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Training Future Designers: A Study on the Role of Physical Models

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Design fixation is a major factor that hinders design innovation. When designers fixate, they replicate example features and the ideas from the their past experiences in their designs, creating more redundant designs. Building and testing designs is one potential approach for reducing design fixation. The study presented in this paper investigates the role of building working prototypes and warnings about negative example features in mitigating design fixation in freshmen. Two hypotheses are investigated here: (1) The fixation to undesirable example features can be mitigated by building and testing physical models of the designs; (2) providing suitable warnings to novice designers can help them in avoiding design fixation. These hypotheses are tested using a quasi-experiment conducted during a freshmen class project. Students complete their projects in three different experimental groups. One group receives a fixating example with an undesirable feature. The feature negatively influences the functionality of the design. The second group receives the same fixating example with warnings about the undesirable feature. The third group completes the project without the help of an example (control). Students are instructed to build and test their designs. The designs are photographed before and after testing. The occurrence of the flawed example feature in each design is studied. The results show that providing warnings about the undesirable feature does not mitigate design fixation. Meanwhile, as students build and test their ideas, they identify the flaws and gradually mitigate the fixation. Their final designs, after many cycles of testing, contain significantly fewer flawed features. This shows that building and testing physical models helps students in improving the functionality of their designs. In our engineering classrooms, building and testing skills need to be encouraged in order to nurture a future generation of innovative designers.

Introduction

Creativity and innovation are two essential qualities of a good designer. These qualities need to be nurtured in current engineering students to develop a future generation of efficient designers. Providing them real-world challenges and hands-on experiences in a classroom environment is critical[1, 2]. Allowing students to learn through their own mistakes can be a very effective strategy to develop their design skills.

The use of simple physical models in classrooms is often encouraged by engineering educators. A physical model can be a prototype of any level of complexity built to demonstrate, communicate or test designers' ideas. They can range from very simple to highly complicated prototypes and from completely non-functional to fully functional prototypes[3]. Regular use of physical models is widely advocated by industry[4] and government agencies, whereas some researchers argue that they can cause design fixation[5, 6]. Design fixation refers to the blind adherence of designers to the features of examples or designs from their prior experiences[7]. However, some recent efforts show that physical models do not cause design fixation; but allow designers to identify the flaws in their designs and rectify them[8, 9]. This potential of physical models can be efficiently used as a tactic to mitigate fixation to undesirable example features. This paper investigates said argument further.

Another potential tactic that can be used to mitigate design fixation is the use of appropriate warnings about the fixating undesirable features. If the designers are explained why certain example features are undesirable in their designs, they may mitigate their fixation to those features. This argument is proven to be true in the experiment conducted by Chrysikou and Weisberg[10]. However, the results from a more recent study do not support this argument[11]. The study reported in this paper bridges a few differences that exist between the above mentioned studies and further investigates the defixation effects of warnings about unwanted example features.

This paper reports a classroom experiment conducted to investigate the above arguments. Student design teams building stunt vehicles as a part of their class project participate in this study. The students are divided into three groups and the example given to them is varied: no example, a flawed example or the flawed example with warnings about the undesirable feature in it. These examples are provided to the students in pictorial form. The teams are allowed to build and test LEGO models of their designs. The students are instructed to make necessary changes based on the feedback from their testing. The resulting designs are analyzed to investigate the extent of design fixation in their designs. A more detailed description of the method followed and the results are depicted in the following sections.

Background

Design Fixation and its Mitigation

As described previously, blind and unintentional adherence to features of examples or initial solutions can be referred to as design fixation[7]. Existing literature in psychology and engineering design have shown the existence of design fixation in open-ended problem solving[7, 12]. When designers are provided with an example, they tend to copy the features from that example. Studies have shown that both experts and novices fixate to examples[13, 14]. Design fixation is disadvantageous in engineering design, as it inhibits the designer's ability to come up with novel solutions. When they are fixated, the new ideas they generate are variations of the example they fixate on.

A few efforts to mitigate design fixation do exist. One major tactic recommended by the literature is incubation[15]. Incubation refers to situations where attention is returned to a problem, after being set-aside for a while. Studies have shown that designers are less fixated after a period of incubation[16, 17]. The use of provocative stimuli, where designers are given random stimuli to divert their attention from the fixating stimuli, is another tactic suggested by the literature[18, 19]. Linsey et al.[20] have shown that a set of defixation materials containing alternate representations of the design problem can help engineering faculty in mitigation of their fixation. However, this method is not equally effective for novice designers[14]. Chrysikou and Weisberg[10] have proposed the use of warnings about the fixating features as a tactic to mitigate fixation. In a very recent study, Youmans[21] shows that novice designers building physical models of their ideas tend to fixate less to example features compared to those who do not.

Physical Models in Engineering Design and Education

Physical models are considered to be useful tools in the early stages of design. They help designers externalize their ideas and thereby reduce their cognitive load[22]. They also help designers to visualize and solve open-ended problems involving complex systems[23]. Physical models have the potential to provide continuous feedback to designers and thus supplement their erroneous mental models leading them to more functional ideas[24]. Tom Kelley of the famous product design firm IDEO strongly encourages the frequent use of physical models in the early stages of design[4]. Meanwhile, an observational study by Christensen and Schunn shows that physical models lead to suppression of distant domain analogies, leading designers to less novel solutions[5]. Similarly, Kiriyama and Yamamoto observe that building physical models of their designs lead student design teams to design fixation[6]. However, Viswanathan and Linsey show that the design fixation associated with physical models can be reduced by lowering the cost (in terms of money, time or effort) sunk into the building process[25].

The use of physical models as tools for engineering education is also studied by a few researchers. Horton and Radcliffe[26] observe that physical models can provide very critical information to students pertaining to their projects and help them in the identification of flaws in their designs. Youmans[21] shows that students who build the physical models of their ideas fixate less to the negative features of examples compared to those who sketch only. Some researchers encourage the use of physical models in engineering education as students can test their ideas and learn through their own mistakes[1].

Prior Study by Authors on Mitigation of Design Fixation[27]

Based on the existing literature, in their prior study, the authors hypothesized that design fixation to undesirable example features could be mitigated with the help of suitable warnings and through the testing of physical models of their designs. They conducted a classroom study to investigate the hypotheses. Freshmen designers completing a stunt vehicle project as a part of their regular class project were divided into three groups and each group received a different kind of example: An effective example, a flawed example or a flawed example with warnings about the fixating features. The flawed example contained certain undesirable features that affected the performance of the design. The warnings used in that study cautioned the participants about the use of undesirable example features, but did not explain the reasons for those features being undesirable. The results showed that the fixation to the use of undesirable example features was mitigated by building and testing of physical models, but not with warnings about said features. However, it was possible that the designers were testing their designs with undesirable features out of curiosity, in order to understand why those features were undesirable. The current study eliminates this problem by adding causal explanations of why the features are undesirable.

The current study differs from the prior work by authors[27] in certain aspects. The prior work primarily tests the use of physical models in identification of the design flaws present in an inadequate example provided to novice designers. It also investigates the effect of warnings about the flawed features, but these warnings do not provide any causal explanation for avoiding such features. Adding such a causal explanation can have a significantly different effect as shown by Chrysikou and Weisberg[10]. In addition to studying the effects of physical models in a design process by novice designers, the current study explores the effects of causal warnings on the engineering concept generation. For this purpose, the authors use a setting similar to their previous study[27].

As established by the existing literature on design fixation, designers tend to copy features from familiar designs or examples in their solutions. If these features are undesirable, the fixation can lead to undesired results. At the same time, when they build and test the physical models of their ideas, they obtain continuous feedback about their designs. In this process, they may identify the flawed features and rectify those features, effectively mitigating the fixation. Thus, building and testing physical models may be a potential tactic for the mitigation of fixation to design flaws. Warnings about those undesirable features explaining why those features are undesirable may also help in the mitigation of design fixation. The study presented in this paper investigates the potential of these two tactics for the mitigation of design fixation. The following hypotheses are investigated in this study:

Testing Mitigation Hypothesis: Novice designers fixated to the use of an undesirable feature in a flawed example will mitigate this fixation through the feedback obtained from the testing of physical models of their designs.

Warning Mitigation Hypothesis: Novice Designers' fixation to the undesirable features of a flawed example can be mitigated with the help of warnings explaining why those features are undesirable.

In order to test these hypotheses, a quasi-experiment is conducted as a part of a freshmen design course. The examples utilized in their design project are modified to create the various experiment conditions. The following section outlines the method followed for this study.

Method

Overview

To investigate the hypotheses presented in the previous section, a classroom study is conducted with engineering freshmen completing their regular class project. The example given to them for their class project is modified to create various experimental conditions. Three different sections of the class are used in this study. The first section (No Example Group) is not given any example for their design problem. The second section (Flawed Example Group) is given a flawed example consisting of an undesirable feature that restricts the functionality of the same. The third section (Flawed Example Warning Group) is given the same flawed example with warnings about the undesirable feature. The participants are required to build and test the physical models of their ideas and present a final design to the instructor at the end of the project. Their first and final designs are photographed to identify the presence of the undesirable feature in their designs and how it varies as the designers build and test their ideas.

According to the Testing Mitigation Hypothesis, as the designers test the physical models of their ideas, they receive instant feedback about the use of undesirable features and eliminate them in further iterations. If this is true, the use of said undesirable feature will decrease from their initial designs to the final ones. Similarly, as stated by the Warning Mitigation Hypothesis, if design fixation can be mitigated by the use of appropriate warnings, the designers who receive the warnings fixate less compared to those who do not. The method followed to investigate these arguments is described in detail in the following subsections.

Participants

Engineering freshmen attending a "Fundamentals of Engineering" course at Texas A&M University participated in this study. A total of 257 students was distributed across three experimental groups (No Example: 65, Flawed Example: 96, Flawed Example Warning: 96). Students completed their project in groups of 3-4 students each. Hence the No Example Group had 17 teams and the remaining two groups had 24 teams each. The participants completed this study as a part of their regular class project. Only the example employed was modified for this study. Photographs of the physical models of their initial and final ideas were taken and analyzed to identify their fixation to the undesirable example feature. The students received extra credit in the class as a compensation for their participation.

Design Problem and Materials

The design teams were asked to design and build a stunt vehicle that could be launched as a projectile from a ramp of known dimensions. The vehicle was expected to gain sufficient launch speed to cover a horizontal distance of 100 cm after being released from the top of the ramp. The vehicle was expected to remain intact after its landing on the ground. Figure 1 shows the diagram provided to students along with the instructions, showing the requirements to be satisfied by the projectile. The ramp was set up in their classroom and was accessible to the students throughout the project. They were also provided with a photo gate for measuring the exit speed of the vehicle as it left the ramp. The vehicles were expected to jump through two billboards placed at distances D_1 = 50cm and D_2 = 70cm, as shown in Figure 1. The designers were given a total time of three weeks to design, build, test and finalize their vehicle. After three weeks they were required to demonstrate the performance of their vehicle to their instructor. The teams were provided with a kit containing a variety of LEGO parts to build their cars. They were free to choose the parts to be used in their designs.

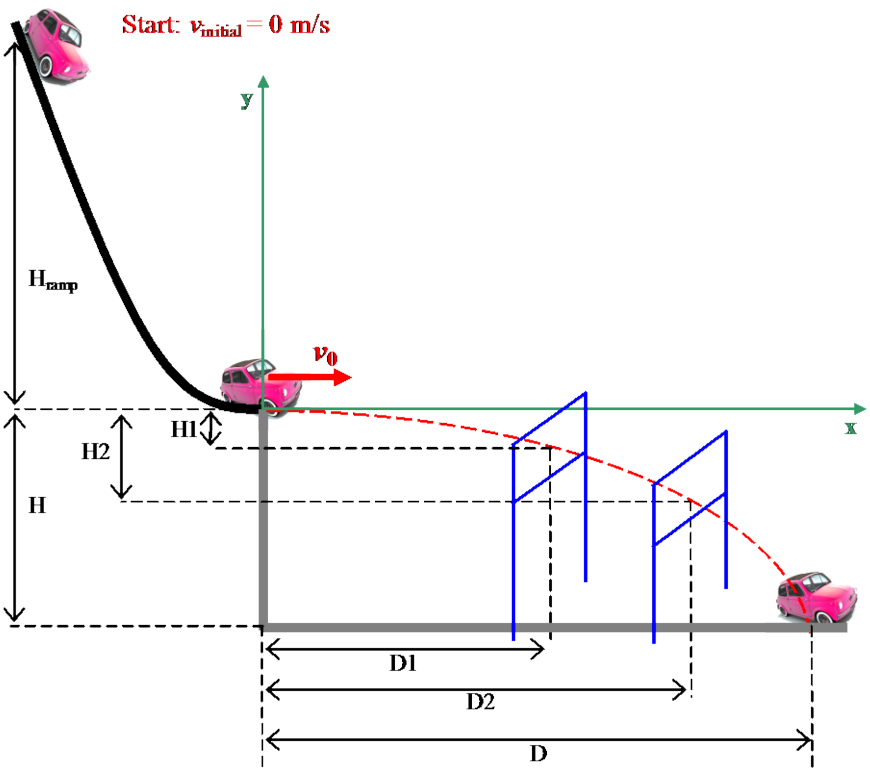

Figure 1. The sketch provided for participants along with instructions that explains the required functionality of the stunt vehicle

Experimental Groups

Three sections of a freshmen engineering class were used for this study. The example given to these sections in their regular class project was modified to create the experimental groups. The first section received no example for the design problem along with the instructions. This section is referred to as “No Example Group” further in this paper. This group received a technical memo with all the instructions pertaining to the design problem and the kit of parts to work on their project.

The second section received the picture of an example stunt vehicle that consisted of an undesirable feature that restricted its functionality. Figure 2 shows the example they received. This vehicle is mainly built with LEGO blocks, which affected its ability to survive the fall from a height. Hence this vehicle was incapable of surviving the crash. Also, the construction with blocks made the car very bulky. The section that received this example is referred to as “Flawed Example Group” further in this paper. The design teams in this group were not informed about the flawed feature of the example.

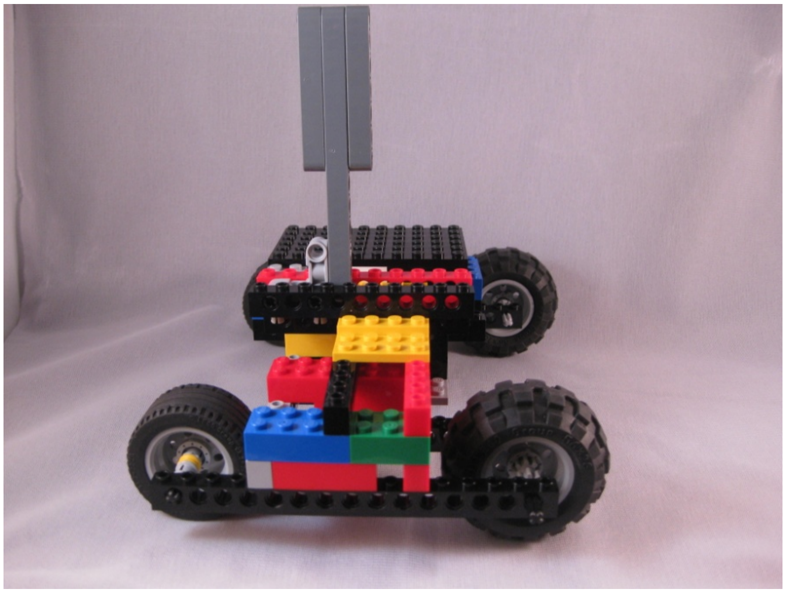

Figure 2. The example provided to Flawed Example and Flawed Example Warning groups

The third section received the flawed example shown in Figure 2 along with some warnings about the undesirable feature in the example. The warnings also explained why said feature was undesirable. The exact wording used in the technical memo was: “Note that this is a bad example as it uses bulky bricks. The main structure of this car is built with bricks and it cannot survive the fall from a height. So try to avoid this feature in your designs.” This section is referred to as “Flawed Example Warning Group” further in this paper.

Procedure

The study was conducted over a span of three weeks. In these three weeks, the students attended four class periods of 1 hour 50 minutes each that dealt with the stunt vehicle project. In the first of these four periods, the instructors gave them a short lecture about projectile motion. Later, the design challenge was introduced to the class as an exercise for learning various aspects of projectile motion. Then, the teams were provided with a technical memo containing the details of the design challenge and the example solution, depending on the experimental group. The teams were required to build and test two stunt vehicles at the beginning. They were required to conduct a drop test on the first iterations of their cars, before they could test the designs on the ramp. In this drop test, they were instructed to drop the car from waist height. They were allowed further to test only if the vehicle remained intact after the drop test. The photographs of each of their designs were taken just before their first drop test. These photographs represented the data before any testing was done on their designs. The students were not informed about the actual purpose of the photographs. They were told that the photographs would be used for investigating how their designs evolve over time. The teams were asked to modify their designs until they achieved two designs that satisfied all the requirements mentioned in the technical memo. The ramp and LEGO kits were accessible to students for modifying and testing their designs during breaks between the class periods. In the further two class periods, they continued working on improving their designs. During the fourth class period, the student teams were required to demonstrate their best designs to the instructor. The pictures of these final cars were also taken and were used as the "after testing" data. The pictures were captured from different angles to obtain sufficient details of the cars, so that reconstructions of the cars were possible, if necessary.

Metrics for Evaluation

The example used in this study contains an undesirable feature that restricts its functionality: the use of bulky bricks as the main construction units of the body of the vehicle. This vehicle cannot survive the fall from a height and is expected to disintegrate during the crash test. To measure the fixation of students to the use of LEGO blocks, a metric called "relative percentage of blocks" is used. This metric is calculated as follows:

$$Relative\ Percentage\ of\ Blocks\ in\ a\ design = \frac{Number\ of\ blocks\ in\ the\ design}{(Number\ of\ blocks\ in\ the\ design + Number\ of\ beams\ in\ the\ design)}$$

Three different kinds of parts are available to the student teams in their kits: LEGO blocks, LEGO beams and other parts including connectors, axles, tires and decorative items. Construction of the vehicles with the LEGO beams is a more efficient method. However, to connect these beams, the teams need to use many connectors. Hence if the absolute percentage of blocks in a design is used, the results can be biased due to the large number of connectors in the designs. Since the use of these connectors is irrelevant to the hypotheses being investigated, their count is not used in the analysis. Thus, the relative percentage of blocks is employed instead of an absolute percentage.

According to the Testing Mitigation Hypothesis, designers mitigate their fixation to the undesirable example features as they build and test their designs. If this argument is true, the use of LEGO beams needs to decrease as the design progresses, since the student teams continually test and modify their designs. Hence the relative percentage of blocks is expected to decrease as the design progresses (from designs before testing to after testing). Similarly, if the Warning Mitigation Hypothesis is true, the designers need to mitigate their fixation to the undesirable feature when they receive the warnings about said features. Hence the Flawed Example Warning Group is expected to fixate less compared to the Flawed Example Group. So, the relative percentage of blocks for the former is expected to be smaller than that of the latter.

Results

The relative percentage of blocks shows very interesting variation across the experimental groups and stages of designs. This variation is shown in Figure 3. As evident from the figure, the type of example does not have a large effect on the use of LEGO blocks. However, the use of blocks reduces significantly after the testing of physical models.

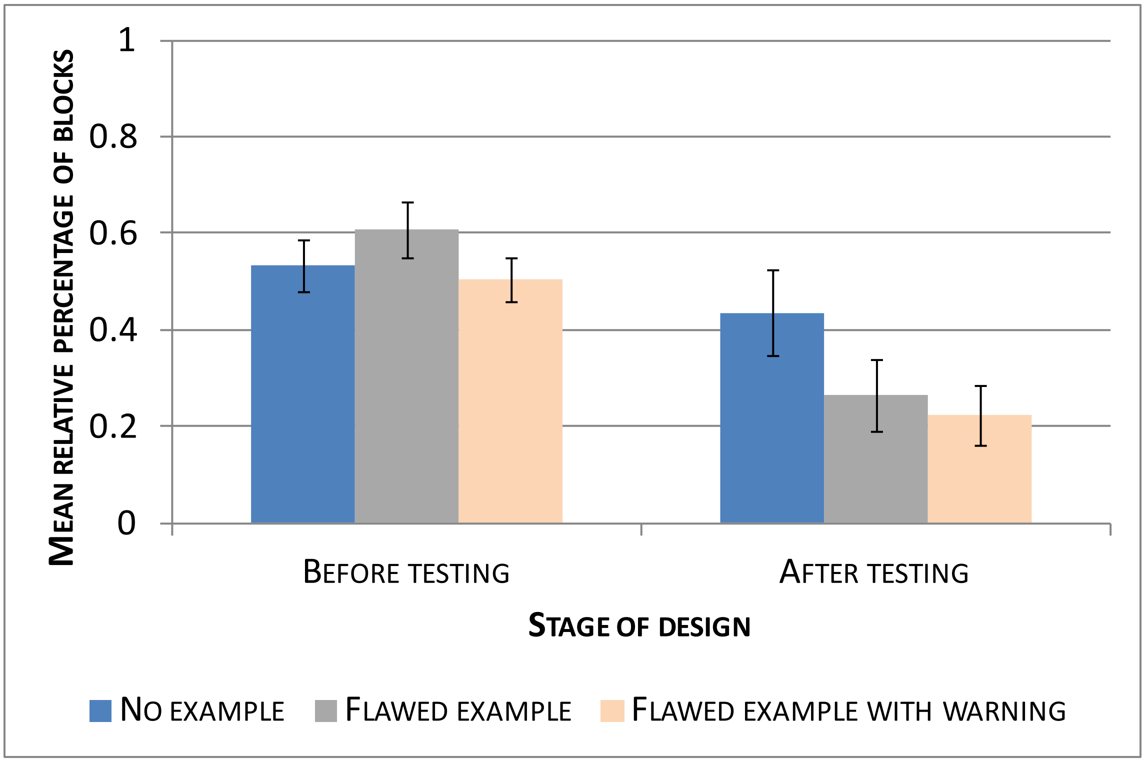

Figure 3. Variation of mean percentage of LEGO blocks across the experimental groups and stages of design. The error bars show (±) 1 standard error.

Statistical analyses are performed on the data to verify the hypotheses. These data do not satisfy the normality and homogeneity of variance assumptions for an ANOVA[28]; hence an equivalent 2-way permutation test is used for the analysis[29]. Two factors are used for this analysis: the type of example (no example, flawed example or flawed example with warnings) and the stage of the design (before testing or after testing). The results show that the interaction of these two factors is not significant ($F = 1.26$, $p = 0.29$). Further, the main effect of the type of example given is not significant ($F = 0.95$, $p = 0.37$), whereas that of the stage of the design is statistically significant ($F = 8.96$, $p < 0.01$). This shows that designers reduce the use of LEGO blocks as they progress with their designs by building and testing the physical models of them. To evaluate the hypotheses, pairwise a-priori comparisons[28] are also performed on the data. The results are shown in Table 1.

Table 1. Results from pairwise a-priori comparisons of the relative percentage of blocks data

Conditions compared	**Significance (p-value)**
Within Experimental Groups (Testing Defixation Hypothesis)	
No Example Group: Before vs after testing	0.40
Flawed Example Group: Before vs after testing	< 0.01*
Flawed Example Warning Group: Before vs after testing	< 0.01*
Within Initial Designs (Warning Defixation Hypothesis)	
Flawed Example Group vs Flawed Example Warning Group	0.16

* denotes statistically significant comparisons at $\alpha = 0.05$

Discussion

The results show that designers use LEGO blocks as their construction units for their stunt vehicles regardless of the presence of the flawed example. This shows that designers fixate to the use of blocks. When the example is present, the designers may be fixating to the use of blocks in that example. When the example is not given to them, they may be fixating to the use of LEGO blocks in their prior exposure to LEGO building kits. In general, blocks are more popular in children's' LEGO construction kits than beams; hence students may be more familiar with them. When they are given kits containing both blocks and beams, they start building with blocks due to the inherent familiarity with blocks rather than beams. This can be considered as fixation to the previously experienced feature. The fixation to the use of blocks in the two groups that receive the flawed example can be caused by this prior exposure and the presence of the example that is primarily built up with blocks, together.

Interestingly, the data provide strong support to the Testing Mitigation Hypothesis, when an example is given to the design teams. For both the Flawed Example Group and the Flawed Example Warning Group, the relative percentage of blocks reduces significantly from their designs before testing to those after testing. This indicates that as they build and test their vehicles, they receive feedback about the use of blocks and gradually reduce the number of them in their designs. Thus, building and testing physical models of designs can be a potential tactic to mitigate design fixation to unwanted example features.

This result has very important implications in the development of new products. The ideas generated by designers often contain errors. Building and testing physical models of their ideas can help them in identifying these errors before the idea progresses to a more advanced stage, where it is costlier to rectify. This result is also consistent with the arguments available in existing literature[8, 9, 21]. Thus, the ability of physical models in providing feedback to designs can be utilized as a potential design tactic to reduce design fixation.

These results also indicate that encouraging students to build and test the physical models of their design can be a very effective way of teaching them. Many times educators are not careful about the selection of their examples and if the example is flawed, that can negatively influence the learning outcome. However, as they build and test their designs, they receive continuous feedback and identify the flaws themselves. This strategy of learning through their own mistakes is adopted by some of the universities in Europe and is proving to be very effective[1, 2, 30].

The data provide no support for the Warning Mitigation Hypothesis. From the a-priori comparisons, it is clear that even when the designers receive warnings about the flawed feature, they fixate to the same extent as those who do not (comparison between Flawed Example and Flawed Example Warning groups on their designs before testing). This result is in agreement with the prior study by the authors[27]. However, in that study, the designers are not given reasons for a feature to be undesirable. The Flawed Example Warning Group in this study goes one step further and provides them the reason for the use of blocks being an undesirable feature. Combining the results, it can be argued that the designers are not testing designs with blocks due to their curiosity; but they are fixated to the use of this unwanted feature. This also shows that providing warnings about fixating features may not be an effective tactic for the mitigation of design fixation.

It is interesting to note that the No Example Group, do not mitigate their fixation to a great extent during the testing of their physical models. There is a reduction in the mean relative percentage of blocks from the designs before testing to those after testing; but this difference is not significant, statistically. This group is mainly fixated to the use of LEGO blocks in their prior exposures to the construction with LEGO kits. Their fixation to this prior use of blocks may be very strong and hence they may be reluctant to use beams instead of blocks, even when they receive continuous feedback from the testing of physical models. Whereas, for the other groups, fixation may be mainly caused by the example given to them and this fixation may be easily mitigated by testing of physical models. This argument requires further exploration.

Overall, it is observed that student designers fixate to the use of LEGO blocks in their designs. This fixating feature is either derived from the example directly provided to them or from their own prior exposure to these LEGO building blocks. In either way, when students are fixated, they generate designs that are similar to the flawed example which contain LEGO blocks mainly, that restricts the performance of their designs. The fixation to such example features limit the creativity of the designer too. However, when they build physical models of their designs, the feedback from the models help them to reduce this fixation. Thus they generate more designs with better performance.

The use of relative percentage of LEGO blocks as a measure of design fixation possesses a limitation. The students may be more familiar and comfortable with the use of LEGO blocks because of their prior exposures to the same. LEGO beams are much less common in the kits given to children. These familiarity and comfort level factors may affect the use of LEGO beams in their designs, effectively biasing the results. However, this is expected to happen in all the experimental conditions. Hence any difference occurring across the experimental conditions may be due to the design fixation effects.

Conclusions

This paper explores the use of physical models and warnings about undesirable example features as potential tactics to mitigate design fixation. A quasi-experiment method is adopted for this study. The examples given to freshmen students completing team projects is modified to create three experimental groups: No Example Group, Flawed Example Group and the Flawed Example Warning Group. The first group completes the project without an example. The latter two groups receive an example with an undesirable feature that affects the design's ability to satisfy the project requirements. The students are required to build stunt vehicles that can pass a crash test. The flawed example is mainly built of LEGO blocks and cannot survive the crash. The use of blocks by the design teams in their designs is tracked using photographs of the design in the initial and final stage. It is observed that the design teams are fixated to the use of blocks in their initial designs and gradually mitigate this fixation as they build and test their designs. As a result, their final designs contain a significantly lower percentage of blocks. At the same time, it is observed that warnings about the use of the undesirable example feature do not help in mitigating fixation. In summary, building and testing physical models is a very effective tactic to mitigate design fixation. Tomorrow's designers need to be trained to effectively build their designs and to test them in order to be more effective innovators. Courses which emphases experimental design are critical.

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