

J. S. Linsey
Mechanical Engineering Department,
Texas A&M University,
224 Engin. Physics,
3123 TAMU College Station, TX 77843
e-mail: jlinsey@tamu.edu

I. Tseng
e-mail: iht@andrew.cmu.edu

K. Fu
e-mail: katherine.fu@gmail.com

J. Cagan
e-mail: cagan@tamu.edu

Mechanical Engineering Department,
Carnegie Mellon,
Scaife Hall 214,
5000 Forbes Avenue,
Pittsburgh, PA 15213

K. L. Wood
Mechanical Engineering Department,
The University of Texas at Austin
e-mail: wood@utexas.edu

C. Schunn
Department of Psychology,
University of Pittsburgh, LRDC 821,
3939 O'Hara St.,
Pittsburgh, PA 15260
e-mail: schunn@pitt.edu

A Study of Design Fixation, Its Mitigation and Perception in Engineering Design Faculty

The bridge between engineering design and cognitive science research is critical to understand the effectiveness of design methods as implemented by human designers. The study reported in this paper evaluates the effects of design fixation in a group of engineering design faculty, and also provides evidence for approaches to overcome design fixation. Three conditions are compared, a control, a fixation group whom were provided with an example solution, and a defixation group whom were also given materials to mitigate their design fixation. Measures include indicators of design fixation and participant perceptions. The study demonstrates that the engineering design faculty show statistically significant evidence of design fixation, but only partially perceive its effects. This study also indicates that design fixation can be mitigated. The group of participants in this study, due to their background in engineering design research and experience with student design teams, was expected to have more accurate perceptions or awareness of design fixation than the typical participant. Understanding the incongruities between participant perceptions and quantitative design outcomes are particularly of interest to researchers of design methods. For this study, clear evidence exists that designers, even those that study and teach design on a regular basis, do not know when they are being influenced or fixated by misleading or poor information. [DOI: 10.1115/1.4001110]

Keywords: design fixation, analogy, conceptual design

1 Introduction

Engineering design was rigorously studied, arguably since Simon's *Sciences of the Artificial* was published in 1968 [1]. The field has explored formal and heuristic approaches to design refinement, manufacturing, generation, and computation [2–4]. A critical part of engineering design is how designers think about the problem, how they reason about problem-relevant information, and how they are able to generate novel problem solutions. The study of such questions falls in the field of cognitive-based innovation and requires methods and knowledge from the field of cognitive psychology, integrated with process knowledge and participants from the field of engineering design. The field of researchers who have actively pursued cognitive-based engineering is small but diverse, examples falling into the following five nonexhaustive categories.

- Representation—the means to reason about and search for a solution to a design problem [5–13];
- Fixation—barriers to solution based on real and perceived constraints [14–17];
- Analogy—the mapping of knowledge from one domain to another supported by abstract representations [9,18–29];

- Computational models—models for cognitive simulation and generative tools [30–32];
- Teams—effective negotiation strategies, compatible representations, effective communication, trust among team members [7,33–42].

Results in this field have begun to bear fruit, and the time is ripe for rigorous research efforts in this area.

As such, in January 2008, an NSF sponsored workshop was held in Knoxville, TN, as part of the CMMI Grantees Meeting. The workshop, entitled “Discussion on Individual and Team-Based Innovation,” brought approximately 50 educators and researchers from the field of engineering design together for a day to learn about the current work and discuss potential directions for new research in the area of cognitive-based engineering design. As part of the workshop, participants took part in a formal cognitive study on the role of fixation and the use of analogies to overcome fixation. The experiment was formally developed, piloted, approved by the lead institution's Internal Review Board, and then run during the workshop. This paper presents the results of this study. One goal of the study was to allow participants to experience a formal and rigorous cognitive experiment. Since most of the participants had only engineering backgrounds, it was unlikely that many had participated in such studies.

Another goal of the study was to advance the state of the field of cognitive-based engineering design by learning (1) if engineering educators experience design fixation during a design problem solving exercise, (2) how design fixation can be overcome, adding to the current knowledge base of the field, and (3) whether the

Contributed by the Design Education Committee of ASME for publication in the JOURNAL OF MECHANICAL DESIGN. Manuscript received June 19, 2009; final manuscript received January 24, 2010; published online April 13, 2010. Assoc. Editor: Janis Terpenney.

participants accurately perceive the effects of provided examples and materials to mitigate design fixation. On one hand, the study group is interesting because they have experience in design, as demonstrated by survey results showing considerable industrial projects and patents, but on the other hand, they think about the process of design through teaching courses in design and through research in the broader field of design. It is interesting to see whether this cohort is susceptible to aspects of fixation that have been prevalent in other studies of design students or practitioners.

What follows is a discussion of the current state of the art of cognitive-based engineering relevant to this work, a presentation of the experiment, results, discussion, and insights from the study.

2 Background/Previous Work

A number of studies showed that design fixation effects can occur when example solutions are introduced to participants [15,43–47]. Jansson and Smith [15] were the first to apply an experimental approach to study engineering design fixation. They found that showing example solutions can reduce the range of design solutions generated by a designer, and that aspects of the example solution, including aspects that were shown to violate goals of the problem statement, can find their way into the designers' solutions. A number of later experiments by others used the same and similar design problems to further investigate the issue of design fixation [47,48]. Purcell and Gero [47] suggested that the susceptibility of a designer to fixation may depend on the discipline of the designer, and that design fixation is more likely if the example problem embodies principles that are in line with the knowledge base of that discipline. These studies, as a whole, demonstrate that introducing examples can cause design fixation, resulting in less creativity during ideation.

2.1 Possible Approaches to Overcoming Design Fixation.

Some approaches to reducing design fixation have been identified. Using the same fixating examples as Jansson and Smith, Chryssikou and Weisberg [48] found that including defixation instructions can negate the fixating effects of the examples. Another possible approach to breaking or mitigating design fixation, beyond defixation instructions, is to assist the designer in finding a new way to frame the problem, which may lead to new and improved solutions. The power of analogical inspiration, as part of problem framing, is supported by empirical evidence, as well as by examples of professional designers using analogies to solve problems [9,49–51].

Within the literature, a number of approaches for enhancing analogical retrieval and use have been noted. Some of these depend on the expertise of the participants, and some are more general findings. Casakin and Goldschmidt [49] found that visual analogies can improve design problem solving for both novice and expert architects. Ball et al. [52] found experts use more analogies than novices do, so experience seems to increase retrieval frequency. Expertise also enhances the ability to retrieve high-level principles derived from sets of analogies (schema-driven). Novices tended to use more case-driven analogies (analogies where a specific concrete example was used to develop a new solution [29]) rather than schema-driven analogies (more general design solution derived from a number of examples [53,54]). This difference can be explained because novices have more difficulty retrieving relevant information when needed and have more difficulty mapping concepts from disparate domains due to a lack of experience [55].

Tseng et al. [17] found that the effectiveness of analogical inspiration in design was dependent on the timing of when the inspiring information is given, as well as how apparently similar the information is to the problem being solved. More specifically, information that shares similar keywords or domains can be applied to problem solving, even if the information is given before the designer has begun work on the problem, while information

that is relevant but does not share similarity of keywords or domains only affects problem solving when the designer has already begun work on the problem.

Additionally, Dahl and Moreau [56] demonstrated that subjects exposed to within-domain examples employed fewer far-domain analogies in generating solutions, and that the originality of the solutions produced was increased when subjects were encouraged to use analogies extensively and given no example solutions. Marsh et al. [57] found that within-domain examples caused subjects to be biased toward generating solutions that had similar features to those found in the examples. These findings led to the expectation for our experiment that a within-domain example solution given to participants prior to ideation would cause design fixation, as exhibited through fewer solutions generated and the appearance of features from the example in the solutions generated.

2.1.1 Breaking or Mitigating Fixation: Formal Design-by-Analogy Methods. Analogy is a likely candidate for alleviating design fixation. A few formal methods have been developed to support design-by-analogy. These include Synectics [58], French's work on inspiration from nature [59,60], Biomimetic concept generation [26,27], the WordTree Design-by-Analogy method [20,61], and analogous design through the use of the function and flow basis [24]. Synectics is a group idea generation method that uses four types of analogies to solve problems: personal (be the problem), direct (functional or natural), symbolic, and fantasy [58]. Synectics gives little guidance to designers about how to find successful analogies. Other methods also base analogies on the natural world. French [59,60] highlights powerful examples that nature provides for design. Biomimetic concept generation provides a systematic tool to index biological phenomena [26,62]. In biomimetic concept generation, the functional requirements of the problem and the keywords are first derived. The keywords are then referenced and relevant entries can be found. Like biomimetic concept generation, the WordTree method is also based on keywords. The WordTree method takes the key functions or customer needs of a design problem, and systematically rerepresents them through the intuitive knowledge of the designers and through the WordNet database, particularly with synonyms known as hypernyms and troponyms. Analogous concepts can be also identified by creating abstracted functional models of concepts and comparing the similarities between their functionality. Analogous and nonobvious products can be explored using the functional and flow basis [24].

Other database supported computation tools for design-by-analogy have been recently developed. Examples of such tools are the work by Kurtoglu and Campbell [63], Chui and Shu [26], and Chakrabarti et al. [64]. Each has created an automated tool to provide inspiration to designers as part of the idea generation process. Based on the function or behavior of a device, analogies from nature or other devices are provided as potential sources of inspiration to the designer.

2.2 The Perception of Being Fixed. One reason why design fixation is difficult to overcome is that designers are often not conscious of the fact that they are fixated. Ward and co-workers [45,65] found that the examples were not constraining the subjects consciously by causing them to believe that they should produce solutions similar to the given examples, but rather subconsciously constraining them; when participants were asked to avoid producing solutions that were similar to the examples, the similarity between the examples and generated solutions did not significantly decrease when compared with participants' solutions who were not told to avoid solutions similar to the given examples. In general, participants did not have control over their use of the knowledge gained from the examples. These results suggest that designers are unaware that they are being influenced by example solutions or previously generated solutions [44,45,65]. Consistent

with this finding, Linsey et al. [19] also observed that engineers were unaware that they were implementing prior examples to which they had been exposed.

2.3 Summary and Breaking New Ground. It is clear from this literature review that experiments have been deployed for studying fixation and the underlying causes within designers. We build on these studies and the associated results in this paper. Mitigating strategies for alleviating fixation have been studied, but much fertile ground has yet to be explored, especially in the domain of engineering and for the use of analogies. It is also clear, to the best of our knowledge, that academics from engineering design research have not been a focal group as part of fixation studies. Our cognitive-based study here addresses these limitations, and constructs a framework on the foundation of the previous research.

3 Research Questions

Design fixation is a common problem for both inexperienced and experienced designers. In this study, we seek to answer three fundamental research questions: (1) Do engineering academicians, both design researchers and educators, experience design fixation? (2) How can design fixation be overcome or mitigated? (3) Do the participants accurately perceive the effects of provided example solutions and of the materials to mitigate design fixation? These three research questions, our associated hypotheses, and our motivation for answering these questions are discussed in the following sections. In our study, three experimental conditions are implemented: a control, a fixation condition in which a negative example solution is presented, and a defixation condition in which the negative example solution is given along with a list of possible solution directions to consider; these conditions are referred to in presenting our hypotheses and defined in Sec. 4. In addition, all participants filled out a survey prior to the workshop that obtained demographic information and perceptions about the design process.

3.1 Evidence of Design Fixation. For this study, we explore the effects of fixation on experienced academic engineering designers. The group of participants for this experiment has a unique background that makes them interesting to study. All of the participants attended a workshop on the cognitive aspects of engineering design and developing cognitive experiments in engineering design. They have clear interest in design and cognition. In addition, most of this group has experience teaching design and most are researchers in design. Therefore, this group is aware of design methods, they have spent time thinking about many of the issues related to design, particularly the “fuzzy-front end,” and they are likely to be aware of some of the difficulties that designers have during idea generation. They are also aware of methods such as design-by-analogy and some of the short-comings of traditional group brainstorming. Overcoming design fixation is a difficult task. Yet, because of this group’s background in design theory and methods, with their knowledge and skills, might they be able to more effectively overcome design fixation? We therefore seek to answer the following research question and contemplate the following hypothesis:

Research Question 1: Do academic engineering design educators show evidence of design fixation?

Hypothesis 1: Academic engineering design educators will show evidence of design fixation. They will produce fewer total ideas when provided with example solutions and repeat ideas from provided examples as compared with the control group.

3.2 Overcoming/Mitigating Design Fixation. Prior research has shown that it is possible to reduce design fixation by instructing participants to not focus on the negative aspects of the design and describing those short-comings [48]. This is clearly one approach for reducing fixation, but based on anecdotal commentary in the design literature, it is likely that there are other approaches

to mitigating fixation. Many product design books describe the benefits of functions, analogies, categories, and back-of-the-envelope calculations in the design process [66–69]. In addition, analogy is noted as a tool for innovative design and a prolifically implemented strategy by designers [9,19,70]. These observations lead to the following research question and hypothesis:

Research Question 2: What can engineers do to reduce their fixation on particular design solutions? Can analogies, functions, categories of energy sources, and back-of-the-envelope calculations assist in overcoming design fixation?

Hypothesis 2: Design fixation can be reduced. The defixation group will produce more ideas and repeat fewer ideas from the provided example solution than the fixation group. The defixation group will implement more analogies than the other two conditions.

3.3 Participant Perceptions. Participants’ perceptions frequently are not consistent with quantitative outcomes of their performance [37,44,45]. Unfortunately, perceptions are easily obtainable and may be the basis that an individual or a company uses to choose to implement a particular method. For example, one of the reasons for group brainstorming’s popularity, in spite of numerous studies contradicting its purported effectiveness, is that individuals feel more productive during group brainstorming than when generating ideas alone [37]. In contrast to the participant’s perceptions of productivity, numerous studies quantitatively demonstrate a reduction in the number of ideas per person when comparing brainstorming in a group to individual brainstorming (see Ref. [71] for a review). The basic group brainstorming method must be adapted to produce the quantity of results greater than the sum of the individuals [64].

The group of participants in this study has experience with design methods and is at least somewhat familiar with their short-comings. In addition, the majority of this group has taught design classes and observed their students’ performance. Therefore, it is likely that the participants in this study will be much more aware of the effects of a provided example solution and additional defixation materials on their performance than participants who do not study design. In contrast, the prior literature indicates that participants are likely to inaccurately perceive the effects of an introduced example solution and the associated defixation materials, if they are introduced. Therefore, we seek to answer the following research question and test the related hypothesis:

Research Question 3: How well do participant perceptions of design results correspond to quantitative assessment of the results?

Hypothesis 3: Participants will inaccurately perceive the effects of a provided example solution and associated defixation materials. Results from survey questions collecting the participants’ perceptions will be inconsistent with the quantitative metrics.

4 Experimental Method

The experiment evaluates the effects of fixation on experienced academic engineering designers. To answer the research questions and hypotheses, we implement three experimental conditions: a control, a fixation, and a defixation condition. All participants are given the same experimental procedure and documentation media. Participants in the fixation condition are provided with an example solution. Participants in the defixation condition are also provided with the same example solution, but also with additional materials to potentially break or mitigate the design fixation (detailed below in Sec. 4.4). All participants are told that the goal of the experiment is to generate as many solutions to the design problem as possible, where a prize will be given to participants with the greatest number of solutions. This prize is an incentive for participants to devote serious effort to the design activity. All conditions end with a short post-experiment survey, which measures prior exposure to the design problem, perceptions of participants’ performance and perceived influence of a provided example

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.

Consider the following solution as an example that might be created for this design problem.

Fig. 1 Design problem description

solution. In the case of the defixation condition, participations are asked questions regarding the defixation materials and their perceptions of these materials.

4.1 Description of the Design Problem. All participants are provided with the same design problem. The design problem is to design a device to quickly shell peanuts for use in places like Haiti and West African countries, and is based on a real-world problem posted on ThinkCycle [72]. Participants are told that no electrical energy sources are available and are given customer needs (Fig. 1). This problem is chosen because it is a real world problem that is appropriate for an engineer, it has intrinsic incentive for solutions given its need-based nature, and the problem has a diverse set of available solutions. This problem has also been used in previous research on idea generation [35,73,74]. It is very unlikely that any of the participants would have extensive prior experience in solving this problem, yet shelling a peanut is a task that all of the participants have likely experienced.

4.2 Control Group. The control group is given the design problem as stated in Fig. 1. They are not provided with an example solution or alternative representation of the problem.

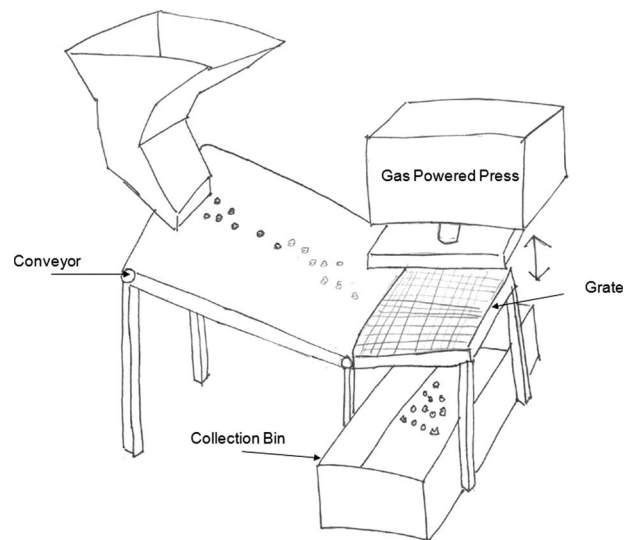
4.3 Experimental Fixation Group. The fixation group is given the design problem as stated in Fig. 1 and an additional negative solution example (Fig. 2). They are not given an alternative representation of the problem. The example solution uses a gasoline powered press to crush the shell, and does not separate the nut from the shell. The example solution focuses exclusively on a mechanical concept that crushes the shell and uses external fuel energy. This solution is difficult to control in terms of damaging the peanut, complex, and costly to manufacture for the West African environment. The participants all have graduate degrees in engineering, so these short-comings should be obvious to them. In addition, these particular process solutions are many of the common solutions found by participants in a prior experiment [35,73]. Common solutions to design problems were shown to create greater fixation (fewer total solutions) than unusual solutions [14,75].

4.4 Experimental Defixation Group. The defixation group is presented with the design problem, as in Fig. 1, and also alternative representations of the problem (Fig. 3). The alternative representations provide a brief functional description, useful analogies, a list of available energy sources, and a quick back-of-the-envelope calculation result. Some of the analogies were identified using the WordTree Design-by-Analogy method with the key word of "remove" and "shell" to find the associated hypernyms and troponyms from WordNet [20].

4.5 Participants. Fifty engineering academics expressed interest in attending the NSF sponsored workshop: "Discussion on Individual and Team-Based Innovation." 38 from this group filled

out the online presurvey for the workshop, and 34 actually attended the workshop. These thirty-four participants are randomly assigned to one of three conditions prior to the workshop, equally distributing the senior (associate and full professors) and junior faculty (assistant professors). The study serves to demonstrate to the workshop participants an example cognitive study in engineering design, while at the same time, providing useful experimental data. Based on the preworkshop survey results, which are only partially presented here, participants are faculty members (85%), plus a few research scientists and graduate students (12%), and federal government employees (3%). There were no participants from industry. Almost half the participants are assistant professors (45%); 12% are associate professors and 27% are full professors. Most participants have mechanical engineering backgrounds. Most have at least 1 year of industrial experience (64%) and have consulted with industry at least once (79%). There is also a high representation of women relative to the field of engineering (33% females).

A number of preregistered intended participants did not attend the beginning of the workshop so three participants were switched to different groups to compensate. Unintentionally, they were switched from the defixation condition to a different condition, and they therefore had briefly seen the defixation materials. These three participants were removed from the data set.



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

Fig. 2 Example solution provided to the participants in the fixation group

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.

Fig. 3 Defixation materials

5 Metrics

To understand the effects of design fixation and evaluate the research questions, a set of measures are employed. To quantify the degree of fixation, five metrics are implemented: (1) number of ideas, (2) number of times features from the example solution appear in generated concepts, (3) percentage of features from the example solution that appear at least once in participant solutions, (4) number of energy domains, and (5) percentage of the solutions that employ a gas engine. To evaluate the effects of providing defixation materials, along at least one dimension, the number of analogies is also measured. To provide inter-rater reliability, one of the authors evaluated all of the data for each metric, while a second rater evaluated two from each condition or at least 18% of the data.

5.1 Quantity of Ideas. Building from the procedure developed by Shah et al. [76], a set of procedural rules are defined for what constitutes a single idea, see Ref. [77] for more details. Our basic definition for an idea is something that solves one or more functions of the design, as defined by the functional basis (a clearly defined and tested language for expressing design functions [78,79]). The total number of unique (nonredundant, nonrepeated) ideas is calculated for each person. Pearson's correlation coefficient [80] was 0.97, indicating that the measure is highly reliable. A high degree of Pearson's correlation indicates that if one evaluator had a higher score, then the other evaluator also tended to give a higher score.

5.2 Repeated Example Solution Features and Percentage of Features Used. Figure 4 illustrates the example solution provided to the participants and all of the design ideas contained within it (number of ideas), categorized by function. The number of times each participant employs one of the design features from the example solution is counted. This procedure results in two metrics, which indicate the degree of fixation: the total number of times a feature is repeated and the total percentage of features from the example that is implemented at least once. One of the authors evaluated all of the data, while a second rater measured two from each condition or 18% of the data. In half of the cases,

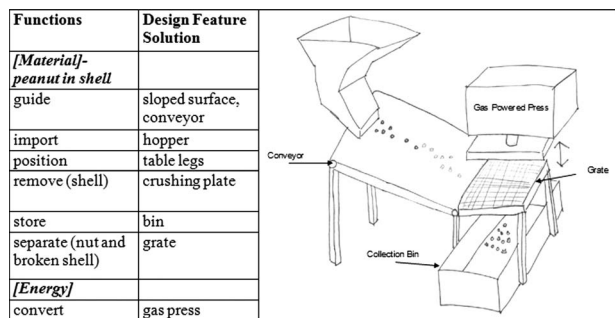


Fig. 4 Example solution provided to participants

Table 1 Energy source categories

Wind	Anything powered by naturally occurring wind. Includes using a wind generator to generate electricity, a windmill to directly turn a mechanism, and naturally allowing the wind to blow peanut shells away. Does not include a fan or other wind source powered by another energy source.
Solar	Anything powered by the sun. Includes both solar panels to generate electricity and using the sun directly to heat water or roast the peanuts.
Water streams	Uses naturally existing water streams such as a water wheel in a river to power the system, either by generating electricity or directly powering the mechanical system.
Captured rain water at a height	Capturing rain water at a height to accomplish much the same as the previous category.
Water (other)	Can include the soaking of peanuts to soften them, and many other uses.
Human	Includes manual shelling, turning a hand crank, and any other human power.
Animal	Includes using animals to motivate a mechanical system, training or genetically manipulating animals to shell peanuts.
Nuclear	Nuclear power station to provide energy.
Electrical outlet	Any solution where the concept involves plugging into a wall socket for electricity.
Fire	Anything that uses a fire to generate power, excludes internal combustion or steam engines, but includes using a fire to roast peanuts or burn off shells.
Gas engine	Gasoline powered internal combustion engine.
Engine (other)	Any other type of fuel engine.
Fuel cell	Hydrogen or other type fuel cell.
Fluid density difference	Concepts based on whether something floats or sinks, often used to sort peanuts and their shells.
Chemical	Any chemical process to generate power that is different than seen above, or to burn or dissolve the peanut shell off.
Genetic	Genetically altering the peanut itself. Does not include genetic manipulations on animals (which should be categorized as animal).

the two raters had identical scores for the number of repeated features, and their Pearson's correlation coefficient [80] was 0.97, indicating that the measure is highly reliable. Cohen's Kappa [80] is not used since the metric of interest is the relative number of repeated features across conditions, not whether or not the participants use a particular feature or the absolute number of repeated features in this setting. To calculate the percentage of the features that each participant reused from the example, the number of features used at least once is divided by the total number of ideas within the example solution (eight ideas, Fig. 4).

5.3 Energy Domains and Percentage of Solutions Employing a Gas Engine. In addition to recording the quantity of ideas, the number of energy sources used by each participant is analyzed (Table 1). These energy sources are categorized into 16 energy categories (wind, solar, water streams, captured rain water at a height, water (other), human, animal, nuclear, electrical outlet, fire, gas engine, engine (other), fuel cell, fluid density difference, chemical, and genetic). The original tally included 18 categories, but it was found, due to the universality of gravity that the two gravity driven categories are difficult to measure reliably between raters, and were thus removed. The total of all energy sources used by each participant is recorded. Since the goal is to determine the breadth of energy sources spanned, a participant receives the same score, regardless of whether they use an energy source once or multiple times. Since the defixation materials provided a list of energy sources to directly break fixation on the gas engine, the percentage of solutions using a gas engine is also calculated.

5.4 Analogies-Breaking Fixation. After 45 min of ideation, analogies were identified by the participants by going back through their solutions, and circling or labeling any analogies used with a red permanent marker. The total number of unique analogies identified by each participant is measured. Some participants circled components of their designs, some drew arrows with textual descriptions, and others described the analogies they used while also circling them. Initially, all of this information is tabulated. If a participant circled something and wrote no textual description, this analogy is counted for that participant toward the total number of analogies they used. If a participant wrote a description, the analogy is counted for that participant toward their total number of analogies. If the participant both circles and writes text, it is determined if the two pertained to separate analogies. One participant stated that they believed all of their ideas were

analogies since all their ideas came from things they had seen before. Although this statement that most of an engineers' design ideas come from prior exposure is true, this is not a working use of the concept of analogy, where a specific idea is borrowed or mapped onto the current problem; thus, this participant's data are not included in the analogy analysis.

Due to the fact that each participant's definition of "analogy" is unique, the analogies identified by the participant are counted as valid analogies. This reduces the amount of biases introduced by the researchers, but there is still subjectivity due to differing participants' definitions. However, the participants' definitions of analogy, as provided in the presurvey, are surprisingly consistent across the participants. Prior studies have used indication of analogies such as "device X is like device Y" to identify analogies in concurrent think-aloud protocols or recorded team conversations [9,23,52]. This study did not include concurrent think-aloud descriptions as the participants were working, nor was there any other indication of which ideas were based on analogies, therefore, the participants' identification of analogy had to be used. Since participants did not provide details on the analogies, it was not possible to further classify analogies along common dimensions such as analogical distance.

In tabulating the analogies metric, as with all other metrics, an inter-rater agreement analysis is performed to ensure objectivity and consistency. In tallying the total number of analogies removing any repeats, the raters achieved 99% agreement and a Pearson's Correlation of 0.99. These measures indicate that the metric is highly reliable, and there is strong consistency between the two evaluators.

6 Results: Design Fixation

A key outcome of this study is on understanding design fixation, participants' perception of it and how to break or mitigate fixation when it occurs. Figures 5 and 6 illustrate examples of typical participant results with high and low degrees of fixation (samples sizes are in Table 2). Four measures are implemented to assess each participant's degree of fixation. From these measures, a participants' fixation may be ascertained and the hypotheses tested.

The number of nonredundant ideas varies across the three conditions (Fig. 7). An ANOVA (analysis of variance) shows a statistically significant effect across the fixation conditions ($F=3.7, p$

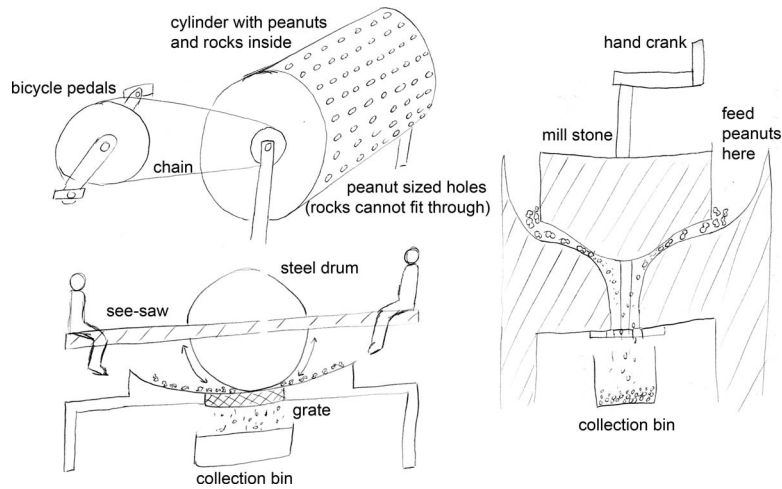


Fig. 5 A set of solutions showing a low degree of fixation on the provided example solution

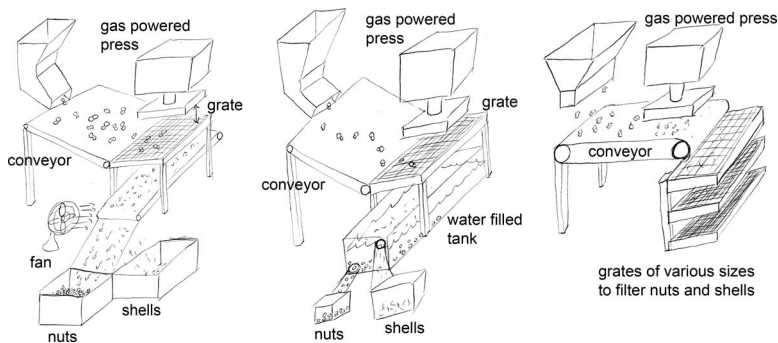


Fig. 6 A set of solutions showing a high degree of fixation on the provided example solution

Table 2 Sample size for each condition

Group	Sample Size
Control	9
Fixation	12
Defixation	10

<0.04).¹ A t-test shows that the control group produces more ideas than the fixation group ($t=2.94, p<0.02$). The other pairwise comparisons are not statistically significant.

The variation in the number of nonredundant ideas indicates that the example did cause design fixation, resulting in fewer ideas being generated. The trend in this data is that the defixation group produces more ideas on average than the fixation group, indicating that the additional materials assist in reducing their fixation.

6.1 Number of Example Solution Features Used. Another indicator of the degree of fixation is the number of times that the participants reuse features from the provided example solution. This metric differs across the three conditions and ranges from 1 to 43 repeated features (Fig. 8). The control group did not see the example solution, but they still may think of the same features that are present in the example solution. These data do not satisfy the assumptions for a standard ANOVA since Shapiro–Wilk’s test of

normality shows the data are not normally distributed and Levene’s test for equality of variances shows that the variances are not homogenous; therefore, a Kruskal–Wallis ANOVA is implemented instead. ANOVA can be used when there are only small departures from normality, but if there are also unequal variances across the groups, a different approach is required. A Kruskal–Wallis ANOVA is analogous to a standard ANOVA, but is the nonparametric statistical equivalent and evaluates the relative ranks of the data points. Implementing a Kruskal–Wallis ANOVA, there is a statistically significant difference across the three conditions ($H=7.3, df=2, p=0.03, N=31$).

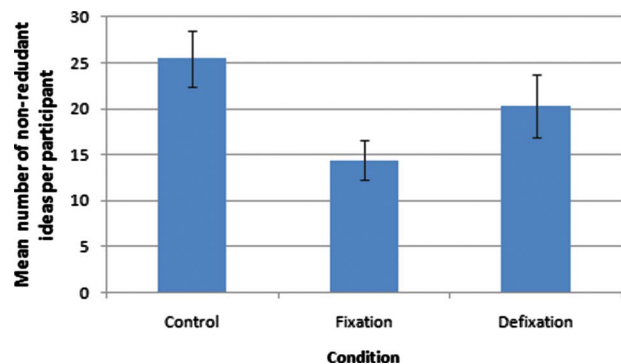


Fig. 7 The fixation group produced fewer ideas, on average, than either the control group or the defixation group. Each error bar is ± 1 standard error.

¹The data are not normally distributed but ANOVA is robust for departures from normality. The remaining assumptions for ANOVA are met. To confirm the ANOVA results, a Kruskal–Wallis ANOVA is also completed on the data ($H=5.7, p<0.06$).

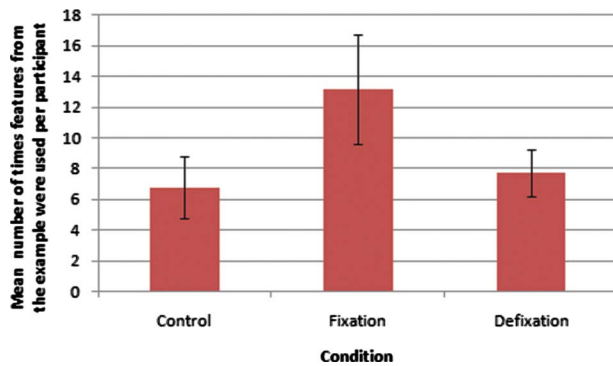


Fig. 8 The fixation group repeated, on average, features from the example solution more often than the other two groups. Each error bar is ± 1 standard error.

The “number of features” data also indicate that the example solution caused fixation, as the features from the example (the fixation condition) are reused more often than for the control. This data indicate that the additional materials are effective in mitigating or reducing the design fixations, since the defixation condition reuses fewer features from the example solution than the fixation condition. In the case of the control group, participants generated features in their concepts corresponding to the example solution. This result is to be expected since some of the features, as shown in Fig. 4, are perfectly acceptable solutions, whereas others, such as the gas-press are not. The control group, however, did not overly use the solutions of the provided example for the fixation condition, whereas the fixation group did offer solutions powered by gasoline or similar fuel-based systems.

6.2 Percentage of Features Used. The three conditions also caused the participants to implement different percentages of the features from the example solution (Fig. 9), another indicator of fixation. The number of times that the participants implemented one of the features from the example solution was counted. Again, these data do not satisfy the assumptions for a standard ANOVA. The Shapiro–Wilk’s test of normality shows that the data is not normally distributed, and Levene’s test for equality of variances shows that the variances are not homogenous; therefore, a Kruskal–Wallis ANOVA is completed instead. There is a statistically significant difference across the three conditions ($H=7.3$, $df=2$, $p=0.03$, $N=31$). A Wilcoxon’s Rank-sum test shows that the fixation group incorporated more of the features from the example in their solutions than the defixation group ($W_s=85.5$, $n_1=10$, $n_2=12$, $p=0.08$) and the control ($W_s=67.5$, $n_1=9$, $n_2=12$, $p=0.02$).

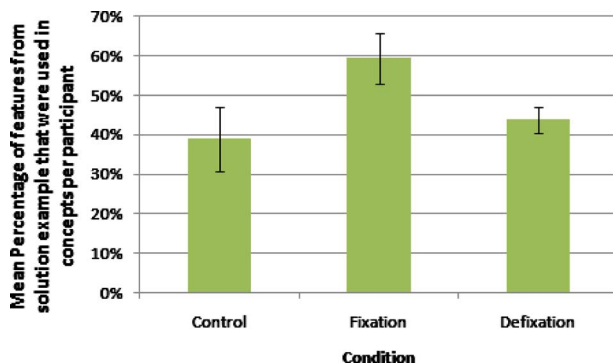


Fig. 9 The fixation group used, on average, a higher percentage of the features from the example solution in their concepts. Each error bar is ± 1 standard error.

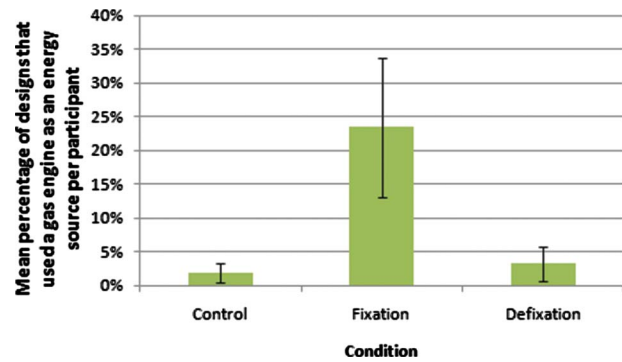


Fig. 10 The defixation group produced more designs powered by a gas engine than individuals in the other conditions. The error bars are ± 1 standard error.

Again the “percentage of features” measure shows that the example solution causes designer fixation. The defixation condition is different from the fixation condition, based on statistical significance, again showing that the defixation materials are assisting the designers in overcoming the fixation induced by the presented example.

7 Results: Energy Sources Fixation

In addition to the number of solutions, the energy source used in the design can be another indicator of design fixation. The defixation condition contained a categorical list of energy sources, Fig. 3.

Participants in the fixation condition were given an example that is powered by a gas engine. It is expected that this example would fixate individuals on using a gas engine. Participants in this condition were given information in addition to the gas engine powered example that is intended to aid in breaking the induced fixation. Individuals in the control condition were given no example on which to fixate. Both predicted effects are observed in the results (Fig. 10). Again, these data do not meet the assumptions for a standard ANOVA, as the data are not normally distributed and the variances are not homogenous. The Kruskal–Wallis ANOVA compares the data based on the relative rank of the results, but this approach is not accurate when there are a large number of equal outcomes as there are with this data set. For this data set, one-way ANOVA via randomization is implemented [81,82]. This approach is analogous to the other approaches, but does not make any assumptions about the distribution or the ranking of the data.

Based on the graphical results shown in Fig. 10, the fixation group is clearly different and distinct from the other two groups. One might expect the other two conditions not to use gas engines at all, but in this study, gas engines were occasionally used. Using a one-way ANOVA via randomization, there is statistically significant difference across the groups ($p=0.05$) [83,84]. The fixation group produced a larger percentage of gas powered designs than the control group, indicating that the example solution caused fixation. The fixation group also showed a strong trend for producing a larger percentage of gas powered designs than the defixation group ($t=1.97$, $p<0.08$), suggesting that the defixation information is effective in breaking or mitigating the induced fixation. Similar to the other measures of design fixation, the results show that fixation is occurring, and the defixation materials are having a statistically significant impact.

The total number of energy sources used in all stages of peanut shelling differed across the three conditions (Fig. 11). Again, these data do not satisfy the assumptions for a standard ANOVA (data are not normally distributed and the variances are not homogenous) so a Kruskal–Wallis ANOVA is implemented. There is not a statistically significant difference across the three conditions

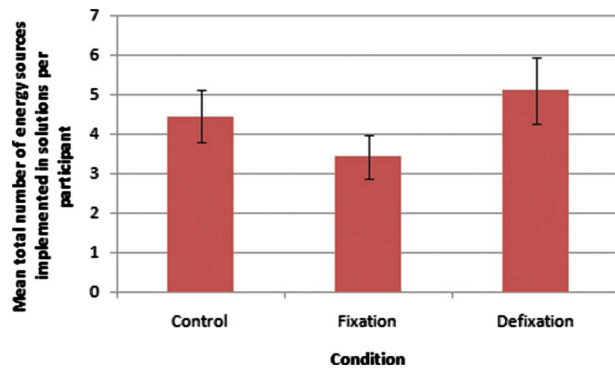


Fig. 11 The defixation group used, on average, more energy sources in total than participants in the other two groups. Each error bar is ± 1 standard error.

($H=3.28$, $df=2$, $p=0.194$, $N=31$). However, the fixation condition produced, on average, fewer energy sources than the defixation condition (Wilcoxon's Rank-sum test, $W_s=112.5$, $n_1=10$, $n_2=12$, $p=0.09$), suggesting that the defixation materials are effective in breaking the induced fixation. The other pair-wise comparisons are not statistically significant.

Consistent with other results from the study, these results suggest that the defixation materials are assisting in mitigating or reducing design fixation. The additional categories of available energy sources are assisting the designers in identifying solutions.

8 General Fixation Results Discussion

The various measures related to fixation clearly illustrate that the example solution causes design fixation. This result is shown by the lower number of ideas generated, by a higher number of features from the example being used in the solutions, and by fewer energy categories being implemented in the participants' concepts. This fixation is of particular interest since these participants are not novice designers. All participants have the required domain knowledge to identify short-comings in the presented example solution. Design fixation is experienced by the engineering design faculty.

Providing participants with analogies and rerepresentations of the problem through categories did assist in reducing their fixation on the example solution, but it did not completely eliminate it. Participants in the control group still outperformed both the fixation and the defixation group in total number of concepts, whereas the defixation group employed a greater diversity of energy-based solutions.

9 Results: Analogies

Many designers employ analogies to inspire solutions to a given problem. The focal metric to consider in this study when examining analogies is simply the quantity identified by the participants across the three conditions. The analogies were identified by the participants after the 45 min of ideation by revisiting their solutions, circling and labeling any analogies used with a red marker.

The number of reported analogies employed did not vary statistically across the conditions (Fig. 12). Again, the data are non-normally distributed with unequal variances, requiring nonparametric tests. A Kruskal-Wallis ANOVA shows there is a not statistically significant difference across the three conditions ($H=1.4$, $df=2$, $p=0.5$, $N=30$). The defixation group did, however, use slightly more analogies, on average, implementing many of the analogies provided in the defixation materials in a variety of ways.

9.1 Analogies Results Discussion. The three conditions implemented in this study produced distinct levels of analogy use.

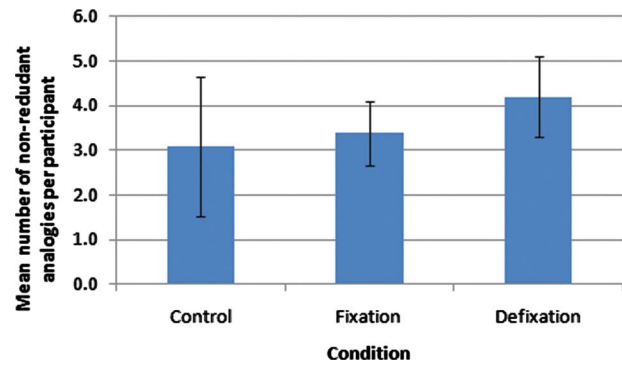


Fig. 12 All groups used analogies in developing solutions to the design problem. The defixation group, on average, employed slightly more analogies during ideation. The error bars are ± 1 standard error.

The fixation group and the control have a similar level of analogy use. However, the defixation group, given both the example solution and the extra information, used slightly more analogies, on average, than that given just the example solution. This could be a result of the fixation caused by the example solution, or further indication that more supplemental information is better for a broader search of the design space. Many of the analogies used by the group given extra information were directly inspired by the key word list supplied in the materials. Future work, with more participants per condition, should investigate whether the observed trend replicates.

An important obstacle to note is the subjectivity of identifying analogies. In order to remove the experimenters' interpretations and biases, a red marker was given to each participant after the ideation session, with which they were to circle and label any analogies used. This removed subjectivity from the experimenters' perspectives, however, not from the participant's perspective. Many participants showed signs of a broader understanding of the definition of analogy, often times circling mechanisms or processes that were taken directly from industry, for example, press. Since the press was being used in an identical way to that which is used in practice, it is not legitimately considered an analogy for the purposes of this study, but more an application of a technology. Despite this discrepancy, all analogies identified by participants were counted as analogies because omitting these would create too much uncertainty in the analysis.

10 Results from Post-Experiment Survey

A post-experiment survey measures a variety of items including the following: participants' opinions about the design problem; perceptions about the effect of the example solution and the additional material; and if they had exposure to the design problem and its solutions prior to the experiment. These measures serve to provide further insights and validity to the experimental results.

The participants' overall opinions of the design problem and activity indicate that, on average, they found it interesting and seriously committed themselves to the task. The participants, on a semantic difference scale, felt that they worked hard on the activity (mean (SD): 1.8 (0.90) 1=worked hard, 5=minimal effort) and found the activity to be somewhat motivating but not inspiring (mean (SD): 2.2 (0.86) (1=motivating and 5=demotivating) and 2.6 (0.78) (1=inspiring and 5=frustrating)). None of these results show a mean shifted substantially to the right of the scales midpoint. For the validity of this study, it is important that the participants were motivated and put in a substantial effort since in a more realistic design setting, it is expected that engineers are generally well motivated to solve a given design problem.

Since the presented design problem is an actual existing issue, it is possible that the participants may have had prior exposure to

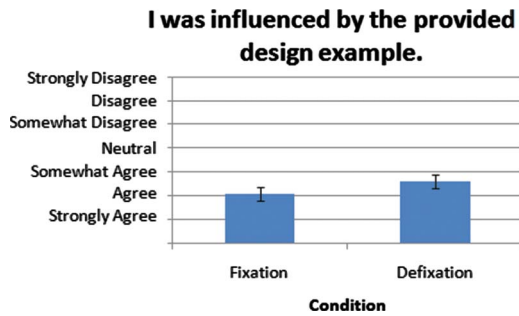


Fig. 13 Participants believe they were influenced by the provided example solution

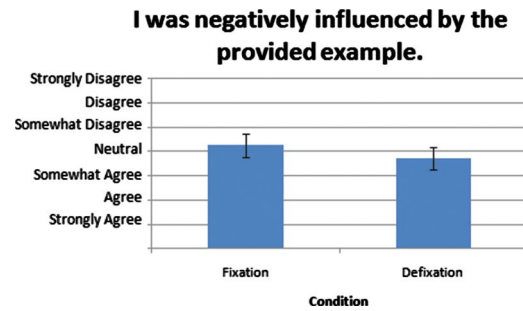


Fig. 15 Participants were undecided if the example solution negatively influenced them

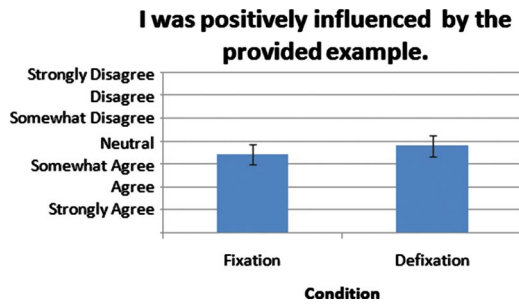


Fig. 14 Participants in the fixation and the defixation group felt the example solution had a positive influence or at least were unsure that the influence was positive or not

the problem and to the solutions. A total of seven participants, evenly distributed across the conditions, had prior exposure to the design problem, with four of them also having exposure to solutions to the design problem. These four participants believed their prior exposure had an insignificant to only some influence on their results (the four responses were 1—insignificant, 2—minor, and 1—some influence). Due to the low level of prior exposure and that the participants were evenly distributed across the conditions, we do not believe that the prior exposure affects the results of this experiment.

The key outcome of the survey is the participants' perception about their performance. The fixation and the defixation groups were asked, using a Likert scale question, if they felt the provided example solution had influenced them, and then if it had positively or negatively influenced them (Figs. 13–15, error bars are 1 standard error). Both groups felt that the provided example solution had influenced them. The participants are recognizing the fact that they are being influenced by the provided design example.

The fixation group tended to believe that the effect of the example solution is positive whereas the defixation group is unsure of the influence. The differences between the groups are not statistically significant, although this lack of statistical significance may reflect the moderate group sizes of this study. The participants' perceptions are in contrast to the quantitative fixation re-

sults that indicate that the example is having a strong negative effect on the fixation group, meaning that the designer may not be aware of the negative influence.

In addition, the participants' perceptions of the effects of the defixation materials were also measured (Table 3). In this case, participants' correctly believe that the additional information is benefiting them with a mean of only agree to somewhat agree (2.7) and a fairly high standard deviation (1.33). This high standard deviation may indicate the some of the participants are more accurate in their perceptions. The quantitative results indicate that there is a very strong positive effect in overcoming the fixation due to the provided defixation materials. While the participant perceptions are generally accurate, in this case, they do not strongly match the quantitative results. This indicates that participant perceptions are not an accurate tool for evaluating design methods.

11 Addressing the Research Questions

Research Question 1: Do academic engineering design educators show evidence of design fixation?

Academic engineering design educators do show evidence of design fixation. The fixation group produced fewer ideas, reused more of the features from the example solution, and implemented fewer categories of energy sources than the control group. Design fixation is evidenced by the presence of a considerable number of solution elements that are clearly not appropriate for the context of the design problem. This group of participants has a high degree of knowledge and can clearly recognize the short-comings of the presented design. Qualitatively compared with undergraduate students in a previous study [73], the design educators produced a larger number of highly novel solutions not identified by the students, providing some validation of their status as design experts. It should be noted, however, that the students did produce a range of novel ideas for the design problem.

Question 2: What can engineers do to mitigate their fixation on design solutions? Can analogies, functions, categories of energy sources, and back-of-the-envelope calculations assist in overcoming design fixation?

Some of the strategies that may mitigate design fixation are analogies, a functional decomposition, rerepresentation of the problem, categories of solutions (such as energy sources), and

Table 3 Participant perceptions of the effect of the defixation materials

Survey question	Defixation group mean (SD)
The provided additional information (functions, analogies, calculation, energy domains) benefited me.	2.7=agree/somewhat agree (1.33)
The provided additional information (functions, analogies, calculation, energy domains) hindered me.	5.1=somewhat disagree (1.45)

Scale: 1=strongly agree, 2=agree, 3=somewhat agree, 4=neutral, 5=somewhat disagree, 6=disagree, 7=strongly disagree

back-of-the envelope calculations. Results from this study clearly indicate that design fixation can be mitigated or reduced through these means. The defixation group did produce more ideas, on average, than the fixation group. In addition, they repeated fewer features from the example solution and implemented a greater number of different energy categories than the fixation group. The results do not indicate which materials are most effective for defixation, but that this set, as a whole, is effective. Future studies will need to consider particular categories of defixation materials and strategies.

Unlike previous studies on design fixation, this study directed participants toward the use of analogy to break design fixation. Participants in past studies likely implemented analogies since analogy is a common and effective design strategy, but our study is much more literal about analogy use. Our study provides further but somewhat indirect support for the importance and impact of analogical reasoning in the design process.

Additional research is needed to fully understand the type of information that eliminates design fixation, including the numerous representations currently existing in the design literature, and how these materials may be generated for novel design problems. Design methods currently exist for functional decomposition [63,66,79] and for analogies [26,62,64,74,85]. As more approaches to reducing design fixation are discovered, new design methods will need to be developed to assist designers.

Research Question 3: How well do participant perceptions of design results correspond to quantitative assessment of the results?

Consistent with other studies on idea generation [37], participants' perceptions of effectiveness during idea generation do not always match the quantitative outcome. Participants in the fixation group inaccurately believe, in general, that the example solution has a positive influence on their idea generation process, or they are unsure as to this influence. It is clear from the fixation results that the example reduces the number of ideas generated, but this is not perceived by the participants.

The defixation group felt that the example solution influenced them, but are not sure if it was positive or negative. The defixation group also correctly perceived that they are assisted by the additional information that is provided, but they do not feel strongly about this. By contrast, the solution data demonstrate that the defixation group is strongly supported by the additional materials. These participant perception results strongly warn against their use as an accurate measurement of ideation effectiveness.

12 Conclusions

This study evaluates design fixation, the use of mitigation strategies, and the perception of design fixation in a group of mostly engineering design faculty. Results show that design fixation is a difficulty encountered even by this group, indicating the strength and importance of this effect in the design process. The participants' perceptions of the effects of the provided fixation example solution and defixation materials are generally not accurate, except with respect to defixation materials. This result is not expected for a group of individuals who study design. This incongruity in perception presents a unique obstacle to engineering design methods research since one of the simplest measures to obtain is the users' perceptions of the method's effectiveness. Based on this study and past work, the participants' evaluation of a method are frequently inconsistent with the quantitative measures and not suitable for accurate evaluation or assessment.

This study compared three groups of participants: (1) a control group, which only received the design problem, (2) a fixation group, which also was provided a negative example solution, and (3) a defixation group, which, in addition to the negative solution, also received a set of materials to mitigate or reduce fixation. The example solution caused design fixation, as demonstrated by a reduction in the number of ideas generated, a greater number of design features from the example being reused and fewer categories

of energy sources considered. Consistent with prior studies, design fixation can be mitigated. The unique fixation mitigation materials, which included functions, energy sources, and analogies, increased the number of ideas generated. It also reduced the frequency of design solutions that were highly similar to the example, and increased the number of energy categories spanned.

Fixation is a commonplace during the idea generation process and warrants much further investigation. Solutions presented or the individuals' own ideas can cause fixation, thus limiting the ideas that are considered. The situations that tend to increase design fixation need to be identified, and more approaches for mitigating or reducing fixation should be created.

Acknowledgment

The authors would like to thank all participants of the 2008 NSF Workshop: Discussion on Individual and Team-Based Innovation and NSF for supporting the workshop and this paper under Grant No. CMMI0740529. The authors specifically thank Judy Vance for proposing the workshop. Support is also acknowledged from University of Texas at Austin College of Engineering, the Cullen Trust Endowed Professorship in Engineering No. 1, with Grant Nos. NSF SBE0738058 and NSF BCS0717957. A version of this paper and some of the data was previously presented at the ICED Conference: Linsey, J., Tseng, I., Fu, K., Cagan, J., and Wood, K., 2009, "Reducing and Perceiving Design Fixation: Initial Results from a NSF-Sponsored Workshop," Proceedings of the 2009 International Conference on Engineering Design, Stanford, CA.

References

- [1] Simon, H. A., 1968, *The Sciences of the Artificial*, MIT, Cambridge, MA.
- [2] Antonsson, E. K., and Cagan, J., 2001, *Formal Engineering Design Synthesis*, Cambridge University Press, Cambridge, England.
- [3] Chakrabarti, A., 2002, *Engineering Design Synthesis: Understanding, Approaches and Tools*, Springer-Verlag, London.
- [4] Stone, R. B., Wood, K. L., and Crawford, R. H., 2000, "A Heuristic Method to Identify Modules From a Functional Description of a Product," *Des. Stud.*, **21**, pp. 5–31.
- [5] Gero, J. S., 1990, "Design Prototypes: A Knowledge Representation Schema for Design," *AI Mag.*, **11**(4), pp. 26–36.
- [6] Shah, J. J., Smith, S. M., and Vargas-Hernandez, N., 2003, "Metrics for Measuring Ideation Effectiveness," *Des. Stud.*, **24**(2), pp. 111–134.
- [7] Shah, J. J., Vargas-Hernández, N., Summers, J. S., and Kulkarni, S., 2001, "Collaborative Sketching (C-Sketch)—An Idea Generation Technique for Engineering Design," *J. Creat. Behav.*, **35**(3), pp. 168–198.
- [8] Yang, M. C., and Epstein, D. J., 2005, "A Study of Prototypes, Design Activity, and Design Outcomes," *Des. Stud.*, **26**, pp. 649–669.
- [9] Christensen, B. T., and Schunn, C., 2007, "The Relationship of Analogical Distance to Analogical Function and Pre-Inventive Structures: The Case of Engineering Design," *Mem. Cognit.*, **35**(1), pp. 29–38.
- [10] Hirschi, N. W., and Frey, D. D., 2002, "Cognition and Complexity: An Experiment on the Effect of Coupling in Parameter Design," *Res. Eng. Des.*, **12**, pp. 123–131.
- [11] Gero, J. S., and Kannengiesser, U., 2004, "The Situated Function-Behavior-Structure Framework," *Des. Stud.*, **25**(4), pp. 373–391.
- [12] Yang, M. C., and Charm, J. G., 2007, "An Analysis of Sketching Skill and Its Role in Early Stage Engineering Design," *ASME J. Mech. Des.*, **129**, pp. 476–482.
- [13] Schunn, C., Lovell, M., Wang, Y. U., and Yang, A., 2008, "Measuring Innovative Apples and Oranges: Towards More Robust and Efficient Measures of Product Innovation," Proceedings of the Design Creativity Conference.
- [14] Perttula, M., and Sipila, P., 2007, "The Idea Exposure Paradigm in Design Idea Generation," *J. Eng. Design*, **18**(1), pp. 93–102.
- [15] Jansson, D., and Smith, S., 1991, "Design Fixation," *Des. Stud.*, **12**(1), pp. 3–11.
- [16] Moss, J., Kotovsky, K., and Cagan, J., 2007, "The Influence of Open Goals on the Acquisition of Problem-Relevant Information," *J. Exp. Psychol. Learn. Mem. Cogn.*, **33**(5), pp. 876–891.
- [17] Tseng, I., Moss, J., Cagan, J., and Kotovsky, K., 2008, "The Role of Timing and Analogical Similarity in the Stimulation of Idea Generation in Design," *Des. Stud.*, **29**(3), pp. 203–221.
- [18] Linsey, J., Laux, J., Clauss, E. F., Wood, K., and Markman, A., 2007, "Increasing Innovation: A Trilogy of Experiments Towards a Design-by-Analogy Method," Proceedings of the ASME Design Theory and Methodology Conference.
- [19] Linsey, J., Wood, K., and Markman, A., 2008, "Modality and Representation in Analogy," *Artif. Intell. Eng. Des. Anal. Manuf.*, **22**(02), pp. 85–100.
- [20] Linsey, J., Wood, K., and Markman, A., 2008, "Increasing Innovation: Presen-

- tation and Evaluation of the Wordtree Design-by-Analogy Method," Proceedings of the ASME IDETC Design Theory and Methodology Conference.
- [21] Schunn, C. D., and Dunbar, K., 1996, "Primary, Analogy, and Awareness in Complex Reasoning," *Mem. Cognit.*, **24**(3), pp. 271–284.
 - [22] Dunbar, K., 1997, "Creative Thought: An Investigation of Conceptual Structures and Processes," *How Scientists Think: On-Line Creativity and Conceptual Change in Science*, American Psychological Association, Washington, DC.
 - [23] Eckert, C. M., Stacey, M., and Earl, C., 2005, "References to Past Designs," *Studying Designers '05*, Sydney, Australia, J. S. Gero and N. Bonnardel, eds. Key Centre of Design Computing and Cognition, pp. 3–21.
 - [24] Mcadams, D., and Wood, K., 2002, "A Quantitative Similarity Metric for Design by Analogy," *ASME J. Mech. Des.*, **124**(2), pp. 173–182.
 - [25] Nagel, R. L., Midha, P. A., Tinsley, A., Stone, R. B., Mcadams, D., and Shu, L., 2008, "Exploring the Use of Functional Models in Biomimetic Conceptual Design," *J. Mech. Des.*, **130**(12), p. 121102.
 - [26] Chiu, I., and Shu, L. H., 2007, "Biomimetic Design Through Natural Language Analysis to Facilitate Cross-Domain Information Retrieval," *Artif. Intell. Eng. Des. Anal. Manuf.*, **21**(1), pp. 45–59.
 - [27] Hacco, E., and Shu, L. H., 2002, "Biomimetic Concept Generation Applied to Design for Remanufacture," Proceedings of the ASME IDETC, Montreal, Quebec, Canada.
 - [28] Hey, J., Linsey, J., Agogino, A., and Wood, K., 2008, "Analogies and Metaphors in Creative Design," *Int. J. Eng. Educ.*, **24**(2), pp. 283–294.
 - [29] Goel, A. K., 1997, "Design, Analogy, and Creativity," *IEEE Expert*, **12**(3), pp. 62–70.
 - [30] Campbell, M., Cagan, J., and Kotovsky, K., 2003, "The A-Design Approach to Managing Automated Design Synthesis," *Res. Eng. Des.*, **14**(1), pp. 12–14.
 - [31] Olson, J., and Cagan, J., 2004, "Inter-Agent Ties in Computational Configuration Design," *Artif. Intell. Eng. Des. Anal. Manuf.*, **18**(2), pp. 135–152.
 - [32] Davies, J., Goel, A., and Nersessian, N., 2009, "A Computational Model of Visual Analogies in Design," *Cognitive Systems Research*, Special Issue on Analogies-Integrating Cognitive Abilities, **10**, pp. 204–215.
 - [33] Leung, P., Ishii, K., Abell, J., and Benson, J., 2008, "Distributed System Development Risk Analysis," *J. Mech. Des.*, **130**(5), p. 051403.
 - [34] Paulus, P. B., and Nijstad, B. A., 2003, *Group Creativity: Innovation through Collaboration*, Oxford University Press, New York.
 - [35] Linsey, J., Clauss, E. F., Kurtoglu, T., Murphy, J. T., Wood, K. L., and Markman, A. B., "An Experimental Study of Group Idea Generation Techniques," Understanding the Roles of Idea Representation and Viewing Methods.
 - [36] Yang, M. C., and Jin, Y., 2008, "An Examination of Team Effectiveness in Distributed and Co-Located Engineering Teams," *Int. J. Eng. Educ.*, **24**(2), pp. 400–408.
 - [37] Paulus, P. B., and Yang, H. C., 2000, "Idea Generation in Groups: A Basis for Creativity in Organizations," *Org. Behav. Hum. Decis. Process*, **82**(1), pp. 76–87.
 - [38] Dong, A., and Agogino, A. M., 1997, "Text Analysis for Constructing Design Representations," *Artif. Intell. Eng.*, **11**(2), pp. 65–75.
 - [39] Cronin, M. A., and Weingart, L. R., 2007, "Representational Gaps, Information Processing, and Conflict in Functionally Diverse Teams," *Acad. Manage. Rev.*, **32**(3), pp. 761–773.
 - [40] Weingart, L. R., Cronin, M. A., Houser, C. S., Cagan, J., and Vogel, C. M., 2005, "Functional Diversity and Conflict in Cross-Functional Product Development Teams: Considering Representational Gaps and Task Characteristics," *Understanding Teams*, IAP, Greenwich, CT.
 - [41] Hanna, L., and Cagan, J., 2009, "Evolutionary Multi-Agent Systems: An Adaptive and Dynamic Approach to Optimization," *J. Mech. Des.*, **131**(1), p. 011010.
 - [42] Dong, A., Hill, A. W., and Agogino, A. M., 2004, "A Document Analysis Method for Characterizing Design Team Performance," *J. Mech. Des.*, **126**(3), pp. 378–385.
 - [43] Smith, S. M., and Blankenship, S. E., 1991, "Incubation and the Persistence of Fixation in Problem Solving," *Am. J. Psychol.*, **104**, pp. 61–87.
 - [44] Ward, T. B., 1994, "Structured Imagination: The Role of Category Structure in Exemplar Generation," *Appl. Cognit. Psychol.*, **27**(1), pp. 1–40.
 - [45] Marsh, R. L., Ward, T. B., and Landau, J. D., 1999, "The Inadvertent Use of Prior Knowledge in a Generative Cognitive Task," *Mem. Cognit.*, **27**(1), pp. 94–105.
 - [46] Jaarsveld, S., and Leeuwen, C., 2005, "Sketches From a Design Process: Creative Cognition Inferred From Intermediate Products," *Cogn. Sci.*, **29**, pp. 79–101.
 - [47] Purcell, A. T., and Gero, J. S., 1996, "Design and Other Types of Fixation," *Des. Stud.*, **17**(4), pp. 363–383.
 - [48] Chrysikou, E. G., and Weisberg, R. W., 2005, "Following the Wrong Footsteps: Fixation Effects of Pictorial Examples in a Design Problem-Solving Task," *J. Exp. Psychol. Learn. Mem. Cogn.*, **31**(5), pp. 1134–1148.
 - [49] Casakin, H., and Goldschmidt, G., 1999, "Expertise and the Use of Visual Analogy: Implications for Design Education," *Des. Stud.*, **20**(2), pp. 153–175.
 - [50] Leclercq, P., and Heylighen, A., 2002, *Artificial Intelligence in Design '02*, 5, 8 Analogies Per Hour.
 - [51] Chiu, I., and Shu, L. H., 2007, "Using Language as Related Stimuli for Concept Generation," *Artif. Intell. Eng. Des. Anal. Manuf.*, **21**(2), pp. 103–121.
 - [52] Ball, L. J., Ormerod, T. C., and Morley, N. J., 2004, "Spontaneous Analogising in Engineering Design: A Comparative Analysis of Experts and Novices," *Des. Stud.*, **25**(5), pp. 495–508.
 - [53] Gick, M. L., and Holyoak, K. J., 1983.
 - [54] Gick, M. L., and Patterson, K., 1992, "Do Contrasting Examples Facilitate Schema Induction and Analogical Transfer?," *Can. J. Psychol.*, **46**, pp. 539–550.
 - [55] Kolodner, J. L., 1997, "Educational Implications of Analogy: A View from Case-Based Reasoning," *Am. Psychol.*, **52**(1), pp. 57–66.
 - [56] Dahl, D. W., and Moreau, P., 2002, "The Influence and Value of Analogical Thinking During New Product Ideation," *J. Mark. Res.*, **39**(1), pp. 47–60.
 - [57] Marsh, R. L., Landau, J. D., and Hicks, J. L., 1996, "How Examples May (and May Not) Constrain Creativity," *Mem. Cognit.*, **24**(5), pp. 669–680.
 - [58] Gordon, W. J. J., 1961, *Synecotics: The Development of Creative Capacity*, Harper, New York.
 - [59] French, M., 1996, *Conceptual Design*, Springer-Verlag, London.
 - [60] French, M., 1988, *Invention and Evolution: Design in Nature and Engineering*, Cambridge University Press, Cambridge, England.
 - [61] Linsey, J., Markman, A., and Wood, K., 2008, "Wordtrees: A Method for Design-by-Analogy," *Proceedings of the 2008 American Society for Engineering Education Annual Conference*, Pittsburgh, PA.
 - [62] Shu, L. H., Hansen, H. N., Gegeckaitė, A., Moon, J., and Chan, C., 2006, "Case Study in Biomimetic Design: Handling and Assembly of Microparts," Proceedings of the ASME IDETC, International Design and Engineering Technical Conferences.
 - [63] Kurtoglu, T., and Campbell, M., 2008, "Automated Synthesis of Electromechanical Design Configurations From Empirical Analysis of Function to Form Mapping," *J. Eng. Des.*, **18**(6), pp. 83–104.
 - [64] Chakrabarti, A., Sarkar, P., Leelavathamma, B., and Nataraju, B. S., 2005, "A Functional Representation for Aiding Biomimetic and Artificial Inspiration of New Ideas," *Artif. Intell. Eng. Des. Anal. Manuf.*, **19**(2), pp. 113–132.
 - [65] Smith, S. M., Ward, T. B., and Schumacher, J. S., 1993, "Constraining Effects of Examples in a Creative Generation Task," *Mem. Cognit.*, **21**(6), pp. 837–845.
 - [66] Pahl, G., and Beitz, W., 1996, *Engineering Design—A Systematic Approach*, Springer, New York.
 - [67] Otto, K., and Wood, K., 2001, *Product Design: Techniques in Reverse Engineering and New Product Development*, Prentice-Hall, Upper Saddle River, NJ.
 - [68] Ullman, D., 1997, *The Mechanical Design Process*, McGraw-Hill, New York.
 - [69] Ulrich, K., and Eppinger, S., 2004, *Product Design and Development*, McGraw-Hill, New York.
 - [70] Ahmed, S., and Christensen, B. T., 2008, "Use of Analogies by Novice and Experienced Design Engineers," Proceedings of the ASME IDETC 2008.
 - [71] Mullen, B., Johnson, C., and Salas, E., 1991, "Productivity Loss in Brainstorming Groups: A Meta-Analytic Integration," *J. Appl. Soc. Psychol.*, **12**(1), pp. 3–23.
 - [72] 2004, Thinkspace: Peanut Sheller, March 2004, http://www.thinkcycle.org/tc-space/tspace?tspace_id=41963
 - [73] Linsey, J., Green, M. G., Murphy, J. T., Wood, K. L., and Markman, A. B., 2005, "Collaborating to Succeed: An Experimental Study of Group Idea Generation Techniques," Proceedings of the ASME Design Theory and Methodology Conference.
 - [74] Linsey, J., Markman, A., and Wood, K., 2008, "Wordtrees: A Method for Design-by-Analogy," Proceedings of the 2008 American Society for Engineering Education Annual Conference.
 - [75] Dugosh, K. L., and Paulus, P. B., 2005, "Cognitive and Social Comparison Processes in Brainstorming," *J. Exp. Soc. Psychol.*, **41**, pp. 313–320.
 - [76] Shah, J. J., Kulkarni, S. V., and Vargas-Hernández, N., 2000, "Evaluation of Idea Generation Methods for Conceptual Design: Effectiveness Metrics and Design of Experiments," *ASME J. Mech. Des.*, **122**, pp. 377–384.
 - [77] Linsey, J. S., Green, M. G., Murphy, J. T., Wood, K. L., and Markman, A. B., 2005, "Collaborating to Succeed: An Experimental Study of Group Idea Generation Techniques," Proceedings of the ASME Design Theory and Methodology Conference.
 - [78] Stone, R., and Wood, K., 2000, "Development of a Functional Basis for Design," *J. Mech. Des.*, **122**(4), pp. 359–370.
 - [79] Hirtz, J., Stone, R. B., and Mcadams, D. A., 2002, "A Functional Basis for Engineering Design: Reconciling and Evolving Previous Efforts," *Res. Eng. Des.*, **13**, pp. 65–82.
 - [80] Clark-Carter, D., 1997, *Doing Quantitative Psychological Research: From Design to Report*, Psychology Press, United Kingdom.
 - [81] Howell, D. C., 2002, *Statistical Methods for Psychology*, Duxbury, Pacific Grove, CA.
 - [82] Howell, D. C., 2007, Resampling Statistics: Randomization and the Bootstrap, 3/2009, <http://www.uvm.edu/~dhowell/StatPages/Resampling/Resampling.html>
 - [83] Howell, D. C., 2000, Resampling Procedures (Software), 3/2009, <http://www.uvm.edu/~dhowell/StatPages/Resampling/Resampling.html>
 - [84] Good, P. I., 2005, *Resampling Methods: A Practical Guide to Data Analysis*, Birkhauser, Boston, MA.
 - [85] Chakrabarti, A., Sarkar, P., Leelavathamma, B., and Nataraju, B. S., 2005, "A Behavioural Model for Representing Biological and Artificial Systems for Inspiring Novel Designs," Proceedings of the International Conference on Engineering Design.