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Build to Learn: Effective Strategies to Train Tomorrow's Designers

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Build to Learn: Effective Strategies to Train Tomorrow's Designers

Designers use various representations to externalize their ideas, physical models being an important one. Physical models are widely used by designers and their use is promoted as an effective design tool by industry and government agencies. However, very little is known about the cognitive effects of physical models in the design process. The available guidelines are conflicting. Some researchers argue for the frequent implementation of physical models; others observe that the use of physical models fixates designers. In light of these conflicts, this research project focuses on understanding the cognitive effects of physical models and developing guidelines for aiding designers in their implementation. We adopt a combination of controlled lab studies and qualitative studies to achieve this goal. The results from our controlled studies show that physical models supplement designers' erroneous mental models and help them to come up with more ideas satisfying the problem requirements. However, this study failed to show presence of design fixation. This difference in the results from prior observational studies leads us to the theory of Sunk Cost Effect in design problem solving with physical models, which is investigated in more detail with another controlled study. According to Sunk Cost Effect, as designers spend more time building physical models of their initial ideas, they tend to fixate to the variations of those. Our second controlled study confirms this theory. To infer these results in real-life situations, the data from a few industry-sponsored graduate projects and case studies of development of award-winning innovative products are analyzed qualitatively. The results from these qualitative studies show that in real-life design problem solving, building prototypes help designers to identify the problems in their ideas and rectify them. At the same time, building also tends to fixate designers to the variations of their initial ideas, which is in agreement with the prior observational studies. These results suggest that engineers need to be trained to build prototypes of their ideas during idea generation. This can help them in identifying the problems in their idea early on and rectify them. At the same time, due to Sunk Cost Effect, they need to spend minimum time in building. Hence they need to use easily modifiable materials for prototyping purpose. Our engineering curricula need to be updated to include this practice and learn method, so that we can train our future designers effectively.

Introduction

Engineering idea generation is a very crucial stage in the engineering design process. The generation of novel ideas in this stage is very essential for a successful designer. Recent research in design focuses on the factors affecting design cognition and ways to modify the same to effectively improve the generation of novel ideas. Physical models are tools that can help designers in this regard. Physical models refer to any kind of prototypes that designers build at any stage of the design process[1]. They range from very simple to highly complex, non-functional to fully functional prototypes[2]. Figure 1 shows an example of various physical models used by NASA in the development of common lunar lander[3].

Despite the use of physical models as idea generation tools, there are no clear guidelines available in the literature regarding their use. This makes the implementation of physical models difficult for students and novices. The famous product design firm IDEO strongly recommends the frequent use of physical models at the early stages of design[4]. However, their cognitive influences remain largely unknown. This project focuses on the cognitive aspects of the use of physical models in idea generation and how they can be effectively used to help designers in the generation of break-through ideas. To achieve this target, a series of controlled and qualitative studies are used. Details of these studies are discussed in detail in subsequent sections along with a discussion on the overall results.

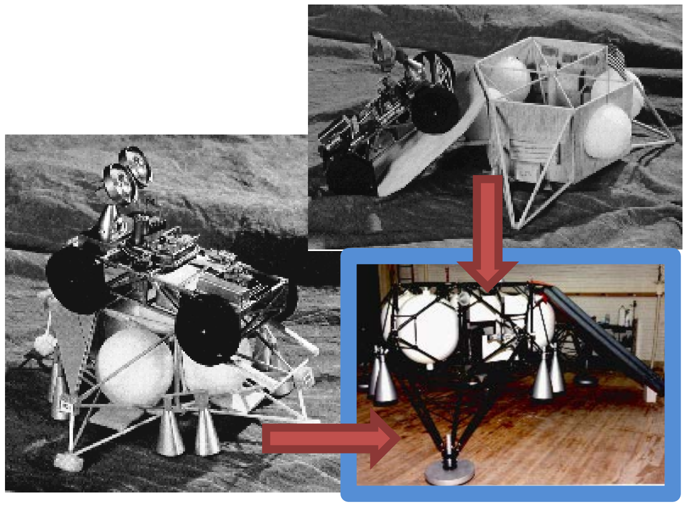

Figure 1. Physical models used by NASA in the development of the common lunar lander[3]

Background

Mental Models and Naïve Physics

The areas of mental models and Naïve Physics deal with the perception of people about the physical world around them[5]. According to Gentner and Stevens[5], the mental models of designers are surprisingly erroneous. Kempton[6] provides a good example for this in the operation of home heat control thermostats. Many people perceive the operation of thermostats similar to a car's accelerator and they keep the settings at high temperatures, expecting the room to be heated faster. The errors in designers' mental models can lead to infeasible solutions generated by them. Hence these errors have wide implications in design.

Design Fixation

Design fixation refers to the blind adherence of designers to the features of presented examples or initial solutions generated by them[7]. The presence of design fixation has been proved in designs by both expert designers and novices[7-10]. Designers fixate to the features in examples in pictorial form, typical function of any part or material used[11] or the solution strategy for a design problem[12]. This restricts the solution space in which the designers search for their ideas, thereby reducing the novelty and variety of the ideas generated. Hence this can be detrimental to the idea generation process.

Empirical Work on Physical Models in Design

Designers use various tools to externalize the ideas in their mind and thereby reduce their cognitive load[13]. Physical models are very effective in this regard. Based on their survey, Romer et al.[14] hypothesize that physical models can provide memory relief. They help designers to visualize and solve complex problems at early stages of design[13]. They help designers to obtain critical information about the functionality of their design and in that process reveal the flaws in their ideas[15]. They aid novice designers to understand the difference between the real behavior of materials and the conceptual models predicting that behavior[16]. They also help designers to validate the assumptions made during the design, thereby reducing the risk associated with product development[17].

Many researchers have provided warnings about the use of physical models as idea generation tools. Christensen and Schunn observe that as designers use physical models in idea generation, their distant domain analogies are suppressed, leading to less novel solutions[18]. Kiriyama and Yamamoto observe that student design teams fixate to their initial ideas while building physical models[19]. Vidal et al. find no difference between idea generation with and without physical models[20]. Baxter warns about the money and time involved in building physical models[21]. Buur and Andreasen[22] state that inclusion of unnecessary details in physical models can lead to wastage of resources in the design process.

In the light of all these conflicting guidelines, this project sheds light on few cognitive effects of physical models in engineering idea generation. The questions being investigated in this project are the following:

Can physical models supplement designers' erroneous mental models and lead them to higher quality solutions to design problems?

Do physical models cause design fixation? If yes, is this fixation inherent in building of physical models? How this fixation can be mitigated?

Is it advantageous for engineering educators to use physical models to train future designers?

What kind of physical models are appropriate for designers generating ideas? What materials are better for building such models?

These questions are investigated through a series of controlled and qualitative studies. Brief descriptions of these studies are given below.

Paperclip Experiment – Physical Models Supplementing Mental Models[23]

This study was designed to evaluate two hypotheses: The Mental Model Hypothesis which stated that physical models supplemented designers' erroneous mental models and the Fixation Hypothesis which stated that physical models caused design fixation. This was a controlled laboratory experiment. Senior undergraduate students and graduate students in Mechanical Engineering at Texas A&M University participated in this study. They were asked to generate ideas for a small object made of steel wire that could firmly bind 10 sheets of paper together without damaging the papers. They were grouped into four different conditions: A Sketching Only condition in which participants were only allowed to sketch their ideas, a Building Condition in which the participants were provided with steel wire to build prototypes of their ideas, a Building and Testing Condition in which participants were allowed to build and test prototypes of their ideas and a Constrained Sketching Condition, in which the participants were given necessary training to build the prototypes and then asked to sketch. The Constrained Sketching Condition was targeted to make the participants aware of the implicit constraints associated with the building process and materials, so that their effects could be separated experimentally.

According to the Mental Models Hypothesis, designers' mental models needed to be supplemented as they built their ideas and that should lead them to higher fraction of ideas satisfying all the design problem requirements. These ideas were referred to as functional ideas. The number of functional ideas normalized by dividing with the total number of ideas generated by the participants was considered as a metric to evaluate this hypothesis and was referred to as percentage of functional ideas. According to the Mental Models Hypothesis, a higher percentage of functional ideas was expected in Building and Building and Testing Conditions compared to Sketching Only. The results obtained for this metric is shown in Figure 2. These were in full agreement with the hypothesis. The differences were also statistically significant. The increase in percentage of functional ideas in Constrained Sketching Condition compared to the Sketching Only Condition showed that implicit constraints also played an important role in the increased functionality of the ideas; however, the majority was contributed by the physical models themselves. These results showed that physical models did supplement designers' erroneous mental models and improved the functionality of ideas and this improvement was a combined effect of the implicit constraints and the building itself.

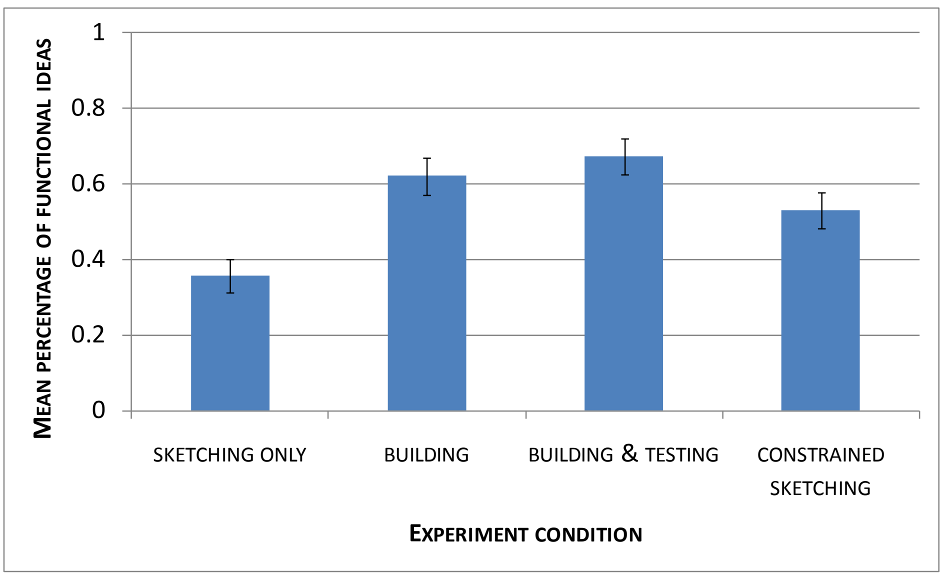

Figure 2. Variation of mean percentage of functional ideas across the conditions (error bars are (±) one standard error of the mean)

Novelty and variety[24] were used as the measures for fixation in this study. If the Fixation Hypothesis were true, reduced novelty and variety were expected in the Building and Building and Testing conditions compared to the Sketching Only Condition. The obtained results did not show such a trend. Figure 3 shows the variation of novelty across the conditions and variety followed the same trend. These measures remained constant across the conditions, showing that physical models did not fixate participants in this experiment. A more detailed description of the results is available elsewhere[23].

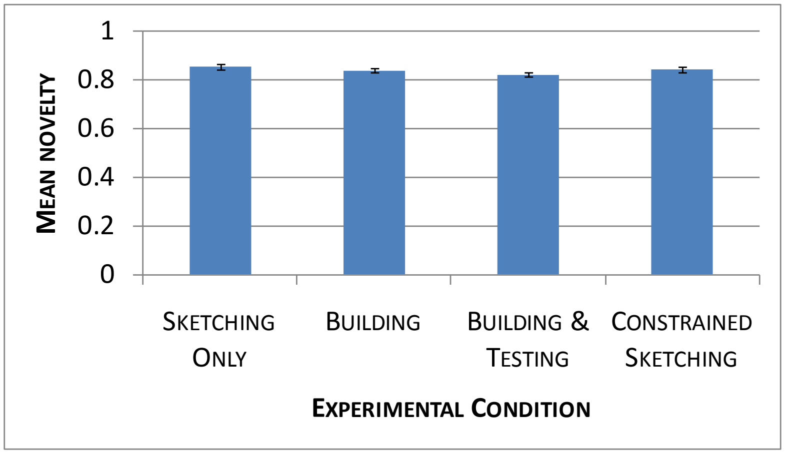

Figure 3. The mean novelty of ideas showed little difference across the experimental conditions (error bars are (±) one standard error of the mean)

Sunk Cost Experiment – Sunk Cost Effect and Design Fixation[25]

The results from the paperclip experiment described above showed that participants were not fixated by the physical models. However, these results contradicted with the observational studies in literature[18, 19] which showed the presence of fixation while using physical models. These studies used comparatively complicated design problems and much more effort was required to solve these problems compared to the paperclip design problem. This difference led to the Sunk Cost Hypothesis which stated that as designers spent more money, effort or time to build physical models for a design problem, they were likely to be fixated more. The fixation to the chosen path of action after a considerable amount of cost (money, time or effort) was sunk into that path was termed as Sunk Cost Effect[26, 27]. The Sunk Cost Hypothesis proposed that the fixation in previous studies with physical models was due to Sunk Cost Effect and fixation was not inherent with physical models.

This controlled study used the same problem as in the paperclip experiment. In this case, there were five different experimental conditions: a Sketching Only Condition, in which participants were allowed to sketch their ideas, a Metal Building Condition in which the participants were asked to build physical models of their ideas using steel wire, a Plastic Building Condition, in which the participants were asked to build physical models of their ideas out of moldable plastic, a Metal Constrained Sketching Condition in which the participants were provided necessary training to build their ideas out of steel wire and then asked to sketch them and a Plastic Constrained Sketching Condition, in which the participants were asked to sketch their ideas after receiving the training to mold them out of plastic. Building physical models out of plastic consumed considerably more time than that out of metal wire and hence the sunk cost is considered to be higher for plastic building condition. If the Sunk Cost Hypothesis were true, participants in the Plastic Building Condition were expected to produce lower novelty and variety ideas compared to the Metal Building Condition. The constrained sketching conditions were targeted to evaluate any possible effect of the implicit constraints of the building process and materials on the outcome.

Figure 4 shows the variation of mean novelty of ideas across the conditions. Variety followed the same trend. This data showed strong support for the Sunk Cost Hypothesis. As shown by these results, Plastic Building Condition yielded significantly lower novelty and variety of ideas compared to all other conditions. This showed that when designers spent considerably longer time on building physical models, they tended to fixate more. This showed that design fixation was not inherent with physical models and the fixation associated with building could be mitigated using building materials and processes that had lower cost (in terms of money, time required to process and extent of effort required to build). For more detailed description of the results, refer Viswanathan & Linsey[25].

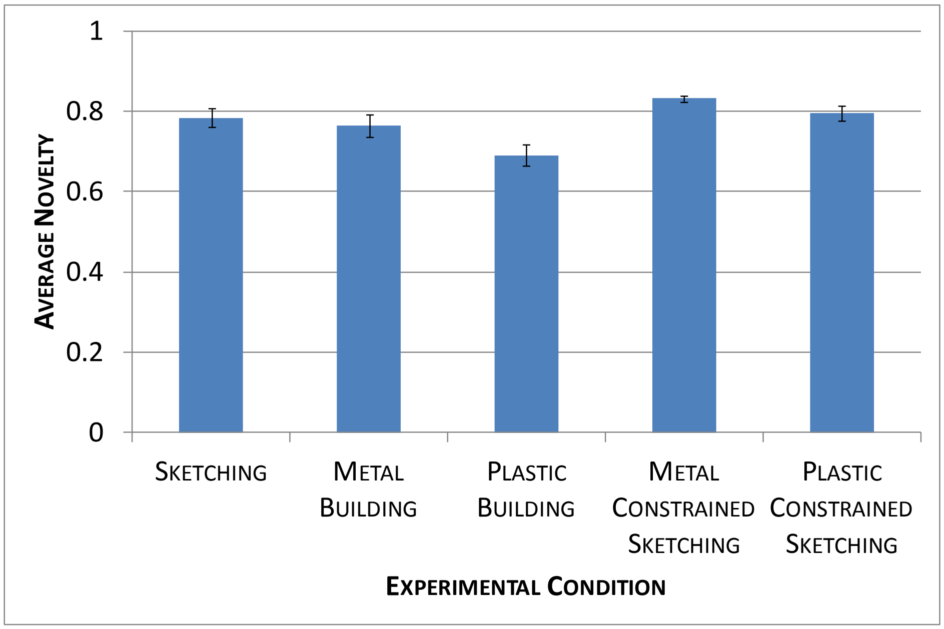

Figure 4. The variation of mean novelty of ideas across the experimental conditions (error bars are (±) one standard error of the mean)

Qualitative Studies – What are Effects of Physical Models in Real-life Cases?[28]

To infer the cognitive effects of building of physical models obtained from the controlled studies in real-life situations, cases from two different sources were analyzed qualitatively. The Mental Model Hypothesis and Fixation Hypothesis were investigated in this study too. The two data sources used were data from graduate design teams building proof-of-concept models for their class projects and cases reported in books[29, 30] regarding the development of a few breakthrough products. Data from 11 different graduate student teams from two semesters and the development procedure of ten award-winning products were considered for this study. More details of these products and the selection criteria used for their selection are described elsewhere[28].

Since this study was not controlled, clear metrics as in the controlled studies for each hypothesis could not be defined. Two measurable outcomes were used to infer the results. Table 1 shows the observable results and the corresponding inferences. For example, in case 1, if design fixation was present and designers' mental models were supplemented, the majority of the changes made during building needed to result in an improvement of the ideas and the frequency of changes resulting from testing needed to be higher than that of changes occurring otherwise. Conversely, if majority of the changes made during building resulted in improvement of the ideas and the frequency of changes resulted from testing were higher than that of changes occurred otherwise, we could infer that design fixation was present and designers' mental models are supplemented.

Table 1. Metrics used to infer the results in the qualitative study

Design Fixation is present	Mental Models are supplemented	Did Changes Improve the Idea?	Comparison of Frequency of changes in features evaluated by the physical model
Yes	Yes	Yes	Tested > Not Tested
Yes	No	No	Tested = Not Tested
No	Yes	Yes	Tested = Not Tested
No	No	No	Tested = Not Tested

Figure 5 and Figure 6 show the results obtained from this study. As observed, in a significantly higher number of cases, the changes during building of physical models resulted in improvements in ideas. Also, majority of these changes resulted from testing. These results were in agreement with case 1 and hence support both the hypotheses used in this study. As designers built physical models of their ideas, their erroneous mental models were supplemented and hence they made changes to their ideas that resulted in the improvement of their ideas. At the same time, the use of physical models fixated them. This result was also in agreement with the Sunk Cost Hypothesis presented in the Sunk Cost Experiment. The design problems that the designers dealt with here were much more complicated than the paperclip problem and were associated with a higher sunk cost. Hence they had a higher tendency to fixate to the features of their initial ideas. For a more detailed description of the results, refer Viswanathan and Linsey[28].

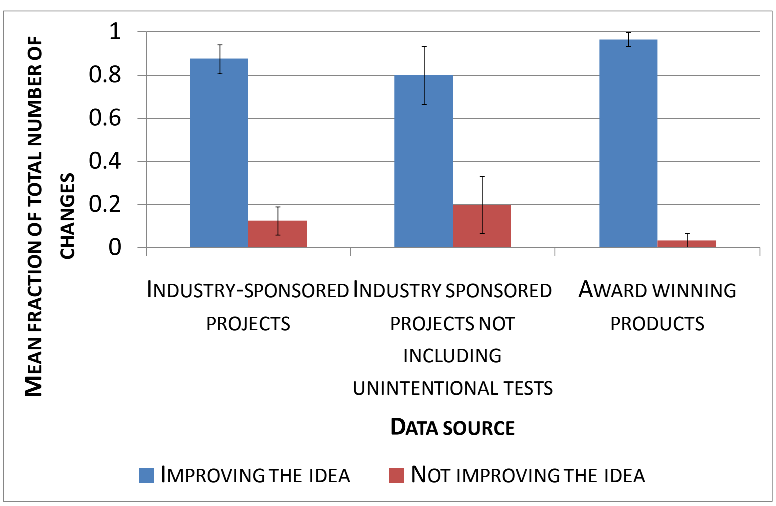

Figure 5. In most cases, the changes during building of physical models resulted in improvements in ideas (error bars are (±) one standard error of the mean)

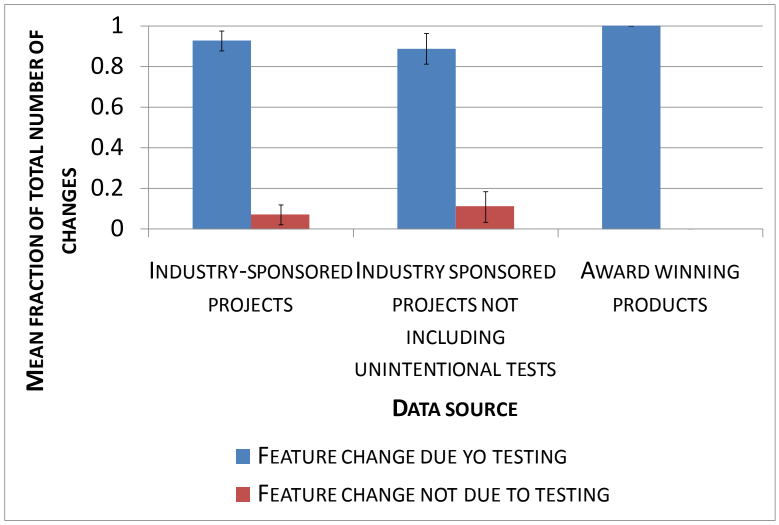

Figure 6. Majority of changes during physical modeling resulted from tests. (Error bars are (±) one standard error of the mean)

Stunt Car Experiment – Uses of Physical Models in Engineering Education[31]

This study investigated the effects of poor examples in engineering education and how physical models helped to mitigate the fixation to features of examples that caused reduced functionality of designs. Two hypotheses were presented in this study: Fixation hypothesis which stated that students fixated to features of provided examples and Mitigation of Fixation Hypothesis which stated that as they built physical models of ideas, they mitigated the fixation to the negative features that restricted the functionality of their designs.

This study was conducted as part of a freshman class project. Students in three different sections of a freshman course volunteered for this study. They were asked to design and build stunt cars that satisfied certain performance requirements. Each section was provided with a different example. One group received a poor example which contained a negative feature that restricted the functionality of the design, the second group received the same poor example with warnings about the negative feature and a third group received a good example without these negative features. The negative feature was the use of LEGO blocks making the designs bulky, which made the survival of the car in the crash test difficult. They were provided necessary LEGO parts to build their cars. They were allowed to test their designs and were asked to modify their cars until they satisfied the performance requirements. Their initial and final physical models were photographed and used for analysis. The percentage of use of blocks in their designs was used as the metric for analysis.

Figure 7 shows variation of the fraction of number of blocks in each design to the total number of blocks and beams combined, which was termed as “relative percentage of blocks”. These results showed that students who received the poor example and poor example with warning copied the negative feature (the higher percentage of blocks in the example design) in their initial designs. The warning did not help much in mitigating this fixation. However, they got rid of this fixation as they built and tested their ideas. Their final designs showed the same relative percentage of blocks across the groups. A more detailed description of these results is available elsewhere[31]. This showed that building physical models helped students to learn from their mistakes and correct those mistakes themselves. This could be considered as a more effective way of training students.

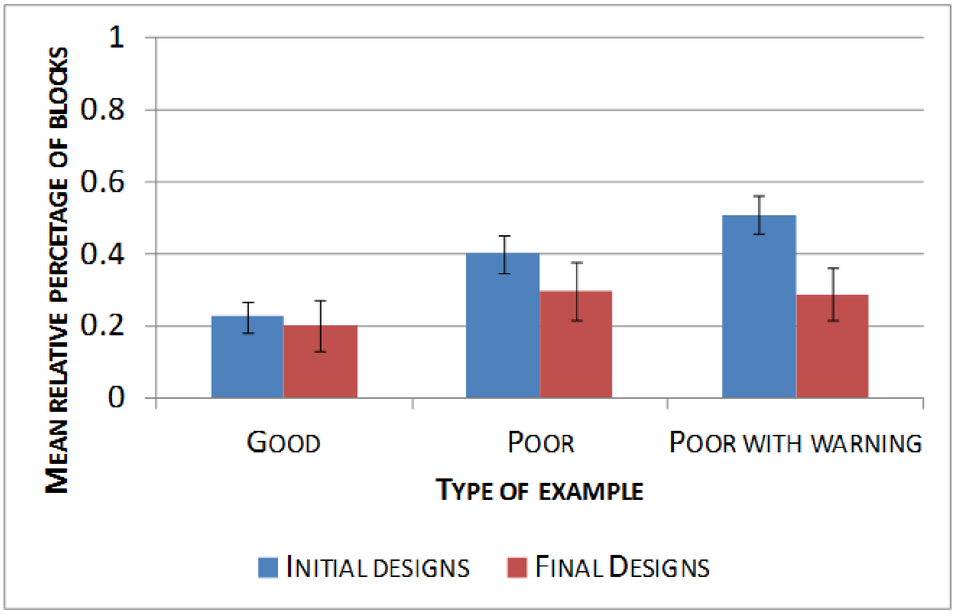

Figure 7. Relative percentage of blocks shows significant variation across the conditions for initial designs and no variation for final designs (Error bars are (±) one standard error of the mean)

Discussion

Physical Models Supplementing Designers' Mental Models

The studies presented here show that physical models supplement designers' erroneous mental models and help them in production of more functional ideas. As evident from the results of the Paperclip Experiment, designers produce more functional ideas when they are allowed to build their ideas. This can be a combined effect of the implicit constraints imposed by the building process and the building process itself. The non-functional ideas generated by the designers can be the result of their erroneous mental models. When they build and test the physical models of their ideas, these erroneous mental models get supplemented and result in higher percentage of functional ideas. This highlights the importance of encouraging designers to build physical models of their ideas. Physical models need to be built at very early stages of the design process, so that the flaws in designs can be eliminated before further development of those ideas.

Physical Models and Design Fixation

The studies described here show that design fixation is not inherent with building of physical models and it is a result of the Sunk Cost Effect. When designers build their physical models with easily modifiable materials with lower sunk cost, as in the Paperclip Experiment, no reduction in novelty and variety is observed compared to those who sketch alone. At the same time, in the Sunk Cost Experiment, when designers build their physical models with materials with higher sunk cost (such as molding paperclips out of plastic), there is a reduction in novelty and variety of ideas generated. This shows that as the sunk cost associated with the building process increases, the chance of design fixation also increases. Thus Sunk Cost Effect plays a very important role in engineering design. The Qualitative Study confirms the presence of Sunk Cost Effect in real life design cases also. Hence it is beneficial to keep the sunk cost at a minimum in engineering idea generation with physical models. Thus the use of easily modifiable, easily available and cheap materials for the fabrication of physical models needs to be encouraged. This also highlights the importance of rapid prototyping techniques, which can be considered as low sunk cost building process.

Physical Models in Engineering Education

The Stunt Car Experiment shows that if novice designers are allowed to build and test their ideas, they can identify the flaws in their designs that constrain the functionality of their designs and rectify them. This can be a very effective strategy of learning in engineering education. When students use a few negative features in their designs and find out the problems caused by those features themselves through building and testing, it can contribute to their learning in a very effective manner. Students need to be encouraged to build their ideas at very early stages of their design process. This can lead to very novel and functional solutions to design problems.

Recommendations for Construction of Physical Models

Sunk cost of the building process and materials needs to be a major guiding factor in the construction of physical models. According to the theory of Sunk Cost Effect, it is advantageous to keep the sunk cost associated with building at a minimum to avoid any potential design fixation. The results from this project recommend the use of physical models at very early stages of engineering idea generation. Very easily available and easily modifiable materials need to be employed for the construction of these models. The construction process needs to be as simple as possible to keep the sunk cost at a minimum. Also, the building of physical models containing only sufficient features required for the purpose of testing is also recommended. This can help to simplify the models and hence keep the associated cost minimum. The latest rapid prototyping techniques can be also very useful for reducing the sunk cost of building.

Conclusions

This paper summarizes various studies conducted by the authors as a part of a project to establish a few guidelines about the implementation of physical models in engineering design. Current guidelines in literature are incomplete and conflicting. This project explores various cognitive aspects of the use of physical models as design tools – the effect of physical models on designers' mental models, design fixation associated with building, the use of physical models as tools for engineering education and type of materials and processes suited for building physical models. The results show that building physical models of their ideas supplement designers' erroneous mental models and lead them to more functional ideas. They also show that design fixation is not inherent with building process, but is due to the Sunk Cost Effect. If the time, money or effort required to build physical models is higher, the chance of fixation is also higher. Hence the use of easily available and easily modifiable materials is required for building physical models. The results also show that if engineering students are allowed to build and test physical models of their ideas, they can learn through their mistakes, which can be a more effective way of training them. The use of physical models as design tools needs to be encouraged and they need to be implemented at very early stages of design. At the same time, designers need to be careful about the choice of materials and processes they select for building, due to the Sunk Cost Effect.

Future Work

The studies summarized here present very useful insights about the implementation of physical models in engineering idea generation. Based on these insights, a design method needs to be developed that can be easily used by novice designers. This design method needs to help designers to use physical models in a very efficient and effective way. This can maximize the benefits of building physical models while keeping the associated sunk cost low.

Acknowledgements

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References

[1] Lidwell, W., Holden, K., and Butler, J., *Universal principles of design: 125 ways to enhance usability, influence perception, increase appeal, make better design decisions, and teach through design*: Rockport Pub, 2010.

[2] Otto, K.N., and Wood, K.L., *Product design: Techniques in Reverse Engineering and New Product Development*, NJ: Prentice Hall, 2000.

[3] NASA," Common Lunar Lander Detailed Design Study",JSC-26094,Houston, TX, 1993.

[4] Kelley, T., and Littman, J., *The art of innovation: lessons in creativity from IDEO, America's leading design firm*, NY: Crown Business, 2001.

[5] Gentner, D., and Stevens, A.L., *Mental models*: Lawrence Erlbaum, 1983.

[6] Kempton, W.," Two theories of home heat control", *Cognitive science* Vol. 10, No. 1, 1986, pp. 75-90.

[7] Jansson, D., and Smith, S.," Design Fixation", *Design Studies* Vol. 12, No. 1, 1991, pp. 3-11.

[8] Linsey, J.S., Tseng, I., Fu, K., Cagan, J., Wood, K.L., and Schunn, C.," A Study of Design Fixation, Its Mitigation and Perception in Engineering Design Faculty", *ASME Journal of Mechanical Design* Vol. 132, No. 4, 2010, pp. 041003.

[9] Chrysikou, E., and Weisberg, R.," Following the Wrong Footsteps: Fixation Effects of Pictorial Examples in a Design Problem-Solving Task", *Jornal of Experimental Psycology Learning Memory and Cognition* Vol. 31, No. 5, 2005, pp. 1134.

[10] Smith, S., Ward, T., and Schumacher, J.," Constraining Effects of Examples in a Creative Generation Task", *Memory and Cognition* Vol. 21, 1993, pp. 837-857.

[11] Maier, N.," Reasoning in Humans: II. The Solution of a Problem and Its Appearance in Consciousness", *Journal of Comparative Psychology* Vol. 12, No. 2, 1931, pp. 181-194.

[12] Luchins, A., and Luchins, E., *Rigidity of Behavior: A Variational Approach to the Effect of Einstellung*, OR: University of Oregon Books, 1959.

[13] McKim, R.H., *Experiences in Visual Thinking*, Boston: PWS Publishing Company, 1972.

[14] Römer, A., Pache, M., Weißhahn, G., Lindemann, U., and Hacker, W.," Effort-Saving Product Representations in Design—Results of a Questionnaire Survey", *Design Studies* Vol. 22, No. 6, 2001, pp. 473-491.

[15] Horton, G.I., and Radcliffe, D.F.," Nature of rapid proof-of-concept prototyping", *Journal of Engeering Design* Vol. 6, No. 1, 1995, pp. 3-16.

[16] Lemons, G., Carberry, A., Swan, C., Jarvin, L., and Rogers, C.," The Benefits of Model Building in Teaching Engineering Design", *Design Studies* Vol. 31, No. 3, 2010, pp. 288-309.

[17] Andreasen, M.M., and Hein, L., *Integrated Product Development*, UK: IFS Publications, 1987.

[18] Christensen, B.T., and Schunn, C.D.," The relationship of analogical distance to analogical function and preinventive structure: The case of engineering design", *Memory & Cognition* Vol. 35, No. 1, 2007, pp. 29-38.

[19] Kiriyama, T., and Yamamoto, T.," Strategic Knowledge Acquisition: A Case Study of Learning through Prototyping", *Knowledge-based Systems* Vol. 11, No. 7-8, 1998, pp. 399-404.

[20] Vidal, R., Mulet, E., and Gómez-Senent, E.," Effectiveness of the Means of Expression in Creative Problem-Solving in Design Groups", *Journal of Engineering Design* Vol. 15, No. 3, 2004, pp. 285-298.

[21] Baxter, M., *Product design: a practical guide to systematic methods of new product development*: CRC, 1995.

[22] Buur, J., and Andreasen, M.," Design models in mechatronic product development", *Design Studies* Vol. 10, No. 3, 1989, pp. 155-162.

[23] Viswanathan, V.K., and Linsey, J.S., "Physical Models in Idea Generation - Hindrance or Help?", *ASME International Design Engineering Technical Conferences - Design Theory and Methodology*, Montreal, Canada, 2010.

[24] Shah, J.J., Smith, S.M., and Vargas-Hernandez, N.," Metrics for Measuring Ideation Effectiveness", *Design Studies* Vol. 24, No. 2, 2003, pp. 111-134.

[25] Viswanathan, V.K., and Linsey, J.S., "Design Fixation in Physical Modeling: An Investigation on the Role of Sunk Cost", *ASME International Design Engineering Technical Conferences - Design Theory and Methodology*, Washington, DC, 2011.

[26] Arkes, H., and Blumer, C.," The Psychology of Sunk Cost", *Organizational behavior and human decision processes* Vol. 35, No. 1, 1985, pp. 124-140.

[27] Kahneman, D., and Tversky, A.," Prospect Theory: An Analysis of Decision under Risk", *Econometrica* Vol. 47, No. 2, 1979, pp. 263-291.

[28] Viswanathan, V.K., and Linsey, J.S., "Understanding Physical Models in Design Cognition: A Triangulation of Qualitative and Laboratory Studies", *Frontiers in Education Conference*, Rapid City, SD, 2011.

[29] IDSA, *Design Secrets: Products*, MA: Rockport Publishers, 2003.

[30] Haller, L., and Cullen, C.D., *Design Secrets: Products 2: 50 Real-Life Projects Uncovered*, MA: Rockport Publishers, 2004.

[31] Viswanathan, V.K., Esposito, N., and Linsey, J.S., "Training Tomorrow's Designers: a Study on the Design Fixation", *ASEE Anual Conference*, San Antonio, TX, 2012.