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PHYSICAL EXAMPLES IN ENGINEERING IDEA GENERATION: AN EXPERIMENTAL INVESTIGATION

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Abstract: 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 fixation. The majority of studies investigate the role of pictorial stimuli in design fixation. 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 are also investigated. The results show that both formats cause the same magnitude of fixation; however, participants utilizing physical examples produce a greater quantity of complete ideas. The defixation materials do not facilitate novice designers' mitigation of their fixation.

Keywords: *Design Fixation, Examples, Idea Generation, Physical Representations*

1. Introduction

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

This study seeks to compare design fixation caused by pictorial and physical examples. The authors hypothesize that physical examples can cause the same level of design fixation as pictorial examples. 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 the final conclusions.

2. Background

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

A number of studies show that, when designers are given example solutions, they fixate (Jansson and Smith, 1991; Chrysikou and Weisberg, 2005; Purcell and Gero, 1996; 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. As a follow-up, Purcell and Gero (Purcell and Gero, 1996) show that industrial designers fixate less to examples compared to mechanical engineers. Linsey et al. (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. A majority of these studies use hand sketches to present their examples. Complimenting these efforts, Cardoso et al. (Cardoso, et al., 2009) 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. Efforts to replicate these results with higher fidelity representations, including three-dimensional virtual models and physical models, are scarce.

Based upon the background literature, the following hypothesis is formulated and further investigated in this paper:

Hypothesis: Designers fixate to both pictorial and physical examples to the same extent.

The following sections present a controlled experiment investigating this hypothesis 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 Linsey et al. (Linsey, et al., 2010) and Viswanathan and Linsey (Viswanathan and Linsey, 2012; 2011a). Participants generated ideas to solve a design problem in four different groups: No Example 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 features in their solutions was studied to identify the extent of their fixation to the example.

All the participants solved a "peanut sheller" design problem (Linsey, et al., 2010; Linsey, et al., 2012; Linsey, et al., 2011). This problem asked participants to generate as many ideas as possible for a device that can quickly and efficiently shell peanuts without the use of electricity and with minimum damage to the peanuts. 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 four experiment groups differed in both the type of additional materials provided and the manner in which the example was presented. The No Example Group received only the design problem statement and no supplemental material. The Pictorial Example Group received an example solution, in the pictorial form, as shown in Figure 1, along with a short description. The description detailed the operation of the example solution. The exact statement was the following: "This system uses a gas powered press to crush the peanut shell. The shell and peanut then fall into a collection bin". The Physical Example Group received the same example solution in the form of a physical model (Figure 1Figure). This physical model was not functional; but the participants were not informed of this. They were told that it could function with a gas powered motor. The Physical Example Defixation Group received the same physical model and the defixation materials used in prior experiments (Linsey, et al., 2010; Viswanathan and Linsey, 2012; 2011a). The defixation materials consisted of a brief functional description of the problem along with some back of the envelope calculations, lists of energy sources and analogies that could help solve the problem. These defixation materials were effective in mitigating design fixation in experts (Linsey, et al., 2010), but not in novices (Viswanathan and Linsey, 2012; 2011a).

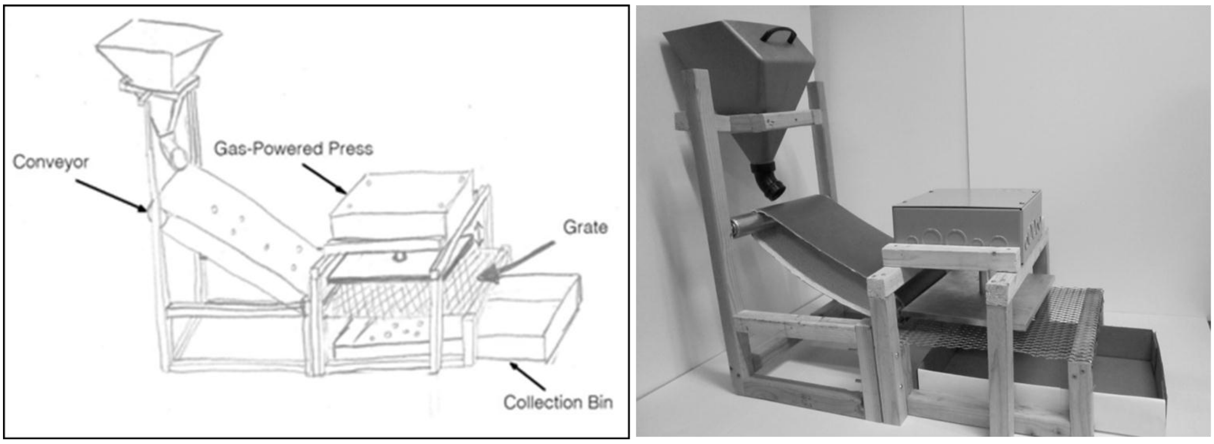

Figure 1. Pictorial example given to the Pictorial Example Group (left) and physical example provided to the Physical Example and Physical Example Defixation groups (right).

Senior undergraduate and graduate students from the Mechanical Engineering Department at Texas A&M University participated in this study. There were a total of 29 participants (21 undergraduate students and 8 graduate students). Six were in the No Example Group, seven in the Pictorial Example Group and eight each in the remaining two groups. The graduate students were equally distributed across the conditions. Six 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.

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. As the experiment began, they received the design problem statement along with the appropriate 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 example were also allowed to inspect it. The physical model was displayed on a table in front of them. These five minutes were followed by a 45 minute idea generation. They were instructed to generate as many ideas as possible. To encourage their participation, they were told that the participant with greatest number of solutions would receive a prize. To ease logistics, this prize was given to all participants, but the participants did not know this prior to the experiment. The 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 of each part. At the end of the experiment, a survey asked the participants about their prior exposure to the design problem and any relevant industrial experience.

4. Metrics for evaluation

To measure fixation, five metric are used: number of repeated example features, percentage of reused example features, quantity of non-redundant ideas, number of ideas for energy sources and percentage of ideas using a gas engine. These metrics are employed by Linsey et al. (Linsey, et al., 2010) in their study on fixation and its mitigation in experts. The number of times example features appear in a participant's solution is counted. 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. Another metric involves the percentage of features reused from example. This is calculated as the ratio of the number of utilized example features to the total number of ideas within each example solution. An inter-rater agreement of 0.86 is obtained for this metric, showing that the metric is reliable.

Building from the procedure proposed by Shah et al. (2000), the quantity of non-redundant ideas metric was developed by Linsey et al. (2011). For this experiment, an "idea" is defined as a component that solves at least one function in the functional basis (Stone and Wood, 2000). A non-redundant idea is a unique, non-repeated idea not present in the example. Even when participants do not see the 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 break down of all solutions. 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: the number of energy source ideas in each participant's solutions and the percentage of solutions utilizing gas power. To calculate the percentage of solutions using gas power the authors take the ratio of the number of solutions using gas power to the total number of solutions 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 ideas utilizing a gas engine, are obtained. Said scores indicate that the measures are reliable.

5. Results

5.1. Number of Repeated Example Features and Percentage of Reused Example Features

The results from the number of repeated example features and the percentage of reused example features indicate that the three groups with examples fixate to the example features (Figure 2). Compared to the No Example Group, all other groups replicate more example features. Since the example contains common solutions to the requisite functions, the No Example Group utilizes some example features in their ideas. Still, the level of utilization is relatively small compared to the other groups. A one-way ANOVA indicates that the mean number of repeated example features varies significantly across the conditions (F(4,25) = 3.38, p<0.03). Pair-wise a-priori comparisons show that the No Example Group generates significantly fewer example features compared to all other groups (No Example vs. Pictorial Example: p<0.08; No Example vs. Physical Example: p<0.001; No Example vs. Physical Defixation: p<0.04). As expected, all other pair-wise comparisons are not statistically significant. The percentage of reused example features follows the same trend (Figure 2). Across the conditions, the data shows an overall significant difference (using one-way ANOVA: F(4,25) = 5.92, p<0.001); moreover, a lower percentage exists in the No Example Group as compared to the other groups (No Example vs. Pictorial Example: p<0.001; No Example vs. Physical Example: p<0.001; No Example vs. Physical Defixation: p<0.01).

These results strongly support the hypothesis. Examples in both the pictorial and the physical model formats fixate participants. The mean number of repeated example features 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 examples; but a follow-up study (Viswanathan and Linsey, 2012; 2011a) shows that these materials are not effective for novice designers.

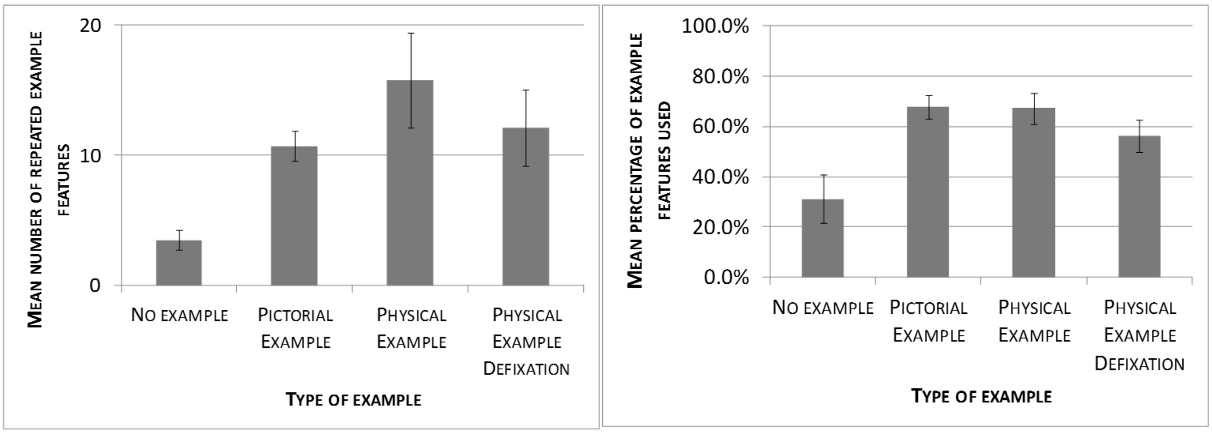

Figure 2. Variation of mean number of repeated example features (left) mean percentage of example features used (right) and across the conditions. Error bars show (±)1 standard error.

5.2. Quantity of non-redundant ideas

The quantity of non-redundant ideas varies across the four groups (Figure 3). A one-way ANOVA shows statistically significant variation of this metric across the groups (F(3, 25) = 2.41, p<0.09). Pair-wise a-priori comparisons show that the Pictorial Example Group produces significantly less ideas than the other groups (Pictorial Example vs. No Example: p <0.09; Pictorial Example vs. Physical Example: p< 0.02; Pictorial Example vs. Physical Example Defixation: p< 0.05). Other pair-wise comparisons are statistically insignificant.

These results highlight extremely interesting trends in the data. As expected, participants with the pictorial example generate a lower quantity of novel ideas, an indication of fixation. Conversely, 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. This indicates that, though the Physical Example Group replicates many example features in their solutions, 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. Said fact 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 features from the example, said fixation does not appear to limit their ability to generate a high quantity of ideas. Contrasting this with prior studies measuring design fixation (Jansson and Smith, 1991; Chrysikou and Weisberg, 2005; Purcell and Gero, 1996), it is essential to consider quantity of ideas as a measure for fixation, in order to get a complete picture.

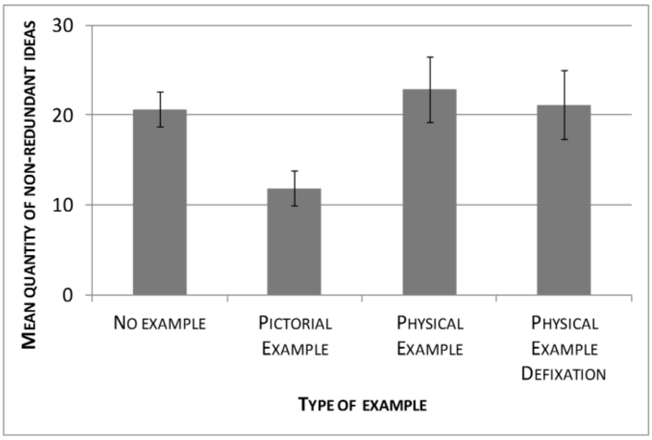

Figure 3. Variation of mean quantity of non-redundant ideas across the experiment groups. Error bars show (±)1 standard error.

5.3. Energy sources fixation

The mean number of energy sources and the mean percentage of solutions using gas as the power source do not vary much across the conditions (Figure 4Figure). A one-way ANOVA indicates that both metrics do not significantly vary across the conditions (Number of energy sources: $F(4,25) = 1.42$, $p = 0.26$; Percentage of solutions with gas powered press: $F(4,25) = 0.21$, $p = 0.88$). Still, the Pictorial Example Group produce a lower mean number of energy source ideas as compared to other groups. Said result is consistent with the prior study by Viswanathan and Linsey (2012).

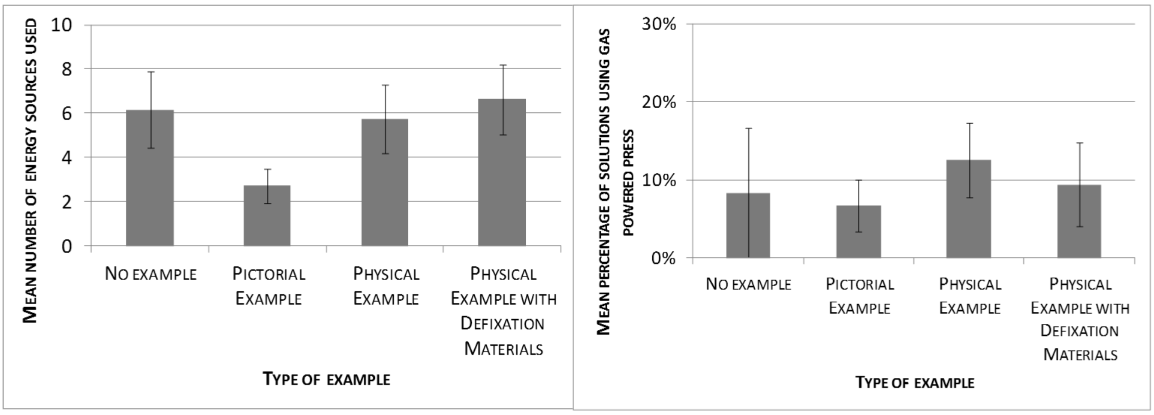

Figure 4. The variation, across the conditions, of the mean number of energy sources (left) and the percentage of solutions using a gas engine (right). Error bars show (±) 1 standard error.

Consistent with prior studies, the Pictorial Example Group produced a lower mean number of ideas for energy sources. The Physical Example Group produced the same mean number of ideas for energy sources as the No Example Group, indicating no fixation. In this study as well, defixation materials did not have any effect on novice designers. Interestingly, the percentage of solutions using a gas powered press remains constant across all the conditions.

6. Discussion

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

Participants utilizing physical examples fixate to the example solution features to the same extent as those utilizing the pictorial example. This result strongly 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 solutions remains the same across all the conditions. Said observation indicates that, for a given solution, the Physical Example Group produces more ideas satisfying the requisite functions. In the No Example and the Pictorial Example groups, participants generate many partial solutions which satisfy only some of the necessary functions of the peanut sheller (for example: a solution contains ideas to only shell peanuts but does not include ways to separate the broken shells). Though some of the ideas are replicated from the example, the Physical Example Group tends to produce a greater quantity of complete solutions. In this case, the physical example may be acting as provocative stimuli through example exposure, which needs further investigation. The presence of fixation is not observed in the use of energy sources in solutions. These results possess extremely important implications for engineering design. More specifically, the results indicate that, though examples in the form of physical models can lead to design fixation, they can also lead designers to more complete 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 function each example feature fulfils.

Pictorial examples containing the same amount of information fail to have the same effect. This indicates designers might derive different magnitudes of information from these two types of 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.

Existing literature provides conflicting guidelines concerning fixation caused by the building of physical models during engineering idea generation. Kiriyama and Yamamoto (1998) observe that novice designers building physical models during idea generation fixate to variations of their initial ideas. A similar observation is made by Christensen and Schunn (2005) in their study on practicing designers. A controlled study by Viswanathan and Linsey (Accepted), with a simple design problem, fails to detect fixation from working with physical models. In a follow-up controlled study (Viswanathan and Linsey, 2011b), they show that the design fixation observed in prior studies occurs because of the Sunk Cost Effect; in other words, fixation is not an inherent part of the building process. The Sunk Cost Effect entails an adherence to a chosen course of action after significant investment is devoted to that path (Arkes and Blumer, 1985; Kahneman and Tversky, 1979). During idea generation, if designers spend a large amount of time, money or effort solving design problems, they tend to fixate to variations of their initial ideas. When designers build their own physical models, they fixate as demonstrated by the prior studies (Kiriyama and Yamamoto, 1998; Christensen and Schunn, 2005). In this study, designers do not fixate to the physical example any more than to the pictorial one because they receive the physical model, and the sunk cost associated with building is low. Similar results are reported by Youmans in a recent study (Youmans, 2011). These results reinforce the argument that the Sunk Cost Effect is a major factor in causing design fixation.

The results also show that the defixation materials do not help novice designers mitigate their fixation to example solutions. This result also validates the study by Viswanathan and Linsey (2012; 2011a), which shows that the same defixation materials do not help novice designers mitigate their fixation to pictorial 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 features. Unfortunately, novice designers fail to utilize these materials in either pictorial (Linsey, et al., 2010) or physical form.

7. Conclusions

This paper investigates the effects of physical examples on design fixation. The study presented hypothesizes that designers fixate to physical examples to the same extent as to pictorial. A between-subject controlled experiment evaluates this hypothesis. In the experiment, participants generate ideas for a design problem with the help of either pictorial or physical examples. The occurrence of example features in their solutions is studied to identify fixation. The results support the hypothesis. The participants fixate to physical examples to the same extent as to pictorial examples. Still, participants with physical examples generate a greater quantity of complete solutions. These results also strongly support the argument that, during idea generation, design fixation is caused by the Sunk Cost Effect and fixation is not an inherent aspect of working with physical models. Due to these reasons, quick prototyping techniques such as rapid prototyping need to be encouraged during engineering design. Designers can also employ separate technicians to build prototypes of their ideas. Said strategy might reduce the Sunk Cost Effect and resultantly lead to a greater quantity of novel ideas.

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