AC 2010-1941: EFFECTS OF AN EARLY PROTOTYPING EXPERIENCE: CAN DESIGN FIXATION BE AVOIDED?

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Effects of an Early Prototyping Experience on the Innovation Process:

Can Design Fixation Be Avoided?

Abstract
It has been well established that introduction of physical artifacts early in the design process can limit the potential solution set in terms of diversity, innovation and number of ideas generated. This limiting effect is known as “design fixation.” While the potential for design fixation exists, concrete, tangible, and physical perceptions of the design task may also be very beneficial during the ideation process. For example, it may increase the feasibility of the concepts generated. Physical testing of preliminary ideas may enable such perceptions. The objective of the study reported in this paper was to understand, at least at the basic and preliminary levels, the role of physical testing and artifacts in the early stages of the design process. To this end, the contemporary design process was augmented with an Early Prototyping Experience (EPE), where the intent was to increase critical understanding of the design problem while maintaining the innovativeness and diversity of the concepts. An experiment was undertaken which included the use of a “control” group that did not participate in the EPE, as well as the “experimental” group that did develop an early prototype. The output from a concept generation exercise for the two groups was rated by experts to determine the level of innovation, diversity and feasibility of the ideas. Experts’ ratings for innovativeness and diversity were very similar between the control and experimental groups indicating that, in these two areas, design fixation was not evident. However, results indicated that the experimental group did experience some level of fixation based on the fact that they generated 30% less unique ideas than did the control group. Feasibility of the ideas was, however, much higher for the experimental group. Because of these mixed results concerning design fixation and the fact that there are other potential benefits of early prototyping, it remains a point of discussion as to whether the EPE has an overall negative or positive effect on the design process.

1.0 Overview and Purpose
Design fixation is a state where the results of the ideation or concept generation process have been degraded; such degradation normally occurs in the areas of innovativeness, diversity or number of ideas generated. While many causes for this design fixation have been identified, the introduction of physical or visual artifacts is one of the most common causes [1-7]. However, there may also be significant benefits to the introduction of embodiments early in the design process. Benefits might include better initial understanding of the feasibility of certain solutions or the uncovering of hidden latent customer needs.

The purpose of this paper is to ascertain the impact of incorporating EPE into the design process. The concepts developed by the experimental and control groups were compared to determine if fixation or other pertinent issues existed, particularly with regard to the quantity, diversity, and innovativeness of the concepts generated. Additionally, feasibility of the concepts was also
compared. A similar experiment was conducted at the University of Texas at Austin, where design groups implemented Empathic Lead User Analysis [9] with rapid prototypes to develop more concrete perceptions of the design task.

### 2.0 Related Work

Loss of effectiveness in the concept generation phase of the design process can be attributed to a variety of different causes. Early exposure to proposed analogies, details of the group dynamics as well as experience with physical, or even virtual, prototypes can all potentially be linked to degradation of brainstorming activities [10-12]. In concept generation, the ability to develop a wide variety of ideas increases the likelihood of finding high quality solutions to the design problem [13, 14]. Most concept generation techniques endeavor to create an environment where development of a large number of innovative, feasible solutions was encouraged. Often in concept generation, the exposure to specific examples and the interchange of ideas between designers is a key component of the process. This exposure and idea exchange [15] has two sides. On one hand, the exposure to similar or analogous systems and principles can work as a catalyst or as a seed, allowing the designer to pull together ideas from different sources and more effectively synthesize an innovative solution [16, 17]. On the other hand, however, this same exposure and idea exchange can also interfere with effective problem solving by promoting design fixation [18, 19].

Design fixation can be thought of as a form of cognitive interference, where external stimuli disrupt or limit the ideal thought processes leading to ideation [20]. Fixation can occur, for example, when designers commit to an artificially limited set of ideas early in the process [18, 21]. This fixation could refer to a specific principle or solution to the design problem, or it could refer to a limited interpretation of the scope of the problem. Such limitation can occur from the way the design problem is introduced, from the designers’ past experiences, or from specific solutions or principles encountered during the concept generation process. As an example, a designer may be exposed to several common solutions already in existence for a certain design problem. That designer may be more inclined to build off of these concepts and focus on small incremental innovations, rather than exploring alternate principles and domains. In another type of fixation, the designer may be exposed to a single, unique solution to a problem. Eager to explore other possibilities, the designer may focus on using other means to accomplish the goal, while deliberately ignoring possible innovations that bear any resemblance to the existing concept [21]. Jansson and Smith [18] describe design fixation as the inability to move from the physical “object space” back into conceptual “problem space.” They also showed that exposure to a specific example solution before concept generation does often result in the inclusion of features from the example solution into subsequent concepts at an abnormally high rate. The question is whether this happens when early prototyping is introduced, and if so, if the occurrence of design fixation outweighs the possible benefits of including this step.

The use of physical prototyping early in concept generation is one way in which the concept generation process could possibly be aided (through exposure to new ideas, social motivation as
real prototypes are created, or through increased physical understanding of the problem) or hindered (through design fixation). Prototypes and other physical or analytical models are an essential part of the design process. However, in most design theory, prototyping takes place after much of the concept generation and evaluation has already occurred [8, 22]; typically, designers select a few of the most promising concepts and develop them into prototypes to test their real-world feasibility.

![Diagram of design process](image)

**Figure 1:** A Contemporary Design Process (from Otto & Wood)[8]

![Diagram of energy harvesting prototype](image)

**Figure 2:** Schematic of Energy Harvesting “Early” Prototype

### 3.0 Experimental Setup
As a basis for the initial study, an EPE was added to the design process shown in Fig. 1 with pilot design groups at the US Air Force Academy and the University of Texas at Austin. By way
of example, an “Energy Harvesting” Capstone Design Group at the US Air Force Academy was tasked with creating power sources which can produce small quantities of power for structural health monitors and transmission devices on bridges. After completing initial background research and basic customer needs analysis, the Energy Harvesting Group began its design process by producing a rapid prototype (Figure 2) in a two-week time period. This model, intended for use on a bridge, was able to capture energy from wind and convert it to electrical energy by the rotating spindles hitting and deforming a piezoelectric material. In order to determine if the introduction of this EPE had positive or negative effects, an experiment was devised to determine if design fixation occurred due to the introduction of the EPE in the design process. The Energy Harvesting Group functioned as an “experimental” group in this experiment, while the “control” group was comprised of students who had backgrounds similar to the experimental group (in this case, similar majors). After the experimental group accomplished the EPE, both the experimental and control groups participated in a “6-3-5” ideation exercise. 6-3-5 is a rotational drawing exercise (sometimes called brainwriting or C-Sketch) commonly used by design groups during concept generation. It is important to note that the control group was given the same customer needs and initial background research that the Energy Harvesting Group used.

Some background on the 6-3-5 method will provide needed context to understand the experiment. In the classic method of “brainstorming,” a small group of people openly discuss possible new solutions to an existing problem or conceptual solutions for a new design problem. While this method may be effective in some forums, it has been shown in some design situations to lack the synergistic effect that is desired; the group might not produce a higher number or quality of solutions in this “brainstorming” environment than a group of individuals working alone [10]. This finding has led many in the design community to the use of a modified brainstorming technique called 6-3-5, which is described graphically in Figure 3. In this technique, a small design group (approximately 6 members) each takes the initial 5-15 minutes of the exercise to develop a small number of concepts (usually three) intended to solve a design problem [8]. These ideas are captured through a combination of sketches and words. Optimally, large sheets of paper and different colored markers are provided for each participant. After a member creates their initial three ideas, they pass the paper to the adjacent group member. An additional 5-10 minutes are now provided for the members to add to/comment on the ideas of their colleagues, or to create entirely new ideas as inspired by the sketches received. This process continues until each member has taken the opportunity to add to the concepts from all other members. No verbal communication is allowed during this entire process until each member receives his/her original concept sheet. This exercise was conducted by both the experimental and control groups. A sample is show in Figure 4.
Figure 3: 6-3-5 Concept Generation Process [8]

Figure 4: Example of 6-3-5 Chart for Energy Harvesting on a Bridge
In order to quantify relevant variables from the 6-3-5 sheets, experts (in this case, faculty project advisors) were used to evaluate the sheets. The technique of using experts to evaluate data like this has been used successfully in the past [11, 12]. In particular, it was desired that four variables be measured: Innovation, Diversity, Feasibility and Quantity. The evaluation rubrics used in the experiment are shown in Figures 5 and 6 below.

Please review the Concept Generation Sheets (from 6-3-5) and provide numerical ratings for the 4 categories as described below:

**Innovativeness** - the level of creativity or "out of the box" nature of the solutions
10 = awesome innovativeness; 7 = great innovativeness; 5 = average innovativeness; 3 = minimal innovativeness 0 = no innovativeness
Ex: the 1st post-it note, Ex: The 1st flip phone Ex: Spill-proof cup Ex: Halogen headlights Ex: Typical problem solution

**Diversity of Concepts** – Based on the distribution of concepts across the possible design space.
10 = top 2 most diverse; 7 = next 3 most diverse; 5 = middle 3 most diverse, 3 = next 3 most diverse 0 = 2 least diverse

**Feasibility of Concepts** – based on your perception of the likelihood that the product can be built and will meet the design requirements
10 = top 2 most feasible; 7 = next 3 most feasible; 5 = middle 3 most feasible, 3 = next 3 most feasible 0 = 2 least feasible

<table>
<thead>
<tr>
<th>Sheet #</th>
<th>Innovativeness of Concepts</th>
<th>Diversity of Concepts</th>
<th>Feasibility of Concepts</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 ... N</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Figure 5: Evaluation Sheet Used by Experts to Rate Concepts from 6-3-5 Sheets

**Functional Embodiment** – Most energy harvesting systems accomplish the 4 functions in the chart below. For each 6-3-5 sheet, list all the embodiment choices used to meet these 4 functions for all the concepts shown on the sheet. As an example concept, consider the typical fan system shown below.

<table>
<thead>
<tr>
<th>Sheet #</th>
<th>Function1=Import Energy</th>
<th>Function2=Transfer Energy</th>
<th>Function3=Convert Energy</th>
<th>Function4=Store Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>Example</td>
<td>Fan</td>
<td>Shaft/wires</td>
<td>Generator</td>
<td>Battery</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Sheet #</th>
<th>Import Energy</th>
<th>Transfer Energy</th>
<th>Convert Energy</th>
<th>Store Energy</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
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<td>2</td>
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</tr>
<tr>
<td>3 ... N</td>
<td></td>
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</tbody>
</table>

Figure 6: Evaluation Sheet Used by Experts to Quantify the Number of Unique Concepts
The table in Figure 5 was used to measure innovation, diversity and feasibility of each sheet. Each sheet was scored separately for each of the three characteristics. The sheets were allowed to receive a score of 10, 7, 5, 3 or 0 and only a certain number of each score were allowed to be used. The top half of the figure explains what each score means.

The table in Figure 6 was used to score the quantity of unique ideas indirectly by having the rater list how four specific functions were accomplished on that sheet. The total count of these ideas is the quantity of unique ideas. The functions to be listed are: Import Energy, Transfer Energy, Convert Energy and Store Energy.

These four variables were obviously chosen to be measured because the team was doing the experiment to determine whether the inclusion of an EPE would limit the diversity, innovation or number of ideas generated. They also were interested in seeing whether the EPE increased the feasibility of concepts generated.

### 4.0 Results

Results from the experiment can be divided into quantitative and qualitative categories. Table 1 shows the ratings data from the three experts. Simple statistics are computed resulting in the summary of the data in Table 2.

<table>
<thead>
<tr>
<th>Expert</th>
<th>Control</th>
<th>Experimental</th>
</tr>
</thead>
<tbody>
<tr>
<td>Expert 1</td>
<td>6.2</td>
<td>5.1</td>
</tr>
<tr>
<td>Expert 2</td>
<td>6.4</td>
<td>6.5</td>
</tr>
<tr>
<td>Expert 3</td>
<td>4.0</td>
<td>4.5</td>
</tr>
</tbody>
</table>

Table 1: Rating Data from Experts

<table>
<thead>
<tr>
<th>Average Ratings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Innovation</td>
</tr>
<tr>
<td>Diversity</td>
</tr>
<tr>
<td>Feasibility</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Control</th>
<th>5.5</th>
<th>5.3</th>
<th>4.2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Experimental</td>
<td>5.4</td>
<td>4.9</td>
<td>6.3</td>
</tr>
</tbody>
</table>

Avg. Difference Between Raters' Scores = 1.39

"Control" produced 30% more unique concepts than "experimental"

The first question one needs to address is if the experts’ evaluations are consistent. In previous studies as few as two experts were deemed sufficient if their evaluations were relatively
consistent. In our case, the evaluations from the three experts were fairly consistent. As can be seen in Table 2, the average difference in ratings between the three experts is 1.39.

Note from Table 2 that the ratings for innovation were very close to the same for the control and experimental groups (5.5 vs. 5.4). This is seen as evidence that the EPE did not create design fixation in the experimental group in terms of the innovation aspect. A similar argument can be made for the diversity ratings with a difference of 5.3 (for the control) vs. 4.9 (for the experimental). This is well within the average difference between the experts’ ratings (1.39) indicating that overall the experts did not see significant diversity differences between the control and experimental groups. However, the number of unique ideas created (30% > for control group) was significantly higher for the control group as compared to the experimental group while the average feasibility of ideas produced by the experimental group was higher (6.3 vs. 4.2) than those produced by the control group. This indicates that, in terms of these aspects of design fixation, the EPE did have an effect.

Qualitative results can also play a role in the overall assessment of the EPE. A number of positive qualitative results from the EPE have been reported by the experimental group. They believe that the EPE provided critical insight into the problem. The team reported being better focused while doing research during the EPE and that they better understood the end goal. This focus during the research step was due to the fact that they quickly found a concept that would work, so they focused their research on deepening their understanding of that topic versus researching a broad range of topics. The EPE also uncovered latent customer needs and helped the team gain first-hand experience into the difficulty associated with meeting some of the design requirements. Some latent customer needs the group discovered dealt with the environmental factors that vary around the country. For example, one of their original concepts included a strip of material that would be laid across a bridge for vehicles to drive over. By driving over it, the pressure felt by the strip would be converted to energy. But in some areas of the country, snowplows are used often. These snowplows could damage the strip; therefore, the group decided not to use that concept. They also considered locations of bridges and their proximity to environmental factors. For example, some bridges cross water, whereas some do not. Therefore, they decided not to design a device that uses water power, although that was one of their original concepts. Specifically, the group gained important insight into the time and effort needed to develop a working prototype. The EPE experience built confidence in the students helping them to realize that they will can and will be successful at this endeavor. Finally, the experimental group reported that motivation during the early part of the design process was significantly enhanced due to the EPE. The team molded quickly and was very energetic about building the prototype. This helped them have a great deal of fun with the EPE.
5.0 Conclusions and Future Work

Design fixation is a state where the results of the ideation or concept generation process have been degraded. While there are many possible causes of design fixation, the introduction of physical artifacts before or during the concept generation step in the design process is one potential cause. An experiment which evaluates the design fixation caused by the introduction of an Early Prototyping Experience (EPE) was recently accomplished, involving the use of a control group which did not experience the EPE and an experimental group which did. After the experimental group accomplished the EPE, both groups performed a similar concept generation process, the output of which was judged by experts. Variables of innovativeness, diversity and feasibility were rated for the concept suite from the two groups, and the number of unique ideas tabulated for each group. These data formed the quantitative evaluation of the level of design fixation. While it had been thought that incorporation of an EPE might result in a downward trend in the areas of innovativeness, diversity and feasibility, the results were mixed:

- The experimental group did not show fixation that degraded its innovativeness or diversity of ideas. That group did, however, develop a lower number of unique solutions when compared with the control group.
- However, the concepts developed by the experimental group contained a greater level of feasibility than those created by the control group.
- Additionally, the experimental group reported significant qualitative advantages due to the EPE, including an increase in motivation and understanding of the customers’ needs.

More research is needed to develop specific recommendations regarding positive or negative aspects of inclusion of an EPE in the design process. Also, in the future, additional data should be developed to indicate the effectiveness of using experts to evaluate variables such as innovativeness and diversity in concept suites.

References


