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Designers implement a variety of models and representations during the design process, yet little is known about the cognitive impacts of various representations. This study focuses on how physical models can assist novices in mitigating design fixation to undesirable features. During idea generation, designers tend to fixate on examples they encounter or their own initial ideas. The first hypothesis states that designers tend to duplicate features of provided examples. The second hypothesis states that this fixation can be mitigated with appropriate warnings. The last hypothesis is that building and testing physical models can help designers in mitigating fixation. To investigate these theories, a quasi-experiment is conducted as part of a freshman class project. Students design, build and test stunt cars in three different experimental conditions, each receiving a different pictorial example: an effective example, a flawed example and a flawed example with warnings about the flaws. The results show that in all conditions, designers duplicate undesirable features from their examples, even when they received warnings about the flawed features. Copying these flawed features creates more complicated and less effective designs. However, through the physical testing of their designs, participants identify and fix the design flaws. These results indicate that existing designs and experiences have the potential to limit innovation and that designers need to be trained with effective methods for mitigating design fixation. Building prototypes can help designers in identifying the flawed features and in reducing design fixation; hence the use of physical models in engineering design needs to be encouraged.

Keywords: Design Fixation, Engineering Design, Physical Models, Prototyping, Idea Generation

1. Introduction

Innovation and creativity are considered to be a successful designer's key qualities (Kelley and Littman 2001, National Academy of Engineering 2004). Generating innovative solutions is not an easy task due to the inherent ill-structured nature of design problems

(Simon 1974). As Cross (2008) explains, designers face the challenging task of generating a well-structured solution for an ill-defined task where they encounter two issues: understanding the design problem and identifying relevant solutions from a relatively undefined solution space. During concept generation, as designers search for ideas, they tend to fixate on ideas related to existing familiar products or examples (Jansson and Smith 1991, Purcell and Gero 1996, Chrysikou and Weisberg 2005). This counter-productive conceptual block is widely referred to as “design fixation”. In the early concept generation, when a wide variety of ideas are sought, the presence of design fixation makes the generation of novel ideas difficult.

This study investigates the influence of flawed examples on design cognition and the importance of encouraging learning design through building and testing. It is hypothesized that if designers build and test physical models of their ideas, the feedback from the testing will mitigate fixation to undesirable example features. To evaluate this argument, a controlled classroom study is conducted with first year engineering students. The results show that when designers test the physical models of their ideas, they identify the flaws in their designs due to design fixation and mitigate those flaws. The subsequent sections in this paper outline the relevant background literature, the experiment method used and a detailed discussion of obtained results.

2. Background

Relevant prior work has focused on design fixation, its mitigation and the effects of physical model building on design cognition. The following subsections outline this literature.

2.1 Design Fixation

There are numerous studies in both engineering design and cognitive psychology dealing with design fixation. When designers fixate, they reproduce features from familiar or presented examples (Jansson and Smith 1991, Purcell and Gero 1992, Purcell and Gero 1996, Dahl and Moreau 2002, Linsey, Tseng et al. 2010, Youmans 2011). Design fixation restricts the solution space where designers look for their ideas, therefore hindering the generation of novel ideas. This cognitive block is prevalent among both novice and expert designers (Jansson and Smith 1991, Linsey et al. 2010) and is present with various representations of examples such as sketches, CAD, photos and physical models (Jansson and Smith 1991, Cardoso and Badke-Schaub 2011, Viswanathan and Linsey 2012, 2013, Atilola and Linsey In Review). In addition, common examples tend to cause more fixation than novel designs (Dugosh and Paulus 2005, Perttula and Sipilä 2007).

One explanation for design fixation from the psychology literature is in terms of the network models of memory. According to these models, information stored in the long term memory is in the form of associative networks of related concepts (Collins and Loftus 1975, Matlin 2005). Hence, when the first concept is retrieved, the inter-connected concepts in the network are more likely to be retrieved next (Collins and Loftus 1975). This process happens unconsciously and leads to the duplication of features in the ideas generated by the designer. In many cases, the initial ideas retrieved contain undesirable features and leads to the retrieval of other related undesirable ideas, impairing the performance or function of further ideas. Thus, design fixation can hinder the generation of novel and high quality concepts.

Other explanations for design fixation do exist. Some researchers attribute this phenomenon to designers' cognitive strategies during the design process. Most design problems are ill-structured, as the entire set of requirements is not available initially. Ho (2001) shows that when designers solve ill-structured problems, they adopt a "working-backwards" strategy, where they formulate the requirements based on their first concept or on an example familiar to them. This leads them to an early commitment to their first concept or example, leading to design fixation (Restrepo and Christiaans 2004). When the example provided to designers contain undesirable features, this type of an early commitment can lead to a lower quality of ideas.

In summary, design fixation can be detrimental to concept generation. In this stage, when a variety of novel ideas is desirable, design fixation restricts designers to a set of ideas that are variants of initial ideas or examples presented to them. Fixation may be beneficial at the later stages of design, such as pre-production prototyping where the cost and resources required for a change is significant (Baxter 1995). However, in early concept generation, it is necessary to devise and implement an efficient way to reduce design fixation.

2.2 Prior Efforts to Mitigate Design Fixation

There exist a few methods in the literature to mitigate design fixation. These include incubation, provocative stimuli, warnings about the undesirable features, abstractions and categories of solutions. In general, the data are very limited on the impact of various methods for reducing design fixation and much further work needs to be done.

Incubation refers to situations where the problem is set aside for a while (Finke, Ward et al. 1992). The problem may be solved relatively easily when the attention is returned to it (Smith and Blankenship 1989, Kohn and Smith 2009). Finke et al. (1992), explain this phenomenon in terms of dissipating fixation. When designers are fixated, the retrieval of appropriate concepts is prevented and inappropriate ones are retrieved more easily. With each repeating attempt, this fixation becomes worse, whereas incubation helps to break the fixation.

Design literature shows the use of provocative stimuli in mitigating fixation. A provocative stimulus can be any external stimulus that can provoke the generation of ideas. When designers are fixated, they are focused on the frame of reference (domain, set of features, solution principles etc.) of a single idea. A random provocative stimulus can break this focus and provide a change of reference (Osborne 1953, De Bono, Arzt et al. 1984), thus mitigating the fixation (Shah, Vargas-Hernandez et al. 2001). With the changed frame of reference, designers can produce more novel ideas. Many idea generation techniques like TRIZ (Altshuller, Shulyak et al. 1997), C-sketch, 6-3-5 and gallery rely on provocative stimuli in the form of ideas generated by other team members (Shah 1998, Shah et al. 2001).

Chrysikou and Weisberg (2005) report that fixation on undesirable design features can be mitigated by providing warnings about those features. Replicating Jansson and Smith's study (1991) in very similar conditions, they find that participants (from psychology) who receive warnings fixate less to the undesirable design features. At the same time, a more recent study on engineers with a more complex design problem fails to reproduce the same mitigation effects of warnings (Viswanathan and Linsey 2013).

Yet another interesting method for the mitigation of design fixation is the use of defixation materials. Linsey et al. (2010) show that a set of materials, including a list of analogies, back-of-the envelope calculations and a list of alternate energy sources, help design faculty in mitigating their fixation. Meanwhile, they do not determine which of the materials reduces design fixation. However, a follow-up study shows that these defixation materials are not equally effective for novices (Viswanathan and Linsey 2013).

Youmans (2011), based on his controlled study with novice designers, shows that physical models can help in the mitigation of design fixation. The participants are given a simple design problem and an example containing a few undesirable features. The study concludes that designers, who interact with physical environments during their concept generation, fixate less and can generate more innovative and better performing ideas than those who only sketch. However, his study is conducted within a limited amount of time and at the end of the experiment, the participants are expected to identify a single working concept. In reality, design is not a controlled activity and is performed for much longer periods of time. Typically, designers generate multiple concepts and select the best design among them for the detailed design. In the study reported here, the participants are given longer time periods (1 week) to complete their design task in a classroom environment and are encouraged to generate multiple concepts.

In summary, more methods for mitigating design fixation need to be developed. As explained above, different experiments on the use of defixation warnings and alternate problem representations produce conflicting results regarding their effectiveness in reducing fixation. As shown by Youmans (2011) physical models are effective in leading designers to ideas without undesirable features. The study presented here explores this argument further in a more realistic design setting. The effects of two methods in the mitigation of design fixation are investigated: the use of warnings about the undesirable features and the instant feedback from testing physical models.

2.3 Effects of Physical Models in Design Cognition

A few empirical and qualitative studies explore the uses of physical models in engineering design. Physical models, at the early stages of design, reduce designers' cognitive load by externalizing their ideas (Römer, Pache et al. 2001). They help designers to visualize and solve problems involving complex systems (McKim 1972). They also assist designers in identifying the flaws in their designs and thus lead them to more feasible ideas (Viswanathan and Linsey 2012). Due to these advantages, engineering industry and product design firms strongly encourage the frequent use of physical models in the early stages of design (Ward, Liker et al. 1995, Kelley and Littman 2001).

There exist a few studies that investigate the undesirable cognitive effects of building physical models. Christensen and Schunn (2007) observe that physical models lead to the suppression of distant domain analogies, leading designers to less novel solutions. Along similar lines, Kiriyama and Yamamoto (1998) observe that student design teams fixate to their initial ideas while solving design problems with physical models. Contradicting these results, and as discussed previously, Youmans (2011) shows that novice designers who build physical models during idea generation fixate less. A more recent study shows that the design fixation associated with physical models can be explained using the cost (in terms of money, time or effort) sunk into the building process (Viswanathan and Linsey 2011, Viswanathan and Linsey 2013). As designers spend more time, money or effort (cost) on solving a design problem, they tend to fixate more. Hence, the fixation effects of physical modeling can be reduced by minimizing the sunk cost associated with building.

Based on the studies described above, it can be argued that the apparent design fixation during building is due to the sunk cost associated with the building process. However, as designers test the physical models of their ideas, they detect and correct the flaws in designs, leading to the elimination of undesirable example features they are fixated on. In this way, physical models may have the ability to reduce design fixation to undesirable example features. This argument is explored further in the study presented here.

Based on the conflicting recommendations in the literature mentioned above, the following hypotheses are formulated and investigated further in this paper:

Fixation Hypothesis: *Designers generating ideas with the help of an example will fixate to the undesirable features of that example.*

Mitigation by Warning Hypothesis*: The fixation of designers to undesirable features can be reduced by providing warnings about those undesirable features.*

Mitigation by Testing Hypothesis: *If designers are allowed to build and test physical models of their ideas, they will identify the flaws in their designs and rectify them.*

This paper presents a quasi-experiment conducted with novice participants to evaluate these hypotheses. The study differs from the past explorations on design fixation in a few ways. First, a more realistic, quasi-experiment setting is used where designers complete a design project in their classroom. This setting is more realistic than a lab experiment and better depicting the industry practice. The design activity is a part of the original class curriculum and is not created for the purposes of this study. An example is provided to students as a part of the original design activity. For the purpose of this study, this example is modified to create the experimental conditions. Secondly, the designers have significantly more time to complete their project compared to a typical controlled laboratory experiment. Here, students are given one week's time to complete and test their designs. Finally, the designers are encouraged to develop, build and test multiple designs and then present their best design. This process is also similar to what many product development firms follow in practice.

3. Method

3.1 Overview

The experiment was conducted at Texas A&M University with novice designers (first year engineering students) solving a design problem and building physical models of their ideas. Three different freshman engineering classes were each given the same design problem. Each class was given a different example to the problem: an effective example, a flawed example, and the same flawed example with warnings about the included undesirable features. The participants were told to design and build stunt cars satisfying a few functional and performance requirements. The photographs of the cars built by the teams were studied to understand the amount of fixation to the undesirable example features and how it varied with the testing of the physical models.

According to the Fixation Hypothesis, teams who received the flawed example should fixate to the flawed features. Hence, the participants in the Flawed Example Condition should produce a higher percentage of the flawed features in their initial ideas compared to those in the Effective Example Condition. The participants who received the flawed example with warnings about the undesirable features should be able to mitigate this fixation, according to the Mitigation by Warning Hypothesis. However, according to Mitigation by Testing Hypothesis, when participants tested their cars, they would realize the disadvantages of the unwanted features and correct them, leading to equal occurrences of flawed features in final designs for all conditions. The method followed is described in more detail in the sections below.

3.2 Participants

A total of 281 engineering freshmen attending a “Fundamentals of Engineering” course at Texas A&M University participated in this study. The Effective Example Condition had 89 participating students in 22 teams, the Flawed Example Condition had 96 participants in 24 teams and the Flawed Example Defixation Condition had 96 participants in 24 teams. Each team had 3to 4 participating students. The participants completed this study as a part of their regular class project. The participants received some extra credit in the class as a compensation for their participation.

3.3 Design Problem and Materials

The main aim of the design project was to teach students about the principles of projectile motion and provide them with design experience. As a part of the experiment, the investigators modified the examples provided to the students. The rest of the instructions and activities remained the same as previous years (Froyd, Conkey et al. 2005, Froyd, Srinivasa et al. 2005, Froyd, Li et al. 2006). As the project involved a realistic design process that spanned over a week, it was an ideal situation to understand the role of fixation in real-life design and how to reduce it.

The teams were asked to design and fabricate stunt vehicles that could be launched as a projectile with a known velocity from a ramp of known dimensions. The vehicle was expected to gain enough launch speed to cover a horizontal distance of 100cm after being released from the top of the ramp. The vehicle needed to remain in one piece after the crash. Figure 1 shows the diagram provided to participants. The ramp, shown in Figure 2, was available to the participants to make the necessary measurements. They were also provided with a photo gate for measuring the speed of the vehicle as it exited the ramp. Two billboards were placed at distances D_1=50cm and D_2= 70cm, as shown in Figure 1. The teams were provided with a kit consisting of standard LEGO blocks, Mindstorm™ beams, connectors and a few decorative items which might or might not be useful for the design task.

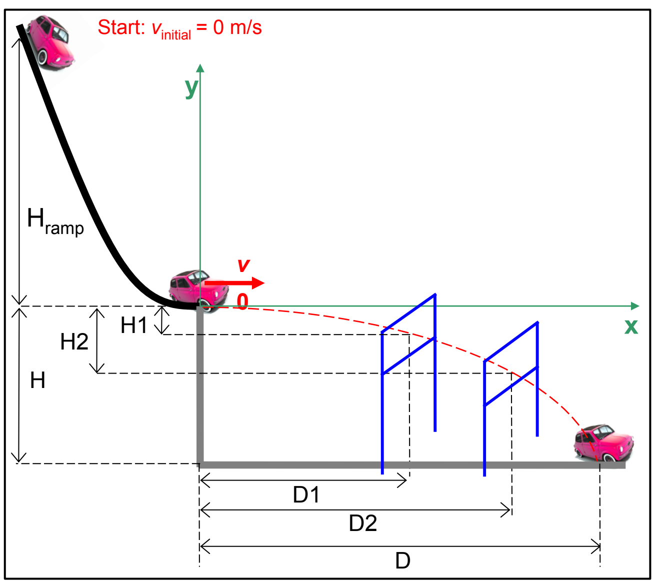


Figure 1. The sketch provided for participants along with instructions

Figure 2. The ramp provided to the designers for testing their cars

3.4 Experimental Conditions

Three freshman engineering classes were used in this experiment, with one type of example per class. The experiment conditions were in different classrooms to avoid any cross-contamination of the data. The first class, the "Flawed Example Condition," received an example solution to the design problem (the flawed example) that consisted of a few

unwanted features (Figure 3

Figure 3). These features were the use of LEGO blocks as the construction units, the use of bulky tires and the use of different size tires in the front and the back. Sturdy cars built of bricks tended to weigh significantly more, tended to not act as effective projectiles and could not survive the crash. The flawed example car also consisted of a pair of bulky tires that were too thick for the ramps and thus restricted the movement of the car on ramps. As evident from Figure 3, this design also used different size tires at the front and back with considerably heavier front tires, which caused an imbalance in the car's center of gravity. Due to this imbalance, the car tipped at the end of the ramp and rotated, instead of remaining horizontal. The participants in the "Flawed Example Condition" were not informed about these defects.

The second class, which comprised of the "Flawed Example Defixation Condition", received the same example as the Flawed Example Condition. They were also presented with the following warning: "Note that this is a flawed example as it uses bulky bricks and heavy tires. It also uses different tire sizes in the front and back causing an imbalance." These warnings did not provide the causal reasons for the specified characteristics to be undesirable.

The third class, the "Effective Example Condition," received an effective example without any flaws. Figure 4 shows the example provided to this group. The car shown mainly consisted of LEGO beams and was a very sturdy design. This design used the same size of tires throughout and the overall design was compact and lightweight. These qualities made the design an excellent projectile and this car could easily satisfy the project requirements. Student could create a working car by copying the features of this example.

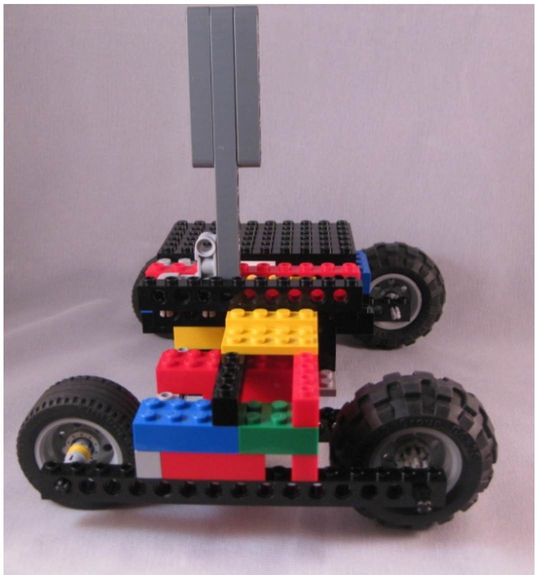


Figure 3. The example provided to the Flawed Example Condition

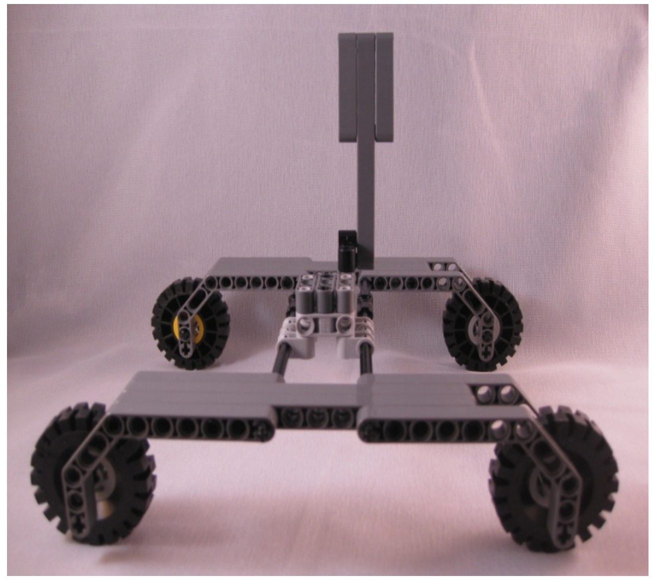


Figure 4. Example provided to the Effective Example Condition

In order to infer design fixation, it was ideal to have a “no example” condition in this study to act as a control. However, the instructors of the class (not the authors) indicated that it was not advisable to provide a project to freshmen without an example; in previous semesters, the students got very confused without an example. Hence, a “no example” condition is not added to this study. Hence, the undesirable features in the flawed example were only considered for the analysis. The Effective Example Condition was not a true control condition; but the effective example did not contain said undesirable features, and thus it could act as a basis for comparing the occurrence of those characteristics. A true control condition for this type of experiment would provide no example. The participants might copy features from the effective example, but this mostly led to effective designs. In this study, adherence to unwanted features was only considered as design fixation.

3.5 Procedure

This study took place during two regular class periods that were 1 hour and 50 minutes long. The two periods were one week apart. In the first class period, a lecture about projectile motion was provided to the students. Then, the teams were given a technical memo containing the details of the design project/challenge and the example. Each group was asked to build two cars out of LEGOs, test them and present the best design to the instructor at the end of the project. In the first class period, the participants made their initial car designs and tested those on the ramp. They were required to conduct a drop test before they could test the cars on the ramp. In the drop test, the cars were to be dropped from waist height and only the cars that survived were allowed on the ramp for the crash test. Pictures of the cars were taken before each drop and crash test. All the data collected in the first class period were the "before testing" data. The participants were not informed about the actual purpose of the pictures, but were told that this helped the instructors to study how their designs evolved over time. The teams were asked to modify their designs until they achieved two designs that satisfied the requirements mentioned in the technical memo. These requirements included a successful projectile motion covering a certain horizontal distance, passing through two billboards and landing on the floor intact. The ramp and LEGO kits were accessible to the participants during the one-week gap between the two class periods. At the beginning of the second class period, the teams were asked to demonstrate the performance of their two cars on the ramp and pictures were taken again to capture the designs during these demonstrations. These pictures were the "after testing" data. The pictures were captured from many different angles to obtain sufficient details of the cars, so that if necessary, the cars could be reconstructed.

4. Metrics for Evaluation

In order to measure fixation, participants' replication of unwanted design features was considered in this study. The undesirable features such as the use of LEGO blocks as construction material, use of bulky tires and the use of different size tires were available only in the flawed example. Since a control condition was not available, it was not possible to measure fixation to all the example features. As the undesirable featured were absent in the effective example, the Effective Example Condition could act as reference for measuring fixation to the undesirable features in all the conditions.

Three metrics were used to measure fixation to the undesirable example features: relative percentage of blocks in a design, percentage of designs using bulky tires and percentage of designs using different sized wheels. The participants used three different kinds of parts in their designs: LEGO blocks, LEGO beams and other parts (like connectors, axles, tires and decorative items). The relative percentage of blocks in a design was calculated as the ratio of number of blocks in that design to the total number of blocks and beams. The ratio of only the numbers of blocks and beams was used rather than the ratio of the number of blocks to total number of parts because it better highlighted the design fixation to blocks as opposed to the more effective solution using beams. The types of bulky wheels that hindered the functionality of cars were experimentally determined. LEGO cars were built and tested with different tires by an independent judge (who was blind to the aim of the study) and the tires whose bulkiness was not suitable for the designs were noted. The pairs of different-sized wheels that caused a center of gravity imbalance were also determined experimentally in a similar way.

The data from the experiment were analyzed by a primary rater and two independent raters. The primary rater was aware of the experimental conditions, but the data were coded to make them indistinguishable based on conditions. Hence the primary rater was blind to the condition to which an idea belonged to. A secondary rater who was completely blind to the experimental conditions reanalyzed all the data. This analysis is reported further in this paper (to ensure that the awareness of the conditions was not biasing the results). A tertiary rater who was also blind to the conditions analyzed 50% of the data to verify the reliability of the procedure. Inter-rater reliability measures including Pearson's correlation and Cohen's Kappa (Cohen 1960, Clark-Carter 1997) were used among the three raters to identify the repeatability of the metrics. A minimum Pearson's correlation (minimum among the three comparisons) of 0.94 was obtained for the relative percentage of blocks, which showed excellent repeatability of this measure. For the use of bulky tires in the design, a minimum Cohen's Kappa of 0.90 was obtained, which was a high value, showing that the raters judged the ideas consistently. In a similar way, a minimum Cohen's Kappa of 0.91 was obtained for the use of differently sized tires in the designs. This again indicated that the metric was reliable.

Based on the hypotheses, certain pair-wise comparisons were expected to be statistically different and therefore, a-priori comparisons were employed. According to the Fixation Hypothesis, participants who received the flawed example would fixate on the undesirable features and replicate those features in their initial designs more often than those who received the effective example. Hence, all the three metrics were expected to be higher for the Flawed Example Condition compared to the Effective Example Condition. In the Flawed Example Defixation Condition, the participants were given a-priori warnings against the use of said undesirable features in their designs. According to the Mitigation by Warning Hypothesis, they were expected to fixate less, keeping their metrics equal to that of participants who received effective example. According to Mitigation by Testing Hypothesis, as the participants built their LEGO models and tested them, they would identify the flaws in their designs due to their fixation on the undesirable example features. Therefore, the final designs of participants across all the groups were expected to produce the same mean value for the three metrics. Table 1 shows the various experimental conditions that were compared to infer the hypotheses.

Table 1. The hypotheses investigated and the corresponding conditions being compared

Hypothesis	**Conditions compared**	**Design Stage**
Fixation Hypothesis	Effective Example vs Flawed Example	Before testing only
	Effective Example vs Flawed Example Defixation	Before testing only
Mitigation by Warning Hypothesis	Flawed Example vs Flawed Example Defixation	Before testing only
Mitigation by Testing Hypothesis	Effective example	Before vs after testing
	Flawed Example	Before vs after testing
	Flawed Example Defixation	Before vs after testing

5. Results & Discussion

Many ideas generated by the participants in this study contained the undesirable features – the use of LEGO blocks, bulky tires and different size tires. Figure 5 shows a few of the participants' designs in each condition with varying degrees of fixation to the undesirable features. The following subsections describe the statistical analysis of the metrics.

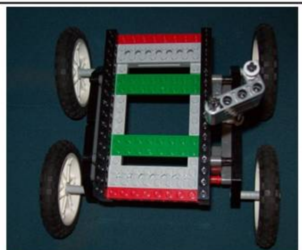
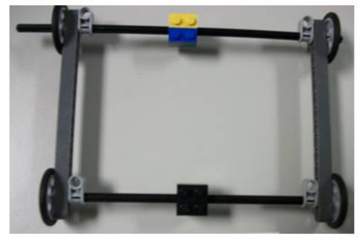
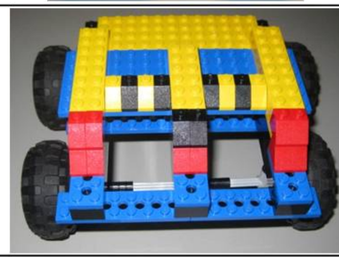
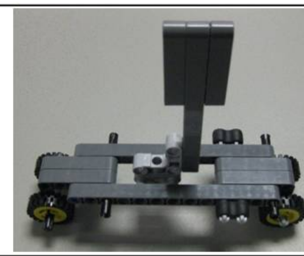
Experimental Condition	Example solutions	
	With maximum undesirable features	With minimum undesirable features
Effective Example		
Flawed Example		
Flawed Example Defixation		

Figure 5. Example solutions generated by participants showing high and low degrees of design fixation to undesirable example features

5.1 Relative Percentage of Blocks

From the results, it was evident that the relative percentage of LEGO blocks varied significantly across the experiment conditions. Participants in all the experimental conditions reused the unwanted features from the flawed example, as shown in Figure 6. It was observed that participants who received the flawed example with or without the defixation warnings about the flawed features produced a higher relative percentage of blocks in their initial designs. Unexpectedly, participants in the Flawed Example Defixation Condition produced designs with higher relative percentage of blocks than those who did not receive any warning. However, as they tested the physical models and made modifications to them, the use of blocks reduced, resulting in a lower relative percentage of blocks in the after test designs.

To determine if the differences were statistically significant, a two-way permutation test equivalent to two-way ANOVA was employed (Good 2000, Anderson 2001, Tabachnick and Fidell 2007). An ANOVA could not be used in this case since the data were not normally distributed and the variances in the different condition were not equal (the data did not satisfy the normality and homogeneity of variance requirements for an ANOVA).The impact of violating these requirements was minimum for a permutation test and hence it was used for analysis(Good 2000, Anderson 2001, Good 2001, Tabachnick and Fidell 2007).The results showed that the relative percentage of blocks was not significantly affected by the interaction between the type of example given and the stage of the design (before testing or after testing) ($F = 1.81$, $p = 0.17$). In order to understand the effects of individual factors, main effect tests using Kruskal-Wallis analysis were used. The results indicated that the relative percentage of blocks in the designs before testing varied significantly across the experiment groups ($\chi^2 = 8.52$, df = 2, $p < 0.02$).This meant that the experimental manipulations applied in this study influenced the extent to which the designers fixated to the use of LEGO blocks.

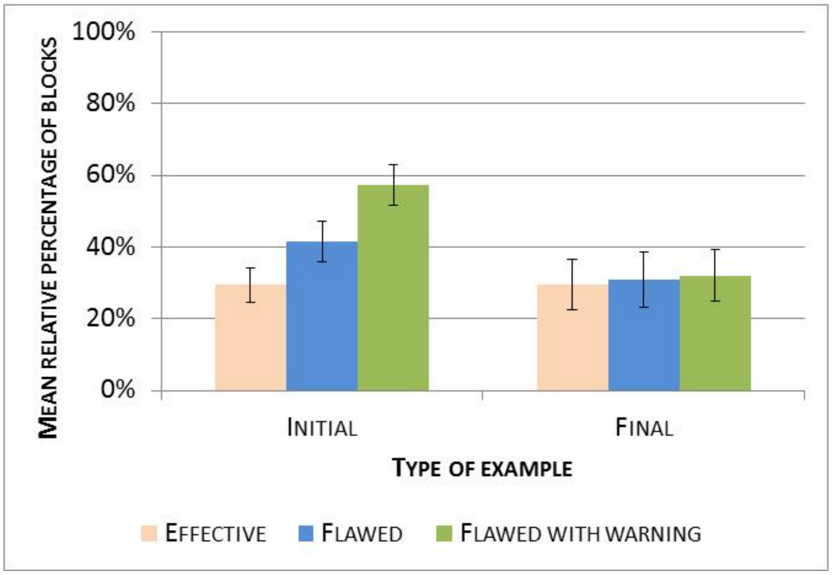


Figure 6.The variation of mean relative percentage of blocks across the experimental conditions and the stages of designs (error bars show (±) 1 standard error)

In order to understand pair-wise differences across the conditions, the comparisons relevant to the hypotheses were identified a-priori and Mann-Whitney tests were conducted on those pairs (Clark-Carter 1997; Ott and Longnecker 2008). The results from these a-priori comparisons are shown in Table 2.

Table 2. A-priori pair-wise comparisons for relative percentage of blocks

Conditions compared	p
Fixation Hypothesis	
Effective Example vs Flawed Example (designs before testing only)	0.32
Effective Example vs Flawed Example Defixation (designs before testing only)	<0.01*
Mitigation by Warning Hypothesis	
Flawed Example vs Flawed Example Defixation (designs before testing only)	0.11
Mitigation by Testing Hypothesis: Comparisons within experiment groups	
Effective example - before and after testing	0.88
Flawed Example – before and after testing	0.27
Flawed Example Defixation – before and after testing	<0.01*

* Statistically significantly at $\alpha = 0.05$

The a-priori comparison results revealed some interesting trends. As shown in Figure 6, the mean relative percentage of blocks in the Flawed Example Condition was higher than that in the Effective Example Condition, indicating the presence of design fixation. However, the a-priori test between these conditions was statistically insignificant, indicating a lack of support for the Fixation Hypothesis. A much higher sample size was required to obtain statistical significance in this case. The only significant comparison was between the Effective Example and Flawed Example Defixation conditions. , Despite the defixation warnings provided to the Flawed Example Defixation Condition, the participants used a significantly higher percentage of blocks compared to the Effective Example Condition. This implied that designers fixated more when they were provided with warnings. Thus, these results offered no support to the Mitigation by Warning Hypothesis, according to which the warnings would mitigate design fixation to said features.

Interestingly, the data provided strong support to the Mitigation by Testing Hypothesis, which stated that designers would mitigate their fixation as they built and tested the physical models of their ideas. Both for the Flawed Example and Flawed Example Defixation conditions, the designs contained significantly lower relative percentage of blocks after testing compared to the ones before testing, indicating mitigation of design fixation to that feature. Statistically, the main effect of the stage of the design (before or after testing) was tested through Krsukal-Wallis analysis and the results confirmed that the testing of physical models led participants to a lower relative percentage of blocks ($\chi^2 = 4.00$, $p < 0.05$). The lack of any significant differences across the experimental conditions for the designs after testing also supported the argument that design fixation was mitigated. Based on these comparisons, it could be argued that designers building and testing of their designs mitigated their design fixation to the use of LEGO blocks.

5.2 Use of Bulky Tires

The percentage of designs created with bulky tires was higher in the experimental conditions that received the flawed example. Figure 7 shows the variation in the number of designs with bulky tires normalized with the total number of designs in each condition. As the data were primarily in a binary format, whether a participant uses bulky tire or not, a log-linear regression (Kennedy 1992, Ott and Longnecker 2008) was used for the statistical analysis. The results showed that the interaction between the type of example and the stage of the design (before or after testing) was not statistically significant ($Z = 0.68$, $p = 0.49$). Within the designs before testing, a Chi-Square (χ^2) test (Ott and Longnecker 2008) showed that the frequency of the use of bulky tires depended on the type of examples given to participants ($\chi^2 = 2.63$, $p < 0.01$). It could also be observed that the participants who received the flawed example with bulky tires copied that feature into many of their designs before testing. At the same time, the designers in the Flawed Example Defixation Condition produced a lower percentage of designs with bulky tires compared to the Flawed Example

Condition, as shown in Figure 7. However, their percentage was higher than that of the Effective Example Condition. After revisions of their models, the designs after testing contained a lower percentage of bulky tires compared to ones before testing, except in the case of the Effective Example Condition. A statistical analysis across the two stages of the designs showed that in their designs after testing, the designers used bulky tires at a significantly lower rate ($\chi^2 = 2.07$, $p < 0.04$).

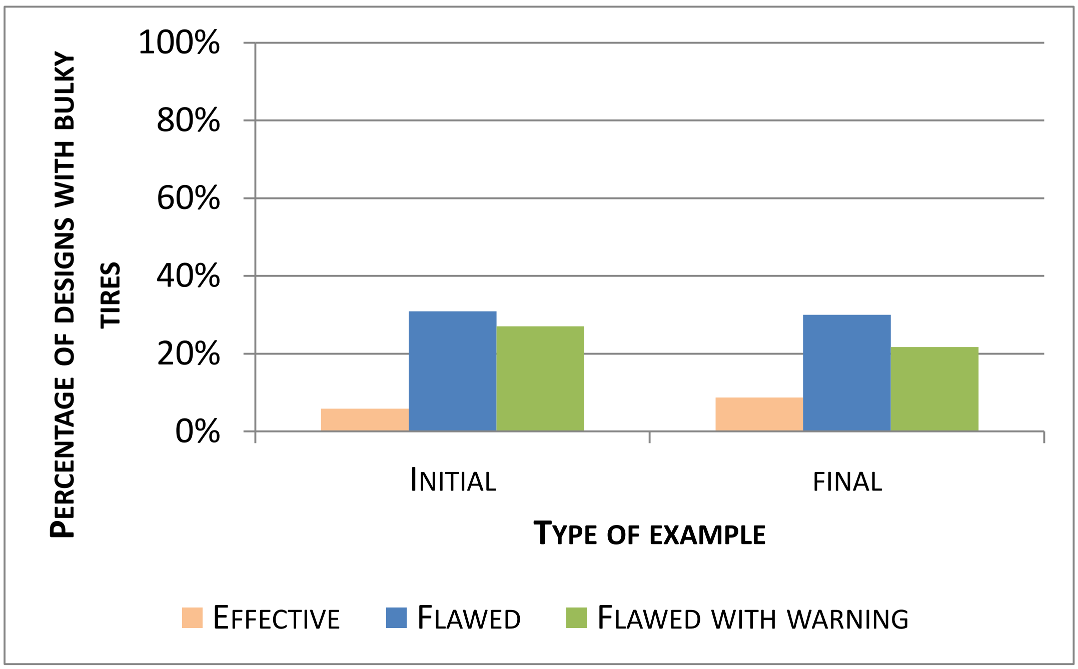


Figure 7.The percentage of designs with bulky tires across the experimental conditions and the stages of designs

The results for this metric showed that designers fixated to the use of bulky tires in the flawed example and they could mitigate this fixation to some extent by testing the physical models of their designs. These results supported both the Fixation and Mitigation by Testing hypotheses. It was observed that the Flawed Example Condition reproduced the use of bulky tires from the flawed example in a significantly higher percentage of cases compared to the other conditions, showing fixation to the example. At the same time, with proper warnings about this flawed feature, this fixation was mitigated to a small extent. These results supported the Mitigation by Warning Hypothesis. As the designers built and tested their ideas, they identified the problems caused by this fixation and eventually mitigated it, leading to a significantly lower percentage of bulky tires in the designs after testing of all groups.

5.3 Use of Different Front and Back Tires

In many cases, designers who obtained the flawed example produced designs with different sized front and back tires before testing. The variation of percentage of designs with different tires is shown in Figure 8. Once again, the data were primarily in a binary format, whether the participant used differently sized tires or not, and a log-linear test (Kennedy 1992) was used for the statistical analysis, as in the previous metric. The results showed that the interaction of the type of example and the stage of the design (before or after the testing) was not statistically significant ($Z = 0.73$, $p = 0.46$). Further, the main effect of the type of example given to the designers was also not significant statistically (Type of example: $Z = 0.69$, $p = 0.49$). However, the main effect of the stage of design was statistically significant ($Z = 3.08$, $p < 0.01$). These results indicated that the testing of physical models was the only factor that affected the use of different sized front and back tires in the designs created by the participants. The lack of statistical significance for the type of example indicated that the participants in all the conditions used this flawed feature to a similar extent. However, while testing the physical models, they recognized the disadvantage of that feature and changed their designs accordingly.

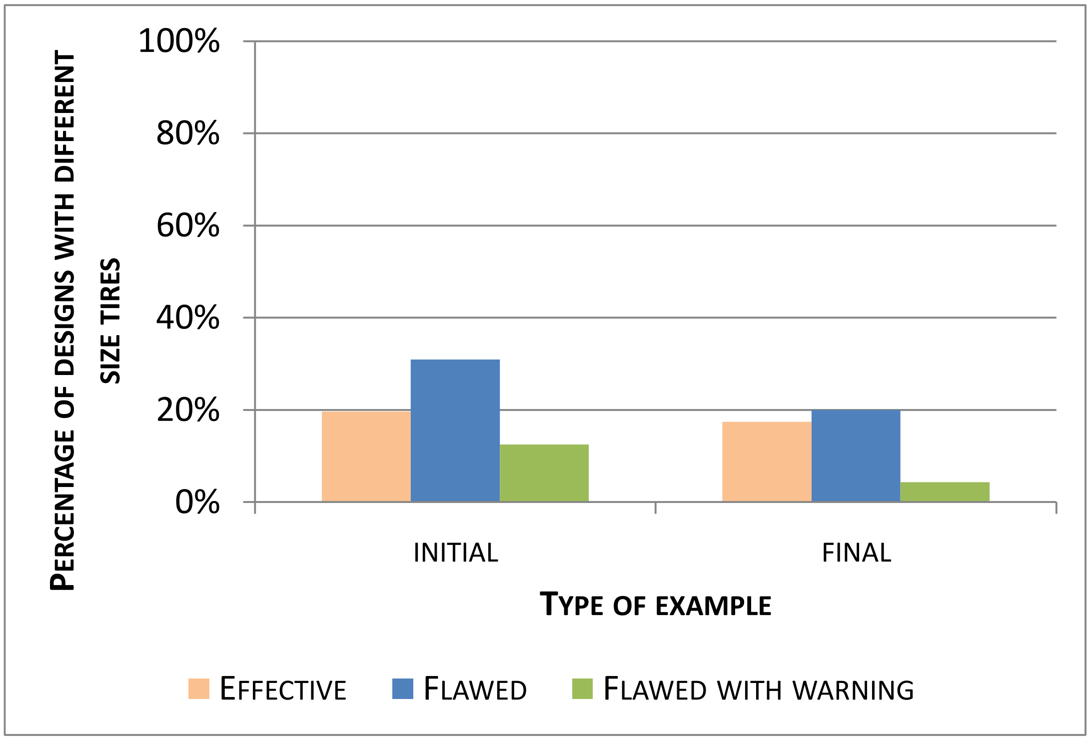


Figure 8.The percentage of cars with different size tires across the experimental conditions and the stages of designs

6. General Discussion

6.1 Fixation Hypothesis

The obtained results support the fact that designers fixate to the features of example solutions. Participants who receive the flawed example with undesirable features reproduce those features in a significantly higher number of initial designs compared to those who receive the effective example. This is true for all three flawed features in this study: percentage of blocks, use of bulky tires and different size tires. This shows that if poor or undesirable examples are given to designers, they may replicate the features, leading to lower quality of ideas. This is especially true in the cases where the ideas are not built and tested or the feedback to the designer is poor. In a practical scenario, the flawed examples may come from the past exposures of the designers or from their own initial ideas.

This result is consistent with many studies that explore design fixation. In the very first study on design fixation, Jansson and Smith (1991) show that designers replicate the features of examples in their solutions, including the features that are undesirable for the problem in hand. The same result has been replicated by many similar studies (Purcell and Gero 1992, 1996, Chrysikou and Weisberg 2005, Cardoso, Badke-Schaub et al. 2009, Linsey et al. 2010, Cardoso and Badke-Schaub 2011), in various experimental conditions. All these results indicate that design fixation is a strong phenomenon and it is present in the concept generation stage, where it is unwelcome.

6.2 Mitigation by Warning Hypothesis

The results from this study also indicate that warning designers against the use of undesirable features in an example does not mitigate design fixation in all cases. Even after providing warnings about the undesirable features in the flawed example, novice designers in this study use a higher percentage of blocks in their initial designs. At the same time, they produce fewer designs with bulky tires and differently sized tires compared to the Flawed Example Group. It can be noted that the defixation warnings given to the designers in this study do not explain why those features are undesirable. The use of bulky tires and different sized tires are two undesirable features that are relatively easy to understand and the designers can identify why they are undesirable without much effort. However, the use of LEGO blocks as construction units is not as easy to identify without testing. It can be argued that the participants are curious to investigate why the use of blocks is undesirable in their designs, leading them to create many initial designs with blocks in them. In the case of the tires, the disadvantages may be clearer and hence they do not use those features in their initial designs. This argument needs to be explored more in future work. The brick type design is also a very common solution type and most of the participants are less familiar with the LEGO beams. Common examples also lead to less novel ideas (Dugosh and Paulus 2005, Perttula and Sipilä 2007) likely due to fixation.

Another explanation for the difference in the use of blocks and tires in the designs after testing is the Sunk Cost Effect (Kahneman and Tversky 1979, Arkes and Blumer 1985, Viswanathan and Linsey 2011). When the participants test their ideas after constructing the cars, they receive feedback about the undesirable features. However, changing the LEGO blocks, which are the major construction units of the cars, takes a significant amount of time. Meanwhile, the tires are comparatively easier to change. In other words, the sunk cost associated with the change of tires is significantly lower compared to that of blocks. Hence, the participants may be replacing the tires more often than the blocks.

Another factor that may affect the extent of defixation with warnings is the designer's familiarity with various LEGO parts. Existing research shows that common examples can cause a higher degree of fixation compared to novel ones (Dugosh and Paulus 2005, Perttula and Sipilä 2007). LEGO blocks are very common parts in children's building toys and it can be assumed that most of the participants possess significant familiarity with those parts. However, they may be less familiar with a variety of tires or the beams. Since the fixation is stronger to the use of blocks, it may be harder to reduce this fixation with the help of warnings. At the same time, the fixation to less familiar tires may be easily mitigated by warnings.

Prior effort by Chrysikou and Weisberg (2005) shows that warnings about undesirable features are useful in mitigating design fixation. The result obtained from the current study does not support this argument. However, in their study, Chrysikou and Weisberg (2005) explain the reasons for considering those specific features undesirable for the given design problem, to their participants. As explained above, this can be a major contributing factor to the mitigation of design fixation. The curiosity of novice designers in exploring the reasons behind the provided warnings in this study can lead them to the usage of the undesirable features in their initial designs.

In a more practical scenario, as in industry, the warnings about unsuccessful designs and design features can be extremely useful. When a design attempt fails, if the designer documents it with sufficient details along with the reasons for failure, that document can act as a guideline for the future designers. Currently, not many firms follow this procedure and thus failures are poorly documented. It is necessary to document unsuccessful designs along with successful ones to avoid unnecessary wastage of resources in future design projects.

6.3Mitigation by Testing Hypothesis

The results provide a strong support for the Mitigation by Testing Hypothesis. It is observed that as the novice designers build and test their models, they make changes to their ideas and their final designs contain a significantly lower percentage of the undesirable features. The final designs of all groups contain the same extent of the undesirable features indicating little to no fixation, whereas undesirable features vary significantly in their initial designs. It can be argued that while building and testing physical models of their ideas, designers receive instant feedback and become aware of the flaws caused by their fixation. This leads them to the mitigation of their fixation, as they move toward their final designs.

These results are also in agreement with the prior study conducted by Youmans (2011). He demonstrates that novice designers who build and test physical models of their ideas fixate less. Youman's study shows that the designers fixate to the example features in their initial ideas and then gradually mitigate this fixation as they build and test their ideas. The current study provides further support to Youmans' argument in a more realistic design setting. Unlike Youmans' study, the current study uses a quasi-experiment setting and the design project is carried out for a much longer period of time. Combining the results from these two studies, it can be argued that the designers receive instant feedback from the building and testing process and thus they eliminate the negative features from their designs.

The results from this study indicate that physical modeling has the potential to mitigate design fixation to undesirable features and thus the use of physical models as idea generation tools needs to be encouraged. Physical models can lead designers to more innovative ideas with higher functionality (Kelley 2001, Youmans 2011, Viswanathan and Linsey 2012). Designers need to understand the necessity for testing their ideas and the benefits of doing so. They need to build quick and simple prototypes of their designs and test them to receive instant feedback on their ideas.

7. Conclusions

This paper investigates two methods to mitigate design fixation: the use of warnings about undesirable features and the building and testing of physical models. Three hypotheses are investigated in this study: (1) Fixation Hypothesis which states that participants fixate to the flawed features of a provided flawed example; (2) Mitigation by Warning Hypothesis which states that designers can mitigate their fixation by using warnings about the flawed features in the example; and (3) Mitigation by Testing Hypothesis which states that participants who build and test their ideas mitigate their fixation. To investigate these theories, participants, building physical models for their class project, are grouped into three conditions: an effective example, a flawed example with three flawed features and the same flawed example with warnings about the flawed features. The occurrences of the flawed features in their designs before and after testing of physical models are recorded. The results show that designers do fixate to the undesirable features of the flawed example and the warnings about the flawed features do not help to mitigate this fixation completely. However, as they build and test the physical models of their ideas, they receive instant feedback about the flawed features and correct them, leading to a smaller occurrence of those features in their designs after testing. These results support the Fixation Hypothesis and the Mitigation by Testing Hypothesis, while providing partial support to the Mitigation by Warning Hypothesis.

This study demonstrates a critical function of prototyping in the design process: it breaks negative fixation, allowing designers to identify ineffective features and improve them. This finding is probably not limited to physical representations. It likely extends to other types of models such as computer simulations, virtual prototypes and mathematical models, as long as the models are accurate depictions of the physical behavior of the system and highlight flaws.

Future work needs to explore why the warnings were effective for some of the design features but not for others. It is likely more difficult to break design fixation to common examples than to more novel ones. Warnings may also be more effective when the participants can clearly understand the casual reason that a particular design feature should not be used. More work is needed to explore this. The internet and other databases supply designers with many example resources on which they can base their designs. These resources need to be designed to maximize innovation and designers need to be well-aware of design fixation and the cases which are most likely to result in fixation. In addition, much more work is needed to explore other methods for limiting design fixation. Designers need tools to help them recognize their fixation and mitigate it, or to completely avoid it.

8. *Implications of Current Results on Engineering Education*

These results have important implications for engineering education. Educators need to be very careful in the selection of examples for teaching students. Students can fixate on unwanted or unreliable features in a poorly chosen example, which may adversely affect the learning outcome. If students are provided with a flawed example and a warning about the undesirable features in it, it can help students in understanding why that feature is unwelcome, but may still cause some amount of fixation.

This also highlights the importance of a hands-on teaching approach to engineering education. Computer simulations, virtual prototypes and other models may have similar effects on design cognition as the physical models, but no model is a perfect representation.

Hence, engineering educators need to train students to learn through building models and recognize undesirable features in their designs. This “make mistakes and learn” approach is very close to the “reflection in action” plan adopted by some educators (Schon 1987, Green and Kennedy 2001), which can prove to be an effective approach for engineering education.

9. Limitations of the Study

The results from this study show that when designers are allowed to build and test the physical models of their ideas, they mitigate the fixation to undesirable design features present in those. This highlights the importance of a more hands-on design process. However, this study possesses a few limitations. The study is not in a highly controlled lab situation so there could be other factors influencing the outcomes that are not being measured. The participants could work on this activity outside of class and they chose how much effort to put in. This is much closer to a real-world design situation than controlled lab studies.

The student design teams in the same condition could see other teams’ designs, but not very well. While the teams were working, they tended to be highly focused on their own design so it is unlikely that this had a significant influence. The desks had computer monitors on them so the view of other teams’ designs is not particularly good.

Similar to many existing studies in literature, this paper also does not investigate the effects of physical models as fixation mitigation tools across the various levels of expertise. A few have shown that the effectiveness of design tools and methods may vary according to the level of expertise of the designer (Brown 1989, Vosniadou 1989, Casakin and

Goldschmidt 1999, Viswanathan and Linsey 2012). This study primarily uses first year engineering students (freshmen) as participants. In order to generalize these results across multiple levels of expertise, more experimentation is necessary.

Though the experiment conditions are controlled, some extent of interaction between the groups in different conditions is possible due to the one week break between the two class periods. During this one week period the participants are allowed to build their cars and test them on the ramps. As the ramps are set-up in locations accessible to all the participants, it is practically impossible to prevent the interactions between the conditions. However, this kind of an interaction is likely to be a minimum and is not expected to influence the outcomes of the study. Further, the amount of practice that participants get during the one week period is not monitored. Meanwhile, it is highly unlikely that one group tests their ideas many more times than the others. Hence the influence of this factor on the final results is expected to be the minimum.

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Figure 6. The variation of mean relative percentage of blocks across the experimental conditions and the stages of designs (error bars show (±) 1 standard error)

Figure 7. The percentage of designs with bulky tires across the experimental conditions and the stages of designs

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