants.

Design Problem - Device to Shell Peanuts

Problem Description:

In places like Haiti and certain West African countries, peanuts are a significant crop. Most peanut farmers shell their peanuts by hand, an inefficient and labor-intensive process. The goal of this project is to design and build a low-cost, easy to manufacture peanut shelling machine that will increase the productivity of the African peanut farmers. The target throughput is approximately 50 kg (110 lbs) per hour.

Customer Needs:

- Must remove the shell with minimal damage to the peanuts.
- Electrical outlets are not available as a power source.
- A large quantity of peanuts must be quickly shelled.
- Low cost.
- Easy to manufacture.

Figure 1. Design problem statement provided to the experiment participants

3.3 Experiment Conditions

The four experimental groups differed in both the type of additional materials provided and the manner in which the solution example was presented. The four experimental groups were: Control (No Example), Pictorial Example, Physical Example and Physical Example Defixation. The differences between these groups are explained in the below subsections.

3.3.1 Control (No Example) Group

The No Example Group received only the design problem statement and no supplemental materials were provided to them. They received plain sheets of paper to record their ideas along with their thoughts or comments and were asked to come up with as many ideas as possible. They were also instructed to label their ideas and add one or two sentences description of their ideas.

3.3.2 Pictorial Example Group

The Pictorial Example Group received the same set of materials as received by the Control (No Example) Group. In addition, they received an example solution, in the pictorial form, as shown in Figure 2, along with a short description as follows: “This system uses a gas powered press to crush the peanut shell. The shell and peanut then fall into a collection bin”.

Figure 2. Example solution provided to participants in the Pictorial Example Group

The example solution provided to the participants possessed several shortcomings. This system employed a gas-powered press, which made the control of damage to peanuts extremely difficult. The system as a whole was very complicated and was inappropriate for less-industrialized economies of developing countries. Also, though the system shells the peanuts, it did not necessarily separate the shells from the peanuts. These shortcomings were not explicitly stated to the participants. However, all the participants possessed significant Mechanical Engineering knowledge and were

expected to infer these. This solution example was originally formulated by Linsey et al. (2010), incorporating the common concept ideas generated by the participants of their prior studies (Linsey, Green, Murphy, Wood & Markman, 2005; Linsey et al., 2011). As the common solutions tend to fixate designers more, this example qualified as a good fixating stimulus (Dugosh & Paulus, 2005; Perttula & Sipilä, 2007). However, the original sketch of the solution example was modified to match the physical model used in the Physical Example Group. This helped to eliminate any bias arising from the differences between the pictorial example and the physical model, other than the modality of the example.

3.3.3 Physical Example Group

The Physical Example Group received the same set of materials and the example solution given to the Pictorial Example Group; but the example was presented to this group in the form of a physical model (Figure 3). This physical model was not functional; but the participants were not informed of this. They were told that it could function with a gasoline powered motor. The physical model was available to the participants throughout the idea generation time and they were allowed to inspect it if desired.

Figure 3. Picture of the physical model of the peanut sheller example provided to the participants in the Physical Example Group

3.3.4 Physical Example Defixation Group

The Physical Example Defixation Group received the same physical model shown in Figure 3 and the defixation materials used in the prior experiments (Linsey et al., 2010; Viswanathan & Linsey, 2012). These defixation materials consisted of a brief functional description of the design problem along with some relevant back of the envelope calculations, lists of energy sources and analogies that could help solve the problem. Figure 4 shows the defixation materials provided to the participants. The prior studies in literature have shown that, when designers use fixating pictorial stimuli, defixation materials were effective in mitigating design fixation in experts (Linsey et al., 2010), but not in novices (Viswanathan & Linsey, 2012).

To assist you in developing as many designs as possible, consider the following clarification to the problem:

Functions:

- Import natural or human energy to the system
- Convert and transmit energy to peanut
- Remove peanut shell (remove outer structure from inner material)
- Separate removed shell (outer structure) from peanut (inner material)

Example Analogies that You Might Find Helpful:

- Hull
- Shuck
- Husk
- Clean (clean a deer, clean a fish or scale a fish)
- Soak
- Heat, Roast
- Dissolve
- Pod
- Pit, stone
- Burr (deburr something)
- Ream
- Bark (bark a tree)
- Skin
- Pare apples
- Pluck, deplume (strip feathers)
- Peel
- Grind (like a nut grinder)
- Brittle fracture

Natural Energy Sources Available:

- Wind
- Solar
- Running water streams
- Captured rain water at a height
- Solar
- Human
- Animal

Back-of-the-envelope Calculations:

A quick analysis shows that a much greater quantity of power (or force) is needed to act on many peanuts simultaneously compared to applying power to a few peanuts at a time.

Figure 4. Defixation materials provided to the participants in the Physical Models Defixation

Group (Linsey et al., 2010)

3.3 Procedure

As the participants entered the experiment room, they were directed to their workspaces. Up to four students participated at a time, and their workspaces were

separated by dividers. All the participants generated ideas individually. As the experiment began, they received the design problem statement along with the supplemental materials as determined by their experimental group. They were given five minutes to read and understand the design problem. The participants utilizing the physical solution example were also allowed to inspect it during the five minutes. The physical model was displayed on a table in front of them. These five minutes were followed by 45 minutes of idea generation. Participants were instructed to generate as many ideas as possible, and also told that the participant with greatest number of concepts would receive a prize. To ease logistics, this prize was given to all the participants, but the participants did not know this prior to the experiment. The solution examples were available to the participants throughout the session. The participants were asked to sketch their ideas and supplement those sketches with labels and short descriptions. At the end of the experiment, the experimenter asked the participants about their prior exposure to the design problem and any relevant industrial experience they possessed.

4. Metrics for Evaluation

In order to measure design fixation, five metrics employed in the prior design fixation studies are used. These metrics are: number of repeated example ideas, percentage of reused example ideas, quantity of non-redundant ideas (Shah, Smith & Vargas-Hernandez, 2003), number of ideas for energy sources and percentage of concepts using a gas engine (Linsey et al., 2005; Linsey et al., 2010).

Consistent with the procedure from Linsey et al. (2010), the number of repeated example ideas shows the number of ideas that the participants replicate from the given example. Consistent with the procedure by Linsey (Linsey et al., 2005; Linsey et al., 2011), each concept was functionally broken down to a component level to identify the

components that satisfy each function in a functional basis (Stone & Wood, 2000; Hirtz, Stone & McAdams, 2002). A component concept satisfying one or more functions in the functional basis is hereafter referred to as an “idea”. In general, each of the participants’ concepts contains several different ideas. In order to calculate the number of example ideas, the number of times example ideas appear in a participant’s solution is counted by one of the authors. To ensure reliability, a second independent reviewer, blind to the experimental conditions analyzes 52% of the data. An inter-rater agreement of 0.95 (Pearson’s correlation) is obtained for this metric. This high value indicates that the metric is reliable (Clark-Carter, 1997).

The percentage of ideas reused from the example indicates the extent of design fixation to the provided solution example. The example contains eight different ideas, as shown in Figure 5. The number of ideas from the example that each participant used in their concepts are counted and is divide by the total number of example ideas to obtain this metric. An inter-rater agreement (Pearson’s correlation) of 0.86 is obtained for this metric, showing that the metric is reliable.

Figure 5. The break down of ideas from the solution example provided to the participants (Linsey et al., 2010)

Building from the procedure proposed by Shah et al. (2000), the quantity of non-redundant ideas metric was developed by Linsey et al. (2011). A non-redundant idea is a unique, non-repeated idea, not present in the solution example. When the participants do not see the solution example, the ideas from the example are also counted to find the number of non-redundant ideas. The quantity of non-redundant ideas is calculated by a functional breakdown of all the concepts generated by the participants. The redundant ideas are eliminated from each concept and the remaining ideas are counted to calculate the quantity. Also, the authors obtain an inter-rater agreement, a Pearson's correlation of 0.87, showing that this measure is reliable.

Two metrics measure the level of fixation to the example energy source (Linsey et al., 2010): the number of energy source ideas in each participant's concepts and the percentage of concepts utilizing gas power. To calculate the percentage of concepts using gas power, the authors take the ratio of the number of concepts using gas power to the total number of concepts generated by that same participant. Inter-rater reliability

scores of 0.88 for the number of energy source ideas and 0.89 for the percentage of concepts utilizing a gas engine are obtained (both Pearson's correlations). These scores indicate that the measures are reliable.

5. Results

The participants generated many concepts to solve the peanut sheller design problem. Many among these concepts provided clear indications of design fixation. Figure 6 shows some example concepts generated by the participants that replicate many of the ideas in the example given to them. The five metrics described in the previous section are used to measure fixation quantitatively. The following subsections outline the results obtained for those metrics.

Figure 6. Example concepts generated by the participants showing high degree of fixation to the given solution example

5.1 Number of Repeated Example Ideas

The results from the number of repeated example ideas indicate that the three groups with solution examples fixate to the example ideas (Figure 7). Compared to the No Example Group, all other groups replicate more example ideas. Since the solution example contains common ideas to the requisite functions, the No Example Group utilizes some example ideas in their concepts. Still, the level of utilization is relatively small compared to the other groups. A one-way ANOVA (Tabachnick & Fidell, 2007) indicates that the mean number of repeated example ideas varies significantly across the conditions ($F = 3.38, p < 0.03$). The data are not homogenous in their variance but are normally distributed, assuring that the ANOVA results are reliable (Tabachnick & Fidell, 2007). Pair-wise a-priori comparisons (Clark-Carter, 1997; Tabachnick & Fidell, 2007; Howell, 2009) show that the No Example Group generates significantly fewer example ideas compared to all other groups, indicating design fixation in the treatment groups. The results of the a-priori tests are shown in Table 1.

Figure 7. Variation of mean number of repeated example ideas across the experimental groups.

Error bars show ($\pm$)1 standard error.

Table 1. A-priori comparison results for the number of repeated example ideas across the experiment conditions

Conditions compared	Significance (p-value)
<i>Presence of Design Fixation in Treatment Groups</i>	
No Example vs Pictorial Example	< 0.06*
No Example vs Physical Example	< 0.01*
No Example vs Physical Example Defixation	< 0.02*
<i>Hypothesis: Fixation to Different Representations of the Example</i>	
Pictorial Example vs Physical Example	< 0.07*
<i>Effect of Defixation Materials</i>	
Physical Example vs Physical Example Defixation	0.23

* represent a-priori comparisons that are statistically significant at $\alpha = 0.1$

These results indicate that the two different representations of the example concept have different effects on the participants' design fixation. The a-priori

comparison between the Pictorial Example Group and the Physical Example Group shows that the Physical Example Group fixates significantly more compared to the Pictorial Example Group. All the treatment groups reproduce significantly more number of example ideas in their concepts compared to the No Example Group, showing that all those groups fixate to the example ideas. Finally, the lack of statistical significance between the Physical Example and the Physical Example Defixation groups shows that the defixation materials may not have a large effect on novice designers in the mitigation of their fixation.

5.2 Percentage of Reused Example Ideas

The percentage of reused example ideas follows a very similar trend as that of the number of repeated example ideas (Figure 8). These data satisfy the normality and homogeneity of variance conditions, required for a one-way ANOVA, and hence this statistical technique is employed for the analysis of the data. Across the conditions, the data show an overall significant difference ($F = 7.33$, $p < 0.01$). Again, a-priori contrasts are employed for pair-wise comparisons and the results are shown in Table 2.

Figure 8. Variation of mean percentage of reused example ideas across the experiment conditions.

Error bars show ($\pm$)1 standard error.

Table 2. A-priori comparison results for the percentage of reused example ideas across the experiment conditions

Conditions compared	Significance (p-value)
<i>Presence of Design Fixation in Treatment Groups</i>	
No Example vs Pictorial Example	< 0.01*
No Example vs Physical Example	< 0.01*
No Example vs Physical Example Defixation	< 0.01*
<i>Hypothesis: Fixation to Different Representations of the Example</i>	
Pictorial Example vs Physical Example	0.17
<i>Effect of Defixation Materials</i>	
Physical Example vs Physical Example Defixation	0.21

* represent a-priori comparisons that are statistically significant at $\alpha = 0.1$

These results provide support to the hypothesis. Solution examples in both the pictorial and the physical model formats fixate participants. The mean number of repeated example ideas is slightly higher for the Physical Example Group as compared to the Pictorial Example Group, but this difference is statistically insignificant.

Interestingly, the defixation materials do not help novice participants mitigate their fixation. These results are consistent with the prior studies. Linsey et al. (2010) show that expert designers successfully mitigate their fixation to pictorial solution examples; but a follow-up study (Viswanathan & Linsey, 2012) shows that these materials are not effective for novice designers.

5.3 Quantity of Non-redundant Ideas

The quantity of non-redundant ideas varies across the four experimental groups (Figure 9). A one-way ANOVA shows statistically significant variation of this metric across the groups ($F = 2.84, p < 0.06$). Pair-wise a-priori comparisons show that the Pictorial Example Group produces significantly fewer ideas than the other groups. The results from these comparisons are shown in Table 3.

Figure 9. Variation of quantity of non-redundant ideas across the experiment conditions. Error bars show ($\pm$)1 standard error.

Table 3. A-priori comparison results for the quantity of non-redundant ideas across the experiment conditions

Conditions compared	Significance (p-value)
<i>Presence of Design Fixation in Treatment Groups</i>	
No Example vs Pictorial Example	< 0.02*
No Example vs Physical Example	0.86
No Example vs Physical Example Defixation	0.45
<i>Hypothesis: Fixation to Different Representations of the Example</i>	
Pictorial Example vs Physical Example	< 0.01*
<i>Effect of Defixation Materials</i>	
Physical Example vs Physical Example Defixation	0.35

* represent a-priori comparisons that are statistically significant at $\alpha = 0.1$

These results highlight extremely interesting trends in the data. As expected, participants with the pictorial solution example generate a lower quantity of novel ideas, an indication of fixation. In contrast, the Physical Example Group does not follow this pattern. In fact, they generate the same mean quantity of non-redundant ideas as the No Example Group. They also generate significantly higher quantity of ideas compared to the Pictorial Example Group. This indicates that, though the Physical Example Group replicates many example ideas in their concepts, they can generate a greater quantity of novel ideas than the Pictorial Example Group. The Physical Example Defixation Group does not show any improvement in the mean quantity of non-redundant ideas. This indicates that the defixation materials do not significantly help the participants. Additionally, the data seems to reveal that, though the Physical Example Group does repeat ideas from the solution example, fixation does not appear to limit their ability to generate a high quantity of ideas. Contrasting this with prior studies measuring design fixation (Jansson & Smith, 1991; Purcell & Gero, 1996; Chrysikou & Weisberg, 2005), it is essential to consider quantity of ideas as a measure for fixation, in order to get a complete picture.

In order to explore this result further, the total number of ideas generated by participants is also investigated. Figure 10 shows the variation of mean total number of ideas generated by the participants in the various experimental groups. It is interesting to note that the Physical Example Group generates higher number of ideas compared to the No Example and the Pictorial Example Group. A one-way ANOVA indicates that the variation of total number of ideas across the conditions is statistically significant ($F = 2.56, p < 0.07$). A-priori comparison results also reveal interesting trends. The results of those pair-wise comparisons are shown in Table 4.

Figure 10. Variation of mean number of ideas generated by the participants across the conditions.

Error bars show ($\pm$)1 standard error.

Table 4. A-priori comparison results for the total number of ideas generated by the participants across the experiment conditions

Conditions compared	Significance (p-value)
No Example vs Pictorial Example	0.66
No Example vs Physical Example	0.04
No Example vs Physical Example Defixation	0.35
Pictorial Example vs Physical Example	< 0.02*
Physical Example vs Physical Example Defixation	0.25

* represent a-priori comparisons that are statistically significant at $\alpha = 0.05$

These results indicate that the presence of a physical solution example stimulate the generation of a higher number of ideas compared to a pictorial solution example. This is a very interesting insight. The Physical Example Defixation Group also generates a higher mean number of ideas compared to the Pictorial Example Group. However, when the defixation materials are present, the total number of ideas drops by a small amount. Considering the lack of any significant difference between the No Example and the Pictorial Example Group, it may be argued that the physical model of the solution example leads them to the generation of more complete solutions. This argument needs further investigation.

5.4. Number of Energy Sources in Participants' Concepts

The mean number of energy sources does not vary much across the experiment conditions, as evident from Figure 11. These data satisfy the normality and homogeneity of variance criteria for a one-way ANOVA; hence it is used for the statistical analysis. The results from one-way ANOVA indicates that, statistically, the number of energy sources does not vary significantly across the conditions ($F = 1.00$, $p = 0.40$). Further, though it appears that the Pictorial Example Group produces a lower number of energy source ideas, a-priori contrast results indicate that this difference is

statistically not significant. This result is consistent with a prior study by Viswanathan and Linsey (2012). The results from a-priori comparisons are shown in Table 5.

Figure 11. Variation of number of energy sources used by the participants in their concepts across the experiment conditions. Error bars show ($\pm$) 1 standard error.

Table 5. A-priori comparison results for the number of energy sources used by the participants across the experiment conditions

Conditions compared	Significance (p-value)
<i>Presence of Design Fixation in Treatment Groups</i>	
No Example vs Pictorial Example	0.18
No Example vs Physical Example	0.91
No Example vs Physical Example Defixation	0.95
<i>Hypothesis: Fixation to Different Representations of the Example</i>	
Pictorial Example vs Physical Example	0.14
<i>Effect of Defixation Materials</i>	
Physical Example vs Physical Example Defixation	0.96

* represent a-priori comparisons that are statistically significant at $\alpha = 0.1$

Consistent with the prior studies, the Pictorial Example Group produced a lower mean number of ideas for energy sources; however probably due to a low effect size, this difference was not significant. The Physical Example Group produced the same mean number of ideas for energy sources as the No Example Group, indicating no fixation. For this metric as well, defixation materials did not have any effect on novice designers.

5.5. Percentage of Gas-powered Concepts

Interestingly, the percentage of concepts using a gas powered press does not vary much across all the experiment conditions (Figure 12). These data are not normally distributed; however they do satisfy the homogeneity of variance criteria. With the available sample size, one-way ANOVA is robust to the violation of normality (Tabachnick & Fidell, 2007). The results from one-way ANOVA statistically confirm the argument that the percentage of gas-powered concepts does not vary significantly across the conditions ($F = 0.71$, $p = 0.55$). Further, a-priori contrasts results indicate that none of the pair-wise comparisons are statistically significant (Table 6).

Figure 12. Variation of percentage of concepts which are gas powered across the experiment conditions. Error bars show ($\pm$) 1 standard error.

Table 6. A-priori comparison results for the percentage of gas-powered concepts across the experiment conditions

Conditions compared	Significance (p-value)
<i>Presence of Design Fixation in Treatment Groups</i>	
No Example vs Pictorial Example	0.41
No Example vs Physical Example	0.17
No Example vs Physical Example Defixation	0.68
<i>Hypothesis: Fixation to Different Representations of the Example</i>	
Pictorial Example vs Physical Example	0.57
<i>Effect of Defixation Materials</i>	
Physical Example vs Physical Example Defixation	0.33

* represent a-priori comparisons that are statistically significant at $\alpha = 0.1$

The lack of any statistical significance for the number of energy sources and the percentage of gas-powered concepts can be due to one of the following reasons: a low

effect size of these metrics, a higher variability in these data or since the participants are not fixating to the energy source in the solution example, in particular. All the treatment groups produce the same mean value for this metric as that of the No Example Group. At the same time, the Pictorial Example Group and the Physical Example Group also produce the same mean value for this metric. To derive conclusions for these metrics, a much larger sample size is necessary. However, from the current data, it can be suspected that the type of representation employed for conveying the solution example may not affect the extent of fixation to the energy source used in the solution example.

6. Discussion

The results indicate that the participants fixate to the ideas in the pictorial solution example. They replicate many ideas from the example in their concepts resulting in a higher mean number of repeated example ideas as compared to the No Example Group. The Pictorial Example Group produces fewer energy source ideas as compared to other groups; still, the percentage of concepts utilizing a gas engine remains constant across the conditions. These results are consistent with prior studies which demonstrate that designers fixate to pictorial solution examples (Jansson & Smith, 1991; Purcell & Gero, 1996; Chrysikou & Weisberg, 2005; Linsey et al., 2010).

Interpreting the results for the number of repeated ideas, it can be argued that participants utilizing physical solution examples fixate more to the ideas of the example compared to those utilizing the pictorial solution example. This result does not support the hypothesis. However, the percentage of example ideas used shows an opposite trend and supports the hypothesis. Also, the Physical Example Group produces significantly more non-redundant ideas as compared to the Pictorial Example Group. In fact, the quantity is comparable to that of the No Example Group. The mean number of concepts remains the same across all the conditions. However, the Physical Example Group

generates significantly higher number of ideas to solve the functions to be fulfilled by the device. Thus, though some of the ideas are replicated from the example, the Physical Example Group tends to produce a greater number of ideas to solve the design problem. In this case, the physical solution example may be acting as a provocative stimulus through the solution example exposure. This effect needs further investigation. Fixation is not observed in the use of energy sources in concepts. Overall, the metrics provide mixed support to the argument that physical models and pictorial solution examples fixate designers to a similar extent. In order to clarify this, further investigations are necessary.

The spatial dimensionality of the solution example may be a potential factor influencing the extent of fixation to the example. In this study, the physical model employed is a three-dimensional representation of the pictorial solution example. It contains the same amount of information as the sketch. However, these two differ in their dimensionality. The presence of a three-dimensional model in front of the designers, rather than a sketch, may be influencing the generation of their ideas, and leading them to a higher amount of fixation.

These results possess important implications for engineering design. Specifically, the results indicate that, though solution examples in the form of physical models can lead to design fixation, they can also lead designers to more novel and non-redundant solutions. The presence of a physical model during idea generation might lead designers to consider each feature of the model and subsequently generate solutions for the functions fulfilled by example features. Pictorial examples containing the same amount of information do not have the same effect. This indicates designers might derive different magnitudes of information from these two types of solution examples. As a consequence, physical representations might play an important role in

the design process because designers might extract a greater amount of information from them. This argument requires further investigation in future work.

The results from this study show that designers replicate the example ideas more frequently when they encounter the solution example in physical form. One potential explanation for this phenomenon lies in the theory of constructive perception (Osborne, 1953; De Bono, Arzt, Médecin & Malta, 1984). According to this theory, when some ambiguity is present in a representation, designers tend to mentally reorganize the details of that representation, leading them to new ideas. Compared to a physical model, sketches are more ambiguous and they may lead designers to more mental reorganizations and re-interpretations. As a result, the amount of fixation may be lower. On the other hand, a physical model provides more details to the designers and can be considered as less ambiguous, leading to less amount of re-interpretation and a higher amount of fixation compared to solution example sketches.

The conflicting results obtained from the multiple indicators of design fixation in this study can be explained with the cognitive mechanism of fixation. According to the working-backwards cognitive strategy adopted by designers while solving an ill-structured problem (see Section 2.2) (Restrepo & Christiaans, 2004; Cross, 2008), fixation is attributed to the constraints formulated by the designers around the solution example given to them. This formulation of constraints leads to a premature commitment towards the example solution, leading designers to fixation. When the solution example is presented in a physical form, it may lead designers to a stronger commitment to the constraints formulated around it, causing a higher extent of fixation, compared to a sketch. At the same time, since the physical model is less ambiguous and conveys all the requirements for a feasible solution to the designers in a better way, they tend to generate more ideas in each concept, leading to an increased quantity. Thus a

physical representation of a solution example may fixate designers more, but has the potential to lead them to a higher quantity of non-redundant ideas. This is consistent with the observations presented in this study.

This study uses a non-working prototype, which can cause some biases in the results. The participants are told that since the solution example uses a gas-powered engine, and it can with a gas-powered motor added to it. However, if the prototype works, the designers may formulate even stronger constraints about the same, which may lead them to an even higher degree of fixation. This will be explored as a future work.

The results also show that the defixation materials do not help novice designers mitigate their fixation to example solutions. This result also validates the studies by (Viswanathan & Linsey, 2012), which show that the same defixation materials do not help novice designers mitigate their fixation to solution examples. Linsey et al. (2010) show that expert designer can use the resources provided to them, in the form of defixation materials, and significantly mitigate their fixation to the example ideas. Unfortunately, novice designers fail to utilize these materials in either pictorial or physical form.

This differential effectiveness of defixation materials may be attributed to the adaptive nature of the knowledge of experts (Hatano & Inagaki, 1986; Barnett & Koslowski, 2002). The defixation materials primarily developed by Linsey et al. (2010) are shown to be effective in engineering design faculty. The design faculty possess a larger amount of knowledge related to design theory and methodology and frequently use this knowledge to solve open-ended design problems (Hatano & Inagaki, 1986; Schwartz, Bransford & Sears, 2005). This makes their knowledge more conceptual in nature and that can be easily adapted to new situations. The defixation materials may

support the transfer of their conceptual knowledge when they encounter a new design problem. However, the knowledge of novices in design is less conceptual in nature, which may lead to a lower effectiveness of these defixation materials on them.

7. Conclusions

This paper investigates the effects of solution example modality on the degree of design fixation. A between-subject controlled experiment evaluates the hypothesis that designers fixate to physical solution examples to a similar extent as to the pictorial ones. In the experiment, participants generate ideas for a design problem with the help of either pictorial or physical solution examples. A control group generates ideas without the help of solution examples. In order to test the effectiveness of the defixation materials by Linsey et al. (2010) on novice designers, another condition uses these materials as well. The occurrence of example ideas in the concepts generated by the participants is studied to identify design fixation. Multiple indicators of fixation are used and they provide mixed support to the hypothesis. All the groups that receive solution example fixate to the ideas in that example compared to the control group. Comparing the treatment groups, the designers with physical solution example replicate the example ideas more often compared to those with pictorial solution example, indicating that the physical solution example causes a higher degree of fixation. However, the Physical Example Group also produces a higher quantity of non-redundant ideas compared to the Pictorial Example Group, pointing in the opposite direction of relatively less fixation. In fact, the quantity of non-redundant ideas of the participants with the physical solution example compares to that of the control group. In general, it can be argued that a physical representation of the solution example can lead designers to a higher degree of fixation but also to a higher quantity of non-redundant ideas. More explorations of this phenomenon with working prototypes and different

solution examples are required to further clarify the role of example modality on design fixation.

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