INTERNATIONAL CONFERENCE ON ENGINEERING DESIGN, ICED11
15 - 18 AUGUST 2011, TECHNICAL UNIVERSITY OF DENMARK

UNDERSTANDING FIXATION: A STUDY ON THE ROLE OF EXPERTISE

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ABSTRACT
Engineering idea generation plays a vital role in developing new products. Recent research has focused on the development of methods to make designers more innovative and creative. In this regard, design fixation acts as a major constraint in idea generation. This paper analyzes how design experience influences design fixation. We hypothesize that people store a greater magnitude of design ideas into their memory set as they gain experience in design. The extent of this set provides for both a greater set of solutions to draw from, resulting in more ideas, and determine the extent to which the engineers fixate. A controlled laboratory experiment replicates the environment described in the study by Linsey et al. [1] with novices rather than experts, and compares the results to this prior study. The results support the increased number of ideas with experience hypothesis but not the reduced fixation. It is observed that experts create significantly more ideas but fixate more as well. While the experts fixate on the example, they still outperform novices. These findings shed light on the importance of exposing students to solving a variety of engineering problems in the curricula.

Keywords: Design Fixation, Expertise, Creativity, Open-ended Problems, Engineering Education

1 INTRODUCTION
Engineering design deals with all the activities requisite in the development of a product, starting with the identification of a product opportunity gap and ending in the embodiment of the selected final concept. This process involves many activities including clarification of the task, determining customer needs, converting customer needs into technical specifications, engineering idea generation, selection of a final concept and materialization of the selected concept. The current competitive market necessitates the development of designers' innovation and creativity, so as to enhance their engineering idea generation capacity. Until recently, the prevailing opinion in industry maintained that innovation and creativity arose through years of experience. However, recent research focuses on developing methods and guidelines to train designers in the skill of creativity.

One of the major concerns in engineering idea generation pertains to design fixation, which hinders the conception of novel ideas. Researchers have studied the effects of pictorial examples, [1-3] example solutions and physical models [4-6] on imparting fixation in engineering idea generation process. A prior study by Jansson and Smith [2] shows that both novices and experts are susceptible to fixation induced by presented examples. Purcell and Gero [3] repeat the same experiment with mechanical engineers and industrial designers, finding that mechanical engineers fixate on the presented examples whereas industrial designers do not. These findings indicate that educational biases may play a role in fixation. Wiley [7] shows that domain expertise in baseball may cause a high degree of fixation in solving problems that requires non-routine thinking such as a remote association task. Baseball experts use baseball related terms to complete the remote association task more frequently than non-experts. The study by Linsey et al. [1] shows that even researchers with experience in design and knowledge of design theory, also fixate upon an example solution. Nevertheless, the manner in which fixation behaviors of design experts differs from those of novices in creative problem solving remains in need of clarification. This paper compares novice mechanical engineers to experts in design research.

This paper hypothesizes that as people gain design experience, they widen their repository of solutions. This repository forms the basis for their initial solution space, hence the broader the repository, the less they fixate. This study combines the data collected from design experts by Linsey et al. [1] with data collected from novices through a controlled laboratory experiment, conducted in a similar environment. The subsequent sections of this paper outline the background literature, an overview of the method followed, the analysis of obtained results and an in depth discussion. The results obtained support the hypothesis that experts develop more solutions due to their greater repository of design ideas, but it does not support the hypothesis that they fixate less.

2 BACKGROUND

2.1 Design Fixation

Design fixation refers to blind adherence to a few initial ideas or presented examples [2]. It is counter-productive in creative design problem solving as it inhibits the ability of the designer to search potential solution space. Presented examples induce a reduction in flexibility in designers' choice of features for their solutions [3]. Their solutions include a preponderance of features from the examples presented. The examples presents them with a potential solution path which encourages them to develop a premature commitment to this initial path [8]. Such a development of premature commitment leads to design fixation and inhibits creative problem solving. This type of a commitment is advantageous in a traditional problem solving setting as in Mathematics, where full focus is needed on the core of the solution path, so that the final solution can be built up from this [9]. In engineering design, problems possess open-ended and ill-structured natures; thus, diversion of focus from the core of a single solution space plays an essential role in the development of highly innovative solutions to these problems.

The results from the study show that in the Fixation condition, participants generate solutions that contain elements from the priming solution provided to them. However, a few works in existing literature provide evidence of the positive aspects of such priming stimuli. A protocol study on practicing expert designers from packaging industry has shown that providing example stimuli from their past projects helps designers to come up with higher quantity and quality of solutions in brainstorming sessions [10]. In a similar protocol study on novices, Benami and Jin [11] show that the example elements stimulate creative ideas. They ask participants to come up with ideas to replace oars in a human-powered boat and they show a bicycle as the example. This is a very common example solution for the problem. On the other hand, the study by Perttula and Sipila [12] shows that design fixation is caused by common examples rather than novel examples. In this study, the example solution comprises of parts which are very commonly used for the respective functions to lead the participants to design fixation. The results from these studies are conflicting. Design fixation needs to be studied in further detail.

2.2 Mental Models and Memory

The area of mental models deals with how people perceive the physical world around them [13]. This theory provides a potential explanation to the design process and how designers fixate. Whenever designers mentally analyze a physical object, mechanism or sketch, they form a mental model of the same in their mind [14], which they unconsciously store in their memory. As they encounter new systems, they continually add onto the design ideas in this repository, ultimately forming a set of design ideas [15]. When they encounter a new design problem, they retrieve this set from their memory and search for any potential solutions using the mental models in the set in their memory [15]. From a design point of view, as designers combine the various component design ideas, in a suitable way, they produce a solution to the problem. However, many times these mental models may, due to their incompleteness, [13] lead to incomplete or infeasible solutions. Badke-Schaub et al. give an example of an erroneous mental model that pilots possess about the cabin altitude alarm [14] which leads to a plane crash. Both the pilots mistake the cabin altitude alarm for a take-off configuration warning, which occurs only at ground. Such an incident demonstrates how catastrophic the effects of erroneous mental models are.

When designers face a new open-ended design problem, they unconsciously check their memory for any feasible solutions. The mental repository acts as the basis for their initial solution space. The statement by Jansson and Smith [2] that designers require prior knowledge to come up with solutions for new design problems, also upholds this argument. Thus, a limited set of design ideas stored in memory can act as major trigger of fixation. By this argument, a person with a large repository of design ideas should fixate less in comparison to one with a small amount of information in their repository.

2.3 Fixation in Experts

By the above argument, experts should fixate less than novices, as their mental model repository is, on the average, larger. So they should possess a larger solution space to develop solutions from. Suwa and Tversky [16] show that experts can derive more information from their long term memory while solving problems than novices. However, when experts face a problem which requires non-routine thinking such as a creative design task, their expertise in a specific field acts a constraint [7]. Their mental model repository pertains primarily to their domain of expertise, leading them to fixation. Results from the study by Jansson and Smith [2] augment this. They explain how years of educational and professional experience contributes to fixation. Wiley's experiment [7] shows that subjects who demonstrate expertise in baseball fixate to baseball related terms in a Remote Association Task. She states that novices possess more flexibility in using their knowledge than experts.

This type of constraint, emerging due to an expert's extensive, domain specific knowledge, might detrimentally effect the completion of engineering design tasks. The primary matter concerns here is the educational or training process that allows an expert to accumulate knowledge from a specific field or domain. Constrained design problems often presented in engineering science courses focus on a problem solving approach in which the students need to identify one core issue and divert their whole focus to that issue [9]. This type of an approach is not helpful in the early stages of engineering design when an innovative solution is desired. At this stage, designers require diverse thinking and defocusing from the solutions already generated. Experimental evidence from Purcell and Gero [3] supports this argument. They show that practicing industrial designers fixate less than mechanical engineers. The practice of mechanical engineers in their domain of expertise leads them to limit the variation in their ideas which center on their domain knowledge. Conversely, the industrial designers' training to defocus their attention from specific domains combined with their diverse set of design ideas lead them to lesser fixation.

Based on these prior works, the following hypotheses are proposed in this study and investigated further:

Set of Design Ideas Hypothesis

Experts with practical experience in design problems have a broader set design ideas in their memory, which forms their initial solution space and hence they will be able to come up with more ideas for a problem than novices.

Fixation Hypothesis

Experts with practical design experience fixate to examples more. In combination with the Set of Design Ideas, they still out perform novices in terms of the number of ideas generated due to their broader set of design ideas.

To investigate this hypothesis, the data from the study by Linsey et al. [1] is compared with the data collected through controlled laboratory experiments with novices, i.e., senior undergraduate engineering students. The method used is detailed in the subsequent sections with the interpretation and discussion of the results.

3 METHOD

This study compares the data from the experiment by Linsey et al. [1] with those collected through controlled laboratory experiments on novices. The study by Linsey et al. is henceforth referred to as "expert study" in this paper. This paper references any data from that study as "expert data". All references to the new experiment in this paper fall under the name "novice study" and the corresponding data, "novice data". The novice study replicates the controlled conditions employed in the expert study. It uses all the experimental conditions from the expert study. The primary difference pertains to the fact that the participants of the expert study possess design expertise, whereas those in the novice study are senior undergraduate design students with limited practical experience with design theory and methods. All participants are given the same design problem and same amount of time (45 minutes) to generate solutions to the problem. Both the expert and novice studies use the same design problem. The participants are told that their task is to generate as many solutions to the problem as possible. Participants in the novice study are randomly assigned to three different conditions, identical to those in the expert study. These conditions are detailed below in the subsequent sections.

The novice study differs from the expert study in only a few minor aspects which should not influence the outcome of the experiments. Only the level of the participants' expertise is expected to influence the outcomes. The environments, in which the experiments are conducted, are different. The expert study is a part of an NSF sponsored design workshop, whereas the novice study is conducted as a controlled laboratory experiment. In the expert study, the participant with the most superior effort receives an incentive. No incentive is given in the novice study, as we do not expect this to change the results significantly based upon our prior studies with novices. In the expert study, participants receive a post-experiment survey, whereas the participants in the novice study receive no survey. In the expert study, the participants note down the time at which they generate their ideas. In the novice study, the participants are encouraged not to monitor time and the time at which they generated ideas is tracked by the experimenter using multi-color pens. This allows the participants to concentrate on their idea generation and allows us to keep track of time at which each idea is generated. It would be ideal to have the novices and experts in perfectly matching conditions including the same experiment room. Unfortunately, the difficulty in obtaining large sample sizes of expert data precipitates the acceptance of comparable expert and novice data from nearly matching conditions.

3.1 Design Problem

All the participants are given the same design problem to design a device to shell peanuts quickly for West African countries. The participants are told that no electricity is available in these countries. As a majority of the participants are mechanical engineers, they are expected to understand the constraints included in this problem and since it is a real-life problem, it is expected to replicate the challenges of solving an actual open-ended problem. None of the participants possesses prior exposure to this problem, as verified by the experimenter. Even so, they are expected to have hands-on experience in shelling peanuts. To complete the problem, they receive a list of customer needs which includes shelling with minimum damage to the peanuts, capacity to process large quantities in minimum time, low cost and easy to manufacture.

3.2 Experiment Conditions

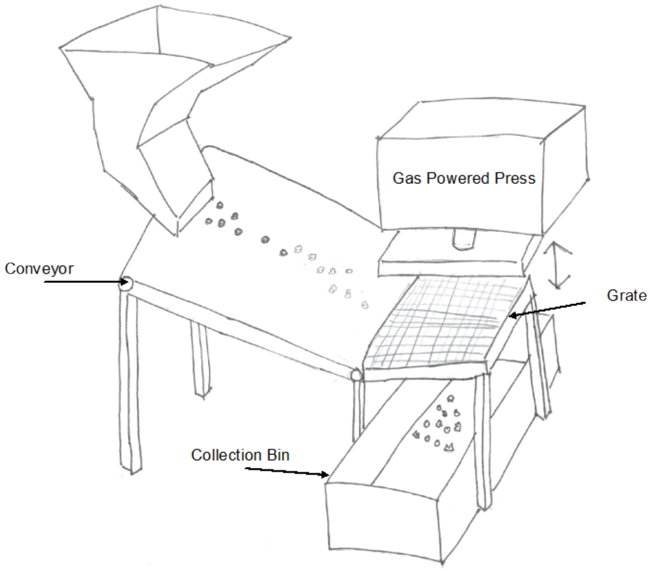
The study assigns the participants to three different groups: Control Group, Fixation Group and a Defixation Group. A description of each group follows:

3.2.1 Control Group

The control group receives the design problem statement and is asked to generate as many solutions as possible to solve the problem. They are not provided with any additional materials.

3.2.2 Fixation Group

The Fixation Group is provided with the design problem statement along with an example solution to the design problem. The example solution is shown in Figure 1. This example shows a gasoline powered mechanical press, which crushes the peanuts to shell them and then uses a grate to separate the peanuts from their shell. The resulting peanuts are directed to a collection bin. The system uses a hopper to import peanuts to the machine and a conveyor/inclined surface combination to guide the peanuts to the press. This solution has a few obvious disadvantages. It is very difficult to control the damage to the peanuts in this system. The entire assembly is complex and difficult for use in a West African country. It is too expensive. These disadvantages are not stated, but as most of the participants have sufficient Mechanical Engineering background, they can infer these.



Solution Description: This system uses a gas powered press to crush the peanut shell. The shell and peanut then fall into a collection bin.

Figure 1 Example solution provided to the participants in Fixation and Defixation Groups

3.2.3 Defixation Group

In this group, the participants are provided with the design problem description along with the example solution shown in Figure 1 and alternate representations of the problem. The alternate representations provided to the participants are shown in Figure 2. These include a brief functional description of the problem along with few analogies that can help to solve the problem and a list of alternate energy sources that can be used. It also includes results from few back-of-the envelope calculations. These materials are expected to help the participants in mitigating fixation imparted by the example solution.

3.3 Participants

The expert data is collected by Linsey et al. [1] in a NSF sponsored workshop titled "Discussion on Individual and Team Based Innovation". 31 engineering academics attend the workshop and they are randomly distributed across the Control, Fixation and Defixation groups. Most of the workshop participants possess experience in academia and are researchers in the field of Engineering Design. Many of them have worked in industry and have experience in consulting with industry.

For the novice data, the participants are senior undergraduate students from Texas A&M University. 19 students volunteered for the experiment and they are randomly assigned across the Control, Fixation and Defixation groups. There are 6 participants each in the Defixation and Control groups and 7 participants in the Fixation Group. Among the participants 18 are Mechanical Engineering students and one is an Electrical Engineering student. All participants are recruited from a senior level design course offered by the Mechanical Engineering Department at Texas A&M University. Out of 19, two are female participants.

3.4 Procedure

The participants are randomly assigned to the various conditions. They are provided with the design problem and the additional materials, if any, as determined by the condition. The participants are told that the goal of the experiment is to generate a maximum number of solutions of as high quality as possible for the given design problem. They are given 5 minutes to read and understand the material followed by 45 minutes of idea generation. Additionally, they are asked to draw sketches of their ideas accompanied with short descriptions or comments. They are also instructed to label various parts of their sketches. For the experts, the experiment ends with a post-experiment survey which collects information regarding their prior exposure to the design problem, perceptions about their performance and the influence of the given example solution. In the Defixation Group, the participants are also asked about perceived usefulness of the defixation material provided. The novices are also asked about their prior exposure to the design problem and their major.

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 2 Defixation materials provided to the participants in the Defixation Group

4 METRICS FOR EVALUATION

To evaluate the hypothesis presented, two different metrics are employed in this study. These are same as the metrics used by Linsey et al. [1] in the expert study. The metrics employed are: (1) Quantity of ideas (2) Number of example solution features appearing in the ideas. The data from all the participants are analyzed by one reviewer and an inter-rater agreement is taken for 18% of the data in the expert study and 32% of data in the novice study to ensure the reliability of these measures.

Quantity of ideas is based on the procedure outlined by Shah et al. [17] and as further developed by Linsey et al. [18]. An idea is defined as a feature that solves one or more functions in the functional basis [19]. The ideas that reuse the parts from the given example are considered to be redundant ideas.

They are eliminated from the list of ideas of each participant and the quantity of non-redundant ideas is computed. An inter-rater reliability score (Pearson's correlation) of 0.97 is obtained on the Expert Data and 0.92 on the Novice Data. The features of the example solution are identified and the number of these features appearing in each participant's solution is counted. A Pearson's correlation of 0.97 is obtained on the Expert Data and 0.99 on the Novice Data. However the expert data and the novice data are analyzed by two different raters. Between these two raters, a Pearson's correlation of 0.95 for quantity of non-redundant ideas and 0.74 for the use of example features are obtained. The percentage difference in agreement between these two raters is 38% for quantity of non-redundant ideas and 55% for use of features from the example. Since this difference is high, the results obtained can be biased. Hence both the data need to be analyzed by the same rater and this is left for future work.

5 RESULTS

5.1 Quantity of Non—redundant Ideas

The quantity of non-redundant ideas varies significantly between the experts and novices, as shown in Figure 3. Since the data does not satisfy the assumptions of ANOVA, a permutation test [20] equivalent to one-way ANOVA is used for the statistical analysis of the data. The permutation test yields significant results for the overall model (F(5,44)=5.55, p<0.00). Pair-wise permutation tests are used for post-hoc analysis. The results show that the Expert Control Group produces more ideas than the Expert Fixation Group (F(1, 19)=5.23, p<0.04), as shown previously by the Expert Study. Novices in Control Group produce significantly lower number of non-redundant ideas compared to experts in Control (F(1,13) = 14.09, p<0.002) and Fixation groups (F(1, 14) = 5.66, p<0.04). Novices in the Fixation Group generate a significantly lower quantity of ideas than experts in all three groups. (Control: F(1, 14)= 17.75, p<0.001; Fixation: F(1, 17)= 3.31, p<0.09; Defixation: F(1,15)= 7.13, p<0.02). Novices in the Defixation Group also generate significantly lower quantity of ideas compared to experts in all the groups (Control: F(1, 13)= 16.28, p<0.001; Fixation: F(1, 16)= 3.49, p<0.08; Defixation: F(1,14)= 6.28, p<0.02).

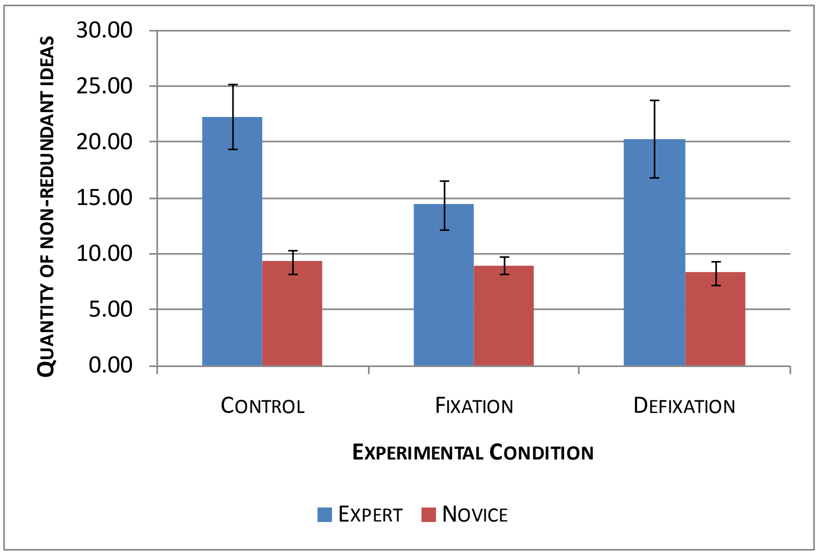


Figure 3 Novices produce significantly lower quantity of non-redundant ideas than experts. Error bars show (±1) standard error.

5.2 Number of Example Solution Features Used

The results show that participants use many features from the example solution repeatedly. Regardless of the condition of the experiment, majority of them use the features included in the example. Figure 4 shows the results obtained from the data. These data do not satisfy the normality and homogeneity assumptions of ANOVA, hence permutation test is employed for statistical analysis in this case too. The results show that neither the overall model nor the pair-wise comparisons are significant, which shows that the use of example features is approximately constant across the various conditions, regardless of the level of expertise. The experts in Fixation group use significantly more number of example features compared to those in Control and Defixation groups, as reported by the expert study. This demonstrates that the priming example causes fixation in experts, but they can be defixated using a set of materials as used in this experiment. For further details, refer to Linsey et al.[1]

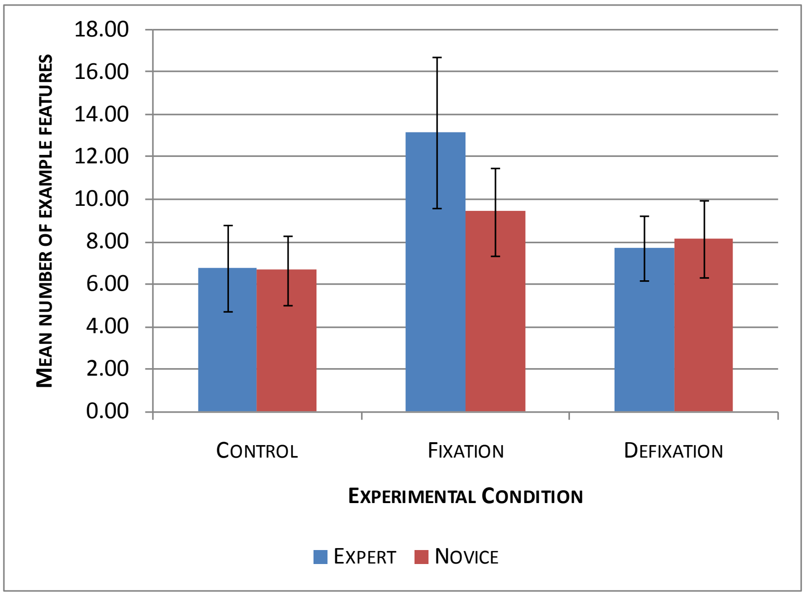


Figure 4 Number of example solution features used by the participants does not vary significantly across the conditions and level of expertise. Error bars show (±1) standard error.

6 DISCUSSION

The results provide very useful insights concerning the difference between fixation behavior in design experts and novices. Our results support the Set of Design Ideas Hypothesis. This experiment showed that design experts in all the three conditions outperform novices in terms of quantity of ideas. One might attribute such a fact to the wide variety of design ideas an expert accumulates through the experience of solving numerous open-ended design problems. Experts possess a broader set of design ideas than novices which may give them a wider initial solution space to develop solutions.

Another interesting result from this study pertains to the fact that, regardless their condition, novice participants generate approximately the same mean number of non-redundant ideas. We observe that participants in the Novice Control Group use most of the example features, even without exposure to the example. The example solution possesses primarily common features, i.e. when a participant initially thinks about the solution those common features come to mind first. This could contribute to why we do not observe a significant variation in quantity across conditions for novice participants. The novice participants in the Control Group may fixate to the initial ideas that come to their mind, the very same features provided to the other groups. Regardless of the presence of an example solution or defixation materials, all the novice groups, on average, produce ideas using the same number of features from the example. Such an observation also implies that defixation materials negligibly influence novices.

The data supports the Fixation Hypothesis. Experts in the Fixation group fixate on example solutions, generating fewer solutions and using more features from the example than the Expert Control participants. While experts do fixate on the example, they can overcome this fixation using the defixation materials. The defixation materials do not measurably affect the performance of the novices.

Overall, these results demonstrate the effects of expertise and the influence of defixation materials. Our results substantiate prior results. Purcell and Gero [3] observe that Mechanical Engineers fixate to examples, while practicing industrial designers do not. The current sample consists mostly of mechanical engineers. From Psychology, in comparison to novices with only basic knowledge of baseball, Wiley [7] shows that people with domain expertise in baseball perform poorly on remote association tasks. Combining these results, it becomes clear that domain expertise plays an important role in the effectiveness of various innovation tools, including defixation methods. Clearly the development of design expertise within the undergraduate curriculum remains important, as does a focus on open-ended design problems. Such a fact agrees with the “reflection in action” [21] currently in use at various European universities. They encourage students to solve problems themselves and learn from it, with teachers acting as facilitators of learning. This might help students gain practical knowledge in a variety of problem solving situations, their developing creativity and innovativeness.

The inter-rater agreement on the expert data is taken from the study by Linsey et al. [1]. To ensure complete reliability, this needs to be repeated by the experimenter and another independent reviewer. This task remains for future work.

7 LIMITATIONS OF THE STUDY

The expert data and the novice data are evaluated by two different raters. The percentage disagreement between these two raters is high. Hence the results shown in this study may be biased. To rectify this, both the data need to be analyzed by a single rater. This will be completed in future.

Another factor that can influence the results of this study is the incentive provided to the participants in the expert study. The participants with superior quality of ideas are offered an incentive in the expert study. However, this is not offered in the novice study as the prior studies by the authors do not show any possible effects of such an incentive. If this is a biasing factor, the comparison of the results from both studies can be inaccurate.

8 CONCLUSIONS

Design fixation imposes significant constraints on engineering idea generation. For designers to increase creativity, they must mitigate fixation. This paper analyzes the effects of expertise in solving open-ended design problems. Building on the prior study by Linsey et al. [1], a comparison is done on the fixation behavior of design experts and novices. This paper hypothesize that experience in solving a variety of open-ended problems helps improve an individual’s set of design ideas, perhaps providing them with a wider initial space to look for solutions and helping to reduce fixation.. The results support the hypothesis that experts’ larger sets of design ideas help them to generate more solutions, conversely does not limit their fixation. Instead experts appear to fixate more, with the defixation materials significantly decreasing fixation in them. At the same time, these defixation materials possess negligible impact on novices. These results also highlight the importance of exposing engineering students to a wide variety of solutions as a part of the engineering curriculum. When engineers are exposed to a wide variety of solutions, they have more options in memory to draw from.

9 FUTURE WORK

The use of physical models influences fixation in engineering design [22]. In the future, a repeat of this study, where designers are given prototypes for the example, could yield interesting data. Additionally, a study in which one sees how a domain expert with experience in a particular domain performs in a similar environment might also yield interesting results. Furthermore, inter-rater agreement needs to be recalculated for the expert data with the experimenter and one independent reviewer to ensure complete reliability of the measures in this study.

ACKNOWLEDGEMENTS

Partial support for this work was provided by the National Science Foundation Award No. CMMI-1000954. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors and do not necessarily reflect the views of the National Science Foundation. We would also like to acknowledge the reviewers who provided very useful feedback which helped us to improve the quality of this paper.

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