PHYSICAL MODELS AND DESIGN COGNITION: TRIANGULATING CONTROLLED LAB STUDIES WITH INDUSTRIAL CASE STUDIES

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Physical models are a potential tool which affects designers' cognition, and very little quantified data exists about the use of physical representation within the idea generation process. Physical models are widely implemented in the engineering design process. There are conflicting results and guidelines about the implementation of these representations as a tool for idea generation. A prior controlled study demonstrates that physical models supplement designers' incomplete and erroneous mental models, thereby leading to more functional ideas but does not cause design fixation. Another observation study indicates physical representations induce design fixation, thereby reducing the variety of ideas. This paper explores the seemingly conflicting results through a qualitative coding of industrial projects and innovative product design case studies. Consistent with prior laboratory studies, the results show that physical models support the mental models of the designer.

Keywords: Design Fixation, Idea Generation, Mental Models, Physical Models.

1. INTRODUCTION

Creativity and innovation play vital roles in the engineering design process. Prototyping is a potential aid that can support designer cognition and thereby spur novel ideas. Designers often use physical models in the idea generation process. Physical models range from very simple models used for the visualization of the idea to complicated three dimensional and fully functional prototypes. Figure 1 shows the various models used for OJex Manual Citrus Juicer by the designers [1]. It is important to identify when to implement physical models in the design process, given the cost and time associated with prototype construction [2]. For this purpose, it is essential to unveil the effects of physical modeling on designer's cognition. A controlled laboratory study indicates that physical models supplement designers' mental models, leading to higher quality ideas [3]. Contrary to this, an observational study indicates a high degree of design fixation associated with the use of physical models in practicing designers [4]. Due to these conflicting findings, physical models' effects on cognition need to be identified.

This paper triangulates the findings from controlled lab studies by the authors [3] to case studies of industry-sponsored teams and innovative products. Reports from industry-sponsored projects and reported innovative product development cases are used as data sources. A qualitative framework is used to analyze and code the data to obtain quantitative outcomes. The method followed and the results obtained are discussed in subsequent sections.

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Figure 1. Various physical models ranging from 2-d motion studies to fully functional prototypes are employed in the development of OJex Manual Citrus Juicer [1].

2. BACKGROUND

2.1. Physical Models in Idea Generation

Physical models are widely implemented as tools for idea generation process. Prototyping provides insights of the real-world requirements to designers and helps them to visualize, evaluate and improve their designs [5]. Prototypes are highly valuable in determining the problems in a design without investing too much time and money [6]. The observational study of design projects in a graduate level course by Kiriyama and Yamamoto shows that prototyping helps to identify the flaws in the design and thus improves the idea [7]. Tom Kelly of the famous product design firm IDEO recommends frequent use of prototyping in the new product development process [8]. In group idea generation process, prototypes serve as boundary objects and facilitate communication between various groups [9].

Despite the importance of physical models in design, very few studies provide guidelines on when and how physical models can be used. Brereton and McGarry show that physical objects support design thinking and communication [10]. Meanwhile evidence of design fixation in the presence of physical models is shown in class projects [7] and in industrial designs by professional designers [4]. Yang [11] showed that prototypes with lesser details are more beneficial. Considering these conflicting findings, further study and evaluation is needed to understand the effects of prototyping in design cognition.

2.2. Mental Models

Psychologists' study of mental models deals with the mental representations of people about the world around them [12]. These internal representations are always incomplete since they are only models and often erroneous [12, 13]. Kempton [13] shows that people mistakenly operate the home heat thermostat similar to a car's accelerator; the higher the temperature is set, the faster they expect a home to heat up. Most home heating systems are either on or off, so a higher temperature setting has no effect on the rate of heating. Hutchins and Hutchins provide a similar example among highly trained scientists [14]. People's mental models are incomplete and erroneous unless they have significant experience or education in that particular activity.

This area of research has wide implications in the design process. The designers' incomplete mental models can cause them to generate ideas with flaws which are not initially evident. Designers' mental models are generally very simple, which enable them to use these mental models in solving unknown problems [15]. Due to this simplicity, sketches are perfect candidates for designers to communicate their mental models [16] and sketches also contain the errors present in their mental models. Methods need to be developed to support designers' mental models so that they generate ideas with fewer errors and thus of higher quality.

2.3. Design Fixation

Fixation is the counter-productive adherence to examples or initial solutions [17]. This limits the quantity, novelty and variety of ideas. Psychology has done much research on fixation. The presence of fixation in engineering design has been explored by few studies. It has been shown in controlled studies [17], in an observational study among practicing designers [4], and in case studies [7]. Hence it is essential to study factors affecting fixation and introduce methods to control it in the idea generation process.

2.4. Prior Controlled Laboratory Experiment [3]

To investigate the effects of physical models on designer's cognition, a controlled laboratory study was conducted by the authors. This study tested two hypotheses: (1) Physical models supplement designers' mental models; and (2) Physical models induce design fixation. The study consisted of a between-subjects controlled lab experiment where participants designed an object made of only steel wire to bind papers together. They were advised to generate as many solutions as possible within the available three hours. There were four conditions: Sketching only, building, building & testing, and constrained sketching. In sketching only, the participants sketched their ideas as they generated them while in building, they also built their ideas. In building & testing, they were allowed to test their built ideas. Constrained sketching was similar to sketching only, except participants were told that they would build their ideas at a later stage.

The results showed that the use of physical models supplement designer's mental models, but no evidence was observed for fixation. When physical models were used for idea generation, the percentage of functional ideas showed significant improvement (Figure 2). A functional idea was defined as an idea that satisfied all the problem requirements. This showed that the physical models supplemented designers' mental models and thereby increased the probability of obtaining a functional idea. Meanwhile, novelty and variety [18] showed no significant difference across the conditions and therefore no fixation (Figure 3).

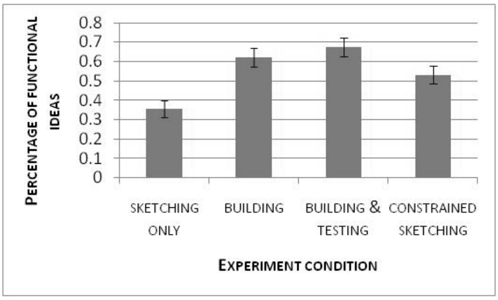

Figure 2. The results from the prior experiment show that physical representations supplement designer's mental models.

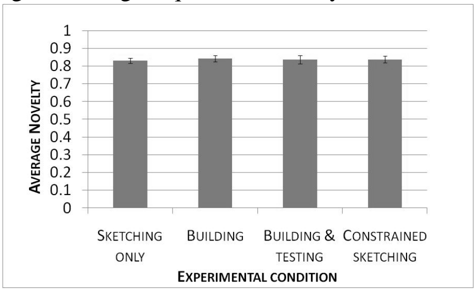

Figure 3. The results from the prior experiments show that there is no significant difference in novelty across the condition.

3. RESEARCH QUESTIONS AND METHOD

This study further evaluates the research questions proposed in the controlled experiment in [3], in more realistic real-world industrial and new product development case studies. The following is the basic research question considered for this paper:

Do physical models supplement mental models leading to higher quality ideas?

The goal of this study is to investigate the effects of external product models (including physical and virtual) on designers' mental models and design fixation. The prior study by Viswanathan and Linsey [3] shows physical models supplement mental models, but fail to produce fixation as observed by other studies. These results will be triangulated with new product development and innovative product case studies. The new product cases are from industry-sponsored graduate course projects at Texas A&M University. The other source is books detailing the development of innovative products [1, 19].

The research questions are investigated using a qualitative study. The effects of physical models on mental models and fixation are not independent of each other in more realistic settings. In controlled experiments, these two effects may be fully separated but in qualitative studies, both are influencing the results simultaneously. A qualitative coding method is used to extract relevant information from the data. This study uses two sources of data: final reports from a graduate level design course and case studies of innovative products reported in books. The method used in this study is consistent with prior similar studies in design [7, 20, 21] and in the social sciences [22]. A comparison between these methods is shown in Table 1.

The effects of physical models on designer's mental models and design fixation cannot be measured independently. In this study, two measurable outcomes are identified which correlate to the presence of these effects: (1) The answer to the following question: Does the change made to the idea at the prototyping stage improve the idea? (2) The frequency of changes made to the features tested compared to that of features not tested by the physical models. Table 2 gives an overview of various possible effects, the results and the corresponding expected outcomes from the coding. Alternatively, knowing the results from the coding, we can infer the presence of these effects in the design process.

Table 1. Comparison of methodologies followed by different works.

Qualitative Coding [22]	Approach for the development of component basis [21]	Method for this study
1. Note down the research concerns	1. State the research goal	1. State research questions and determine coding categories
2. Read the data available & note points relevant to research concerns	2. Collect information from available sources, review sources & store collected information in repository	2. Go through the data in the design reports, templates and books. Note down any feature changes during the design process
3. Group the similarly sounding statements together	3. Review repository data, collect and organize synonymous & similar sounding terms	3. Organize the data into pre-determined groups based on hypotheses
4. Organize the repeating ideas to "themes"	4. Go through the organized terms and identify any patterns	—
5. Organize similar themes to "theoretical constructs"	5. Organize the terms according to the patterns.	—
6. Relate the constructs with the research concerns and develop the theory	—	6. Count the data in each category. Relate the quantified data to the research questions through statistics
—	7. To ensure repeatability, repeat 4 & 5 until a fully refined final list of terms is obtained	7. To ensure repeatability, use inter-rater reliability measures to validate the principles

Table 2. Interpretation of results from possible outcomes.

Case	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
1	Yes	Yes	Yes	Tested > Not Tested
2	Yes	No	No	Tested = Not Tested
3	No	Yes	Yes	Tested = Not Tested
4	No	No	No	Tested = Not Tested

For example consider case 1 (Table 2). In this case, the changes made to the ideas at the prototyping stage improve the idea in significantly higher number of cases and tested features change more frequently than those not tested. This result shows mental models are supplemented as well as design fixation is present. Similarly, if most of the changes improve the ideas and frequency of changes in features tested and not tested are not significantly different, then mental models are supplemented, but fixation is absent in the design process. In cases 2 and 4, the outcomes are the same. In both cases, the changes made do not improve the idea and the frequency of changes in features tested and not tested remains the same. Hence these cases cannot be differentiated using the outcomes.

The coding process begins with the research questions being stated. The reports of the design teams, template filled by the teams and the reports in published books about the design of innovative products are considered as data sources for this study. An author goes through the information available about the prototyping stages in these data sources with the research questions in mind and notes down any information related to the changes made to the ideas at the prototyping stage. The features of each idea at various prototyping stages are also noted down. These data are organized into pre-determined groups based on whether the changes improve the idea or not. To identify this, the stages of the design before and after the changes are carefully analyzed. The objective of each change is identified and the end result is studied to figure out whether that objective is met. If the change results in a satisfactory fulfillment of the objective, it is considered as an improvement. After classifying the data into the above mentioned categories, the data in each category are counted and these counts are used for further analysis. An inter-rater agreement will be performed on this coding procedure to ensure reliability of the results.

3.1. Industrial projects

Advanced Product Design is a graduate course taught by one of the authors. This project-based course covers early product design with a focus on creativity. Students form five groups of three to four students. Each student provides their project preferences and then is assigned a project which involves developing concepts and proof-of-concept models.

To increase the quality of the data collected, teams fill in a template describing their plans for proof-of-concept models (partial example in Table 3). This template asks the participants what they plan to do and why. The template with additional questions about the testing results and changes is also completed after testing. This template is not filled properly by the teams; hence the data available from them is incomplete and additional information from their final reports is used.

At the end of the course, each team selects three of their most innovative ideas and then creates physical or virtual proof-of-concept models. All the details of the projects are included in the reports submitted by the teams and a template about the proof-of-concept models is provided to assist in documentation.

3.2. Innovative products

Another data source is data from two books [1, 19] containing descriptions about the design and development of award-winning products. Ten cases are identified suitable for this study (Figure 4). The criterion for selection is that these cases present multiple stages of physical or virtual modeling.

Table 3. An excerpt of the template used by the students.

Features to be measured	Associated Physical principle(s), equations, or etc.	Associated customer need(s)	Aspect(s) to be measured (Metrics) (Units)
Functional Features			
Deflection in platform supported on spring	Stiffness = Force/ Deflection	Measure weight accurately	Deflection of platform in inches ~1/4 inch
Geometric Features			
Stop mechanism (to stop flow of coffee from hopper)	Amount = flow rate X time of flow	Dispense 1 lbf in rapid manner	Time to stop in seconds
	Frictional force	Dispense 1 lbf in rapid manner	Force to stop the flow (lbf)

Figure 4. Innovative product designs used for the study [1, 19]. The other products not shown are "Clip 'n' Stay", Watercone, Watergate, Bottle stopper/opener, Scorpio 270, Overflowing bath and Snowboard boot.

4. RESULTS AND DISCUSSION

This paper explores the question of whether external models supplement mental models. From Table 2, it can be observed that irrespective of the presence or absence of design fixation, changes made to the idea improves the idea, if mental models are supplemented. Hence this can be used as an independent measure to determine whether mental models are supplemented by external models. In this paper, the relevant data for the changes made during physical or virtual modeling are extracted from a set of reports and new product development case studies. These data are used for analysis.

4.1. Industrial Projects

Following the method described in the section above, the changes made by the team during the proof-of-concept stage are identified from the final reports. Organizing these changes, two different classifications are identified:

1. The idea is improved or not improved by the changes made.
2. The model proves the idea is worthless to proceed further. The participants make no changes to the idea and discard the idea completely.

For this paper, only the first case is considered for analysis and evaluated by one of the authors for improvements in the idea. The second case also probably shows that the physical or virtual modeling exposes the flaws in the mental models, but this cannot be measured with the metrics that we are currently using for this study. There are three cases in which the participants abandon their ideas in this fashion. Metrics showing how this case signifies the effects of physical models on design cognition need to be developed and the corresponding data need to be explored further in future work.

These data are analyzed to see if these changes contribute to the improvement in the design. A total of 29 changes are made in the designs, out of which 25 of them improve the respective ideas. Figure 5 shows the percentage improvement in the ideas with respect to the total number of changes made. Chi-square test shows a significant difference between these two cases ($\chi^2 = 15.21, p < 0.01$),

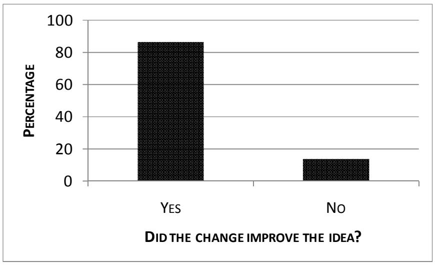

Figure 5. Significantly higher percentage of changes result in the improvement of the idea for the design of industrial projects.

Table 4. Excerpt from the data tabulated for supplementing mental models.

Product Name	Changes Made during Prototyping	Associated Features Tested	Did the Change Improve the Idea?
	Mechanism changed to make it friendly for all kinds of users	Working mechanism	Yes
Orange Juicer	Interior changed to hollow to reduce weight	Material	Yes
	Changed the profile of the strainers to hold back the pulp	Geometry	Yes

showing that in significantly higher number of cases, physical models uncover the flaws in designer's mental models and supplement them.

4.2. Innovative products

Following the method described in Table 1, the relevant data is filtered from the books and the results are tabulated (Table 4). It is observed that in innovative product studies, generally only successful changes made during the prototyping are reported. Hence in most cases, it is observed that the changes made improve the idea and this biases the data.

The results are shown in Figure 6. In the study of innovative product designs, a total of 35 changes are observed spanning the 10 product development cases. Among these, 34 of them resulted in the improvements in the respective ideas. This is significantly higher than the cases in which the changes

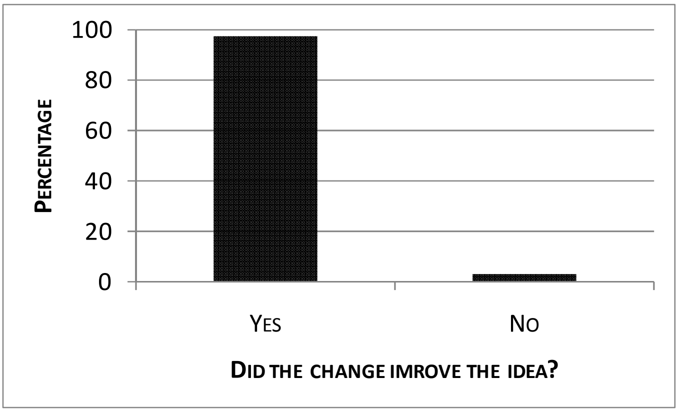

Figure 6. Significantly higher percentage of changes result in the improvement of the idea for the novel product designs.

made do not improve the idea ($\chi^2 = 31.11$, $p < 0.01$). Another important observation from this data is that new features are very frequently added to the ideas in the prototyping stage, whereas a feature is removed very rarely.

4.3. Triangulating controlled lab studies and qualitative studies

The results from the controlled lab and qualitative study [3] clearly shows that designers' mental models are supplemented by physical representations. In the controlled study, use of physical representations results in a greater percentage of functional ideas. Consistent with this in the qualitative study, external representations (e.g., physical or virtual) again supplement the mental models and help the designer to identify the flaws due in their designs. This leads to changes that generally improve the idea. Fixation is not observed in the controlled study and will be evaluated later with the qualitative coding.

4.4. Implications of the results

The results indicate that prototyping generally reveals the flaws in designs and encourages improvement. This has wide implications in industry. While prototyping requires significant amounts of time and effort, they serve a critical function by supplementing designers' mental models. Quick, low effort and cost models need to be encouraged throughout the design process. The effects on mental models is the likely reason why Kelly [8] strongly suggests the use of prototyping and why he finds it useful for making progress.

Another major impact of the results obtained in this study is in the area of rapid prototyping. Rapid prototyping can create fairly accurate details obtained at low cost, fast speed, and low designer effort [23] and this can support designer's thinking process [23]. This suggestion is also in line with the results of this study.

5. CONCLUSIONS

This paper investigates the effects of physical models in designer cognition through a rich set of studies that uses a combination of controlled laboratory studies and qualitative analysis of industry sponsored projects and innovative products. From the previous controlled laboratory studies conducted by Viswanathan and Linsey [3], it can be seen that physical models supplement designer's mental models. They help designers to identify the flaws in their designs and rectify them. This paper extends these results to higher validity situations, studies of innovative products developed by industry and team design projects sponsored by industry. A qualitative coding approach is used to collect data from these sources. The results show that physical models supplement the designers' mental models and majority of the changes made to the ideas during prototyping result in the improvement of ideas. Hence the use of physical models as a tool for product design process needs to be encouraged as it leads to novel, higher quality, less flawed designs. Based on current results, physical models can enhance innovation by supplementing designers' mental models leading to more functional, higher quality designs. These physical models should be quick to implement and require little time, money or effect due to the potential for fixation caused by the sunk cost effect. Future work includes investigation into the fixation hypothesis and measuring inter-rater agreement to assure the results are generalizable.

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