The Prototype for X (PFX) Framework: Assessing Its Impact on Students' Prototyping Awareness

Ms. Jessica Menold, Pennsylvania State University, University Park

Jessica Menold is a third-year graduate student interested in entrepreneurship and the design process. She is currently conducting her graduate research with Dr. Kathryn Jablokow and Dr. Timothy Simpson on a project devoted to understanding how prototyping processes affect product design. Jessica is interested in exploring how a structured prototyping methodology, Prototype for X, could increase the end design's desirability, feasibility, and viability. She is also working to understand how these methods affect students' knowledge, skills, behaviors, and attitudes in regards to prototyping.

Jessica is also working on a startup designing prosthetic limbs for individuals living in rural regions of developing countries. She has studied the design thinking process at the d.school in Berlin and holds design thinking workshops and classes for students and companies around Penn State.

Dr. Kathryn W. Jablokow, Pennsylvania State University

Dr. Kathryn Jablokow is an Associate Professor of Mechanical Engineering and Engineering Design at Penn State University. A graduate of Ohio State University (Ph.D., Electrical Engineering), Dr. Jablokow's teaching and research interests include problem solving, invention, and creativity in science and engineering, as well as robotics and computational dynamics. In addition to her membership in ASEE, she is a Senior Member of IEEE and a Fellow of ASME. Dr. Jablokow is the architect of a unique 4-course module focused on creativity and problem solving leadership and is currently developing a new methodology for cognition-based design. She is one of three instructors for Penn State's Massive Open Online Course (MOOC) on Creativity, Innovation, and Change, and she is the founding director of the Problem Solving Research Group, whose 50+ collaborating members include faculty and students from several universities, as well as industrial representatives, military leaders, and corporate consultants.

Prof. Timothy W. Simpson, Pennsylvania State University, University Park

Dr. Simpson is currently a Professor of Mechanical and Industrial Engineering at Penn State with affiliations in Engineering Design and the College of Information Sciences & Technology. He received his Ph.D. and M.S. degrees in Mechanical Engineering from Georgia Tech in 1998 and 1995, and his B.S. in Mechanical Engineering from Cornell University in 1994. His research interests include product family and product platform design, product dissection, multidisciplinary design optimization (MDO), and additive manufacturing, and he has published over 250 peer-reviewed papers to date. He teaches courses on Product Family Design, Concurrent Engineering, Mechanical Systems Design, and Product Dissection, and he serves as the Director of the Product Realization Minor in the College of Engineering. He is a recipient of the ASEE Fred Merryfield Design Award and a NSF Career Award. He has received several awards for outstanding research and teaching at Penn State, including the 2007 Penn State University President's Award for Excellence in Academic Integration. He is a Fellow in ASME and an Associate Fellow in AIAA. He currently serves on the ASME Design Education Division Executive Committee and is former Chair of both the ASME Design Automation Executive Committee and the AIAA MDO Technical Committee. He is also a Department Editor for IIE Transactions: Design & Manufacturing and serves on the editorial boards for Research in Engineering Design, Journal of Engineering Design, and Engineering Optimization.

Emily A. Waterman, Pennsylvania State University

The Prototype for X (PFX) Framework: Assessing Its Impact on Students' Prototyping Awareness

Abstract
Each year, billions of dollars are invested by large companies in product research and design. Studies indicate that anywhere from 40-50% of those resources are wasted on cancelled products or those which yield poor results[75]. The largest sunk cost of product development occurs during the prototyping phase of the design process, yet engineering design research has largely overlooked this pivotal stage in the design process. This study is a portion of a larger project based on a new theoretical framework for prototyping called **Prototype for X** or **PFX**. PFX draws from human centered design (HCD), design thinking (DT) and Design for X (DFX) frameworks and methods to enhance the design process and allow designers to prototype more effectively. Among the anticipated impacts of PFX is increased confidence in one's prototyping skills, i.e., increased confidence in one's ability to develop prototypes for different conditions. The research described here marks the first step in testing this hypothesis, namely, exploring the impact of PFX on students' prototyping awareness.

In this study, students at a large Mid-Atlantic university were taught three prototyping lenses based on the PFX methodology: (1) Prototyping for Viability, (2) Prototyping for Feasibility, and (3) Prototyping for Desirability. This paper presents preliminary findings on the relationship between these three prototyping lenses and students' prototyping awareness, which we define as students' ability to identify their mental models during the prototyping process. We use prototyping awareness as a proxy to measure adoption and implementation of PFX methods. The Prototyping AWareness Scale, or PAWS was created for this study, and we discuss its internal consistency and future iterations. Data were collected throughout the course of a semester-long design project; the PAWS was distributed at the conclusion of each PFX learning module. Results from both between and within subject experiments are presented.

1.0 Introduction

Research in engineering design has focused primarily on the front-end of the design process, especially ideation[1-4], concept generation[5-8], and other areas related to early stage product development[9-13]. Meanwhile, the later stages design have been largely overlooked, including prototyping and testing. As Camburn summarizes, "prototyping may be simultaneously one of the most important and least formally explored areas of design"[14].

Clearly, prototyping represents one of the largest uncertainties for companies and engineers. Individuals in uncertain environments with low perceptions of control of that environment struggle with motivation, creativity, and persistence in the face of obstacles[15-17]. Bandura[15] found that the opposite is true when individuals are faced with uncertainties yet perceive themselves to be in control of the situation. Specifically, Deci[16] showed that perceptions of high control in uncertain activities can lead to higher cognitive flexibility and creativity. We hypothesize that structured prototyping methods could increase young designers' and student engineers' feelings of control throughout the prototyping process and may lead to an increase in creative output[15], higher levels of motivation[18], and an increase in the quality of final designs[19]. As an initial step in the measurement of these outcomes, we sought to understand what students thought about or were aware of throughout the prototyping process, both when prototyping using Prototype for X (PFX) methods versus "prototyping in the wild" (i.e., without a structured process).

Our work is guided by two overarching research questions: (1) how are end designs affected by following PFX methods and (2) how are designers affected by PFX methods? This paper presents preliminary work exploring the second research question. We begin with a review of design cognition literature, namely, works focused on prototypes or physical instantiations of a design concept. Design cognition is the study of human information processing in the design process, and our work seeks to contribute to the growing body of knowledge at the intersection of design cognition and prototyping. Following this review, we summarize prototyping literature from a variety of fields, including engineering design, engineering management, engineering education, and human computer interaction. From this literature base, we introduce the PFX framework and derive definitions for each of the PFX lenses and provide the theoretical basis for the proposed methods. We then present our hypotheses, research methodology, and measurement tools. Finally, we conclude with a presentation of our preliminary results, a summary of the limitations of our work, and a discussion for future research.

2.0 Design Cognition and Prototyping

2.1 Design Cognition

Eastman[26] defines design cognition as "the study of human information processing in design". Within design cognition, researchers have evaluated how the use of physical objects, models, or prototypes affects designers' mental models[20, 21, 27-30], ideation abilities[6, 7, 22], communications[23, 24], and psychological experiences[18, 25]. Physical models, as defined by Viswanathan et al.[6], refer to "prototypes of any scale built to mimic certain aspects of the final design".

McKim[30], Andreasen and Hein[29], and Bucciarelli[28] all highlight the notion that building physical models in the early stages of the design process can help visualize problems and highlight incorrect design assumptions. Brereton and McGary[31] found that engineering students often seek out physical props or design small scale models when struggling to communicate design ideas. However, Viswanathan et al.[5], Kiriyama et al.[27], and Vidal et al.[32] found that physical models can hinder idea generation efforts by inducing design fixation; Viswanathan et al.[5, 6] refers to this as the "sunk cost effect". The sunk-cost effect was found to affect complex design problems more than simple design tasks[6]; although prototyping led to an increase in feasible designs, the ideas were less novel. Brereton and McGary[31], however, argue that physical models and objects are a necessary component of the distributed cognition of designers, stating that the transition from abstract to material analogies is vital to design learning and thinking.

Design cognition research has typically utilized protocol studies, or "giving small but realistic design tasks to subjects and monitoring their behavior"[26]. This also applies to the prototyping research within design cognition. Viswanathan et al.[6, 7], Dow et al.[33, 34], and Hartman et al.[35] all utilized relatively simple design problems with set and clear tasks, materials, and expected outcomes. Protocol analysis has been criticized for oversimplifying design and design tasks[26], however, and recent prototyping work has attempted to explore more complex design problems[36]. For example, Gerber et al.[25] used ethnographic research techniques to study a design team at a large tech firm; their research found that "the production and rapid visualization of multiple ideas through low-fidelity prototyping allows practitioners to reframe failure as an opportunity for learning, supports a sense of forward progress, and strengthens beliefs about creative ability"[25]. Our work adds to this growing body of literature by exploring what aspects of prototyping student engineers are aware of as they engage in the design process, specifically during prototyping activities.

2.2 Prototyping Literature

In this work, we use Christie et al.'s definition of a prototype as "an initial instantiation of a concept as part of the product development process"[37]. Prototyping represents a large sunk cost for most companies that is overcome through the launch of a successful product; however, estimates indicate that 40-50% of product development costs are spent on failed products or products that do not yield adequate return[14, 37]. Previous research has shown that breakthroughs and innovations made by engineering designers are dependent upon the ability to experiment and test[12]. Understanding prototyping and utilizing a guided and repeatable approach to the prototyping process could help companies develop feasible, viable, and desirable new products more quickly with fewer resources.

Two extensive literature reviews on prototyping research exist[14, 37] and have sorted the domain work into two main fields, namely, engineering[37] and management science[14]. Camburn et al.[14] document prototyping strategies specifically related to engineering during product development. Christie et al.[37] explore prototyping strategies related to business and engineering actions and define prototyping strategies as "the set of decisions that dictate what actions will be taken to accomplish the development of the prototype(s)"[37]. Our work aims to evaluate prototyping approaches that not only incorporate aspects of Human Centered Design, HCD, but extend into the testing phase of the prototyping process. In order to understand prototyping at a deeper level and highlight the gaps in the prototyping literature, 46 papers were critically reviewed. We build upon Christie, et al.[37] and Camburn, et al.'s work[14] by adding literature from engineering education[2, 5, 6, 22, 38-40] , human computer interaction[9, 27, 34, 41], industrial design[44-49], and design thinking studies[7, 50-53]. In the following section we use this literature to derive definitions for each of our prototyping lenses.

After thoroughly reviewing each of these papers, three major gaps were identified: (1) literature within engineering management and management science has largely overlooked how optimizing a design for cost and time affects the product's desirability; (2) literature within engineering design and education has failed to evaluate prototyping in realistic and complex design problems; and (3) while human computer interaction literature has explored aspects of desirability, such as usability and preference, this work has not been translated to the design of non-digital prototypes. We hypothesize that Prototype for X (PFX) will help fill these gaps by supporting designers with structured prototyping methods. We define each of the PFX lenses in the next section; these definitions are based on the aforementioned literature, the Human Centered Design framework proposed by IDEO[54], design thinking methods[55], and Design for X methods[56, 57].

3.0 The Prototyping for X Framework and Related Research Questions

Human Centered Design, HCD, views innovation through three lenses: (1) desirability, (2) feasibility, and (3) viability. The desirability lens asks questions related to how will the user engage with the product, will the user find the product compelling, and how desirable is the product. The feasibility lens ask questions about what is technically and organizationally feasible, and the viability lens asks questions about what is financially and economically viable for the company[54,55]. We propose Prototyping for X (PFX) as a framework to aid product design during the prototyping phase of the process. Prototyping is the least understood phase of the design process[14, 37], and we hypothesize that focusing prototyping methods through the three lenses of HCD can positively impact final design outcomes, namely, the desirability, feasibility, and viability of the end product.

Prototyping for Viability (PFV): We define prototyping for viability as *the practice of creating prototypes that test the design's likelihood of fitting into time and budget constraints*. This definition was created by synthesizing literature within management sciences[58-60] and engineering management[60-63]; both areas focus on evaluating the time and resources spent using a variety of prototyping techniques.

Prototyping for Feasibility (PFF): We define prototyping for feasibility as *the practice of creating prototypes that test the technical functionality of the design*. This definition was created by synthesizing literature within engineering design[7, 18, 33, 34, 39], engineering design education[2, 5, 6, 22, 40, 42], and human computer interaction[31, 35, 42-45]. All three fields have explored the effect of fidelity and frequency of prototyping on the technical feasibility of the end design[18, 22, 37-40].

Prototyping for Desirability (PFD): We define prototyping for desirability as *the practice of creating prototypes that test the purchasability and consumer value of a product or solution*. We found relatively little literature within engineering design that explored or incorporated into research in some way the desirability of a prototype and the effect on the end design. We found that the field of human computer interaction had the highest rate of papers related to a prototype's desirability[46-49].

Before detailing our research questions, we provide a brief overview of the experimental protocol and data collection process to orient the reader. Data was collected using the Prototyping Awareness Scale, or PAWS, a self-assessment instrument developed and being validated by the research team to collect data on students' awareness of their own mindsets, behaviors, and practices during prototyping processes. There are three subscales of the PAWS that relate to the three lenses of PFX, namely, desirability, feasibility, and viability (see Section 4.3). PAWS was administered four times in the experimental classroom (i.e., the classroom that used the PFX method and three lenses), once after each alpha prototype was due and once when the final beta prototype was due (at the conclusion of the course). PAWS was administered once in the two control classrooms when the final beta prototype was due (at the conclusion of the course); because the main researcher did not have control over these two sections the PAWS could only be administered at the conclusion of the course, however in future work the PAWS will be administered to both control and experimental groups at each time point. Results from all four instantiations of the scale in the experimental classroom were compared in order to evaluate how prototyping awareness changed with respect to time and the relevant PFX method. Results from the final instantiation of the PAWS from the experimental classroom are compared with results from PAWS in the two control classes in order to evaluate the difference in awareness between control and experimental classrooms at the conclusion of the course. Figure 1 gives a general overview of PFX methods and control classes with respect to time. The ordering of the PFX methods was not randomized in this pilot study, and a large enough sample size was not feasible; however, in future work the ordering of PFX lenses will be randomized to eliminate sequencing or time effects as a potential variable.

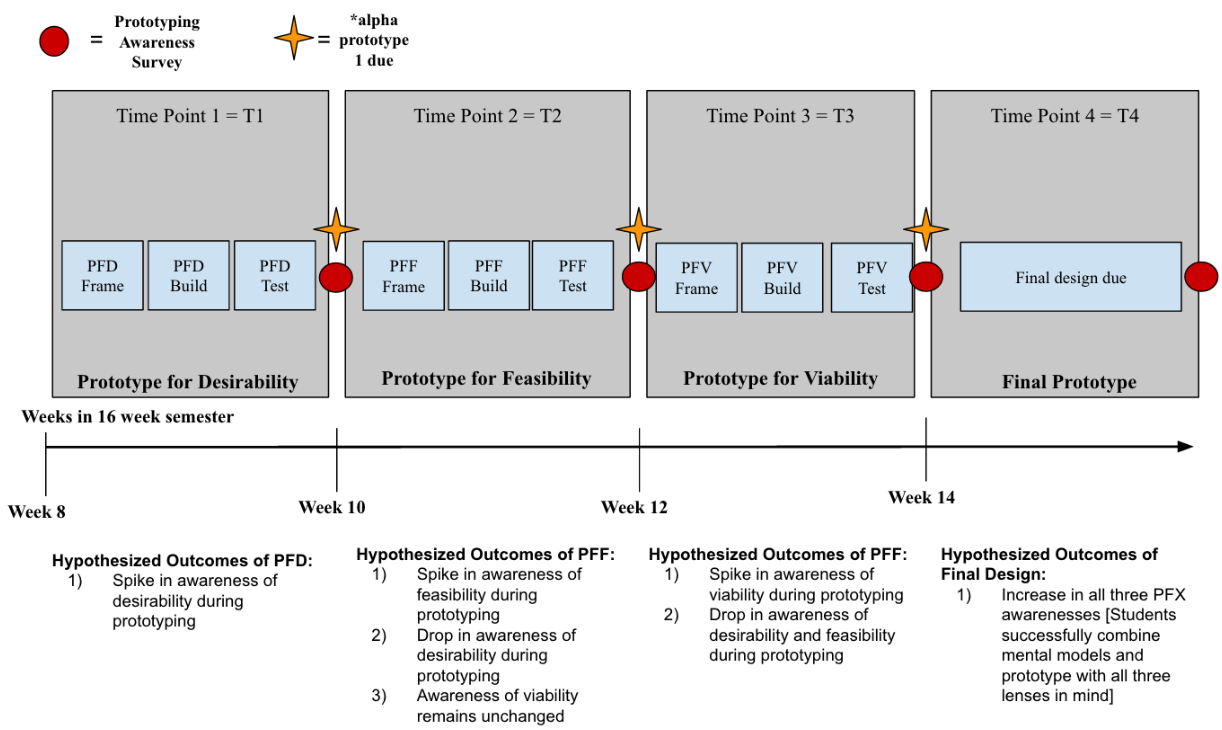

Figure 1: Overview of Experimental Flow

This paper presents preliminary findings on the relationship between the three prototyping lenses and students' prototyping awareness as measured by PAWS. We seek to understand how students engage with, adopt, and implement the PFX methods and use prototyping awareness as a way to measure its efficacy. Based on our review of the literature, we assert that prototyping awareness will mediate the effects of PFX on design outcomes, and so it is necessary to measure and track students' prototyping awareness throughout the course of the PFX interventions. Our hypotheses with respect to prototyping awareness and PFX are as follows:

- *H1a: We hypothesize that students will be more aware of desirability prototyping methods after being exposed to PFD.*
- *H1b: We hypothesize that students will be more aware of feasibility prototyping methods after being exposed to PFF.*
- *H1c: We hypothesize that students will be more aware of viability prototyping methods after being exposed to PFV.*
- *H2: We hypothesize that students exposed to the PFX methods will be more aware of prototyping methods than students who are not exposed to these methods (control).*

4.0 Research Methodology

Students in the experimental classroom were taught each prototyping method in a two-week learning module that was based on one of the three PFX methods. Lectures ranged from 45-90 minutes and covered tools and techniques specific to each PFX method, such as Design for Assembly methods[56] for viability, functional decomposition[10] for feasibility, and design thinking strategies[54] for desirability. Students were instructed to build and test prototypes optimized with respect to each lens. For example, during the Prototyping for Viability module, students were instructed to increase their design's critical part ratio by building a new prototype using fewer non-critical components; critical part ratio is a metric used in design for manufacturing and assembly that describes the theoretical minimum number of parts to total number of parts[56].

4.1 Study Participants

The objective in this experiment was to understand the interaction of prototyping awareness and PFX methods throughout a six-week period during a semester-long project. Participants were juniors in mechanical engineering at a large Mid-Atlantic university, and the experiment took place in the latter half of the semester, when students began to build and test prototypes. Two samples are reported in this work: (1) Sample A is composed of 30 students from the experimental classroom, and (2) Sample B is composed of 60 students from two control classes. Data from Sample A were collected at four distinct time points as shown in Figure 1. This was used to evaluate changes in prototyping awareness throughout the second half of the semester with respect to each implementation of the three PFX methods. Data from Sample A and Sample B are compared as part of the between subjects experiment comparing student's prototyping awareness in the experimental class and control class; these data were collected using PAWS upon delivery of the final prototype.

4.2 Experimental Protocol

Each of the PFX interventions has three components: (1) frame, (2) build, and (3) test. Studies have shown that the framing of a problem can drastically impact the results that designers produce. Specifically, in over twenty studies from creativity and problem-solving literature, problem framing and explicit instructions such as "be creative", have been shown to have some facilitative effect on the end results[64]. Because of this we provided students with a prototyping frame, or context, goals, and needs that they are to focus on when building the prototype. Framing effect, or "the finding that subjects often respond differently to different descriptions of the same problem"[65], has been used to show the dependence of an individual's preferences and actions on the formulation or framing of the problem or task[65, 66].

We used the Design Problem Framework (DPF)[67] as a guide for framing prototyping prompts. The DPF is grounded in research on cognitive styles and problem framing, and it was originally used to understand how the framing of a design challenge affects ideation and solution generation[67, 68]. The DPF breaks design challenges into three components: (1) context, (2) need, and (3) goal. *Context* refers to who needs a solution and what purpose the solution serves, *need* refers to functional requirements and constraints of the design challenge, and *goal* refers to the instructions used to generate ideas and the metrics used to evaluate those ideas. In an experiment studying the effect of DPF on ideation metrics such as paradigm relatedness, researchers demonstrated that the DPF can successfully shift students' ideas based on the framework provided[68]. Because our work is exploring prototyping methods, we adapted the DPF into three separate frames, one for each of our three lenses (i.e., desirability, feasibility, and viability); the problem frames used in this study are shown in Appendix A.

During the test portion, students are instructed to test their prototype with respect to certain metrics. For desirability, students were told to gather feedback from a minimum of five users about the purchasability and user satisfaction of their product. For feasibility, students identified one key sub-system in a functional decomposition that was critical to the technical functionality of their prototype; student's then built this sub-system and tested its overall functionality. For viability, students were instructed to count the number of parts in their products, and calculate the theoretical minimum number of parts, along with estimates of the overall cost to manufacture a minimum batch of the product, using guidelines set forth in design for manufacturing and assembly[56]. Students then re-built their prototypes to reduce part count and cost.

4.3 The Prototyping AWareness Scale (PAWS)

Prototyping literature has typically evaluated the few prototyping methods, tools, and frameworks using design-based metrics, such as binary evaluations of completion of a design task[6, 7]. In other words, there are few prototyping studies that use a scale to evaluate how the designers are being affected by prototyping methods. Dow et al.[33, 34] used a prototyping experience survey when evaluating the potential benefits of parallel prototyping; however, their survey was used to judge prior experience and was not used as an indication of adoption or use of methods. Although Gerber et al.[18] did study the psychological experience of prototyping, results of their ethnographic study were based on observations and field notes from studying a single design team. While Camburn et al.[14] asked a similar question "how well do participants apply prototyping methods", their experimental protocol was not applicable to our case because their experimental methods were significantly different. Camburn et al.[14] had students create a prototyping plan prior to being exposed to their methods, then recreate this plan after exposure; at a later time point, students were asked to rate on a ten point Likert-type scale how well they followed the second prototype plan. Because Camburn et al.[14] proposed what was largely a planning method, and not active prototyping methods, we need to create a separate measure in order to track and evaluate prototyping awareness.

We hypothesized that prototyping awareness or the efficacy of students' prototyping behaviors with the PFX methods will mediate the effect of PFX on design outcomes. In other words, the level of adoption and use of PFX methods will mediate the impact of PFX on design outcomes; design outcomes refer to the final prototypes which were evaluated using a series of metrics measuring viability, feasibility, and desirability.

The Prototyping AWareness Scale (PAWS) asks students to rate their agreement with fifteen statements about the processes, behaviors, and mindsets they engaged in during the prototyping process on a five point Likert-type scale (1 = strongly disagree, 5 = strongly agree). PAWS is provided in Appendix B. PAWS is composed of three subscales, a desirability subscale, a feasibility subscale, and a viability subscale based on the extensive literature reviewed discussed in Section 2. Items from the desirability subscale are based on literature within interaction design[39-40] and human computer interaction[42-45]; an example item would be *when developing my* *prototype I built features I felt would increase user value*. Items from the feasibility subscale are based on literature within engineering design[7, 34, 39] and systems design[10]; an example item would be *when developing my prototype I determined one or more technical functions to test*. Items from the viability subscale are based on literature within management sciences[58-60] and engineering management[61-63]; an example item would be *when developing my prototype I thought about the manufacturability of my design.*

The PAWS overall had a Cronbach's alpha of 0.723, indicating a high level of internal consistency. The desirability awareness construct consisted of five questions and was found to have a high level of internal consistency as determined by a Cronbach's alpha of 0.748. The viability awareness construct consisted of five questions and was found to have a high level of internal consistency as determined by a Cronbach's alpha of 0.808. The feasibility awareness construct consisted of five questions and was found to have moderate levels of internal consistency as determined by a Cronbach's alpha of 0.550. Future work will include editing and rewriting some of the feasibility questions to improve the internal consistency of the overall subscale. For this work, however, the internal consistency of the feasibility subscale is treated as a limitation of our research.

5.0 Data Analysis

5.1 Within Subjects Experiment

For the within subjects test, we seek statistically significant differences in subscale scores on PAWS following each intervention. Review Figure 1 for an overview of the timing and distribution of the PAWS. We hypothesize that students' awareness and focus will shift from desirability, to feasibility, and finally, to viability as each PFX intervention is implemented. At the completion of the final prototype, we hope to see that students are able to combine all three lenses and focus equally on desirability, feasibility, and viability when developing their final prototypes.

A Friedman test[69] was run on each subscale to determine if there were differences in prototyping awareness throughout the course of the PFX methods. Pairwise comparisons were performed using SPSS 2012 with a Bonferroni correction for multiple comparisons. Desirability prototyping awareness was statistically significantly different at the four different time points throughout the PFX methods, $\chi2(2) = 24.611$, $p < .000$. Post-hoc analysis revealed statistically significant differences in desirability awareness from T2 (Mdn = 3.5) to T4 (Mdn = 4.2) ($p < .000$) and from T3 (Mdn = 3.6) ($p = .007$) to T4. There was not a statistically significant difference in desirability awareness between T1 and T4, T1 and T3, or T1 and T2.

Feasibility prototyping awareness was statistically significantly different at the four different time points throughout the PFX methods, $\chi2(2) = 51.05$, $p < .000$. Post-hoc analysis revealed statistically significant differences in feasibility awareness from T1 (Mdn = 3.0) to T2 (Mdn = 4.4) ($p < .000$), T1 to T4 (Mdn = 4.8) ($p < .000$), and T3 (Mdn = 4.0) ($p < .000$) to T4. There was not a statistically significant difference in feasibility awareness between T1 and T3, T3 and T2, or T2 and T4.

Viability prototyping awareness was statistically significantly different at the four different time points throughout the PFX methods, $\chi2(2) = 38.83$, $p < .000$. Post-hoc analysis revealed statistically significant differences in viability awareness from T1 (Mdn = 2.2) to T3 (Mdn = 3.7) ($p < .000$), T1 to T4 (Mdn = 3.6) ($p < .000$), T2 (Mdn = 2.2) ($p < .000$) and T3, and T2 and T4 ($p < .000$). There was not a statistically significant difference in viability awareness between T1 and T2, and T3 and T4. Figures 2-4 show the median scores for each subscale at each of the time points at which the prototyping awareness survey was administered (see Figure 1). Times that correspond with the PFX module that matches the subscale are starred (e.g., PFD method was implemented at T1 as indicated by the star in Figure 2.

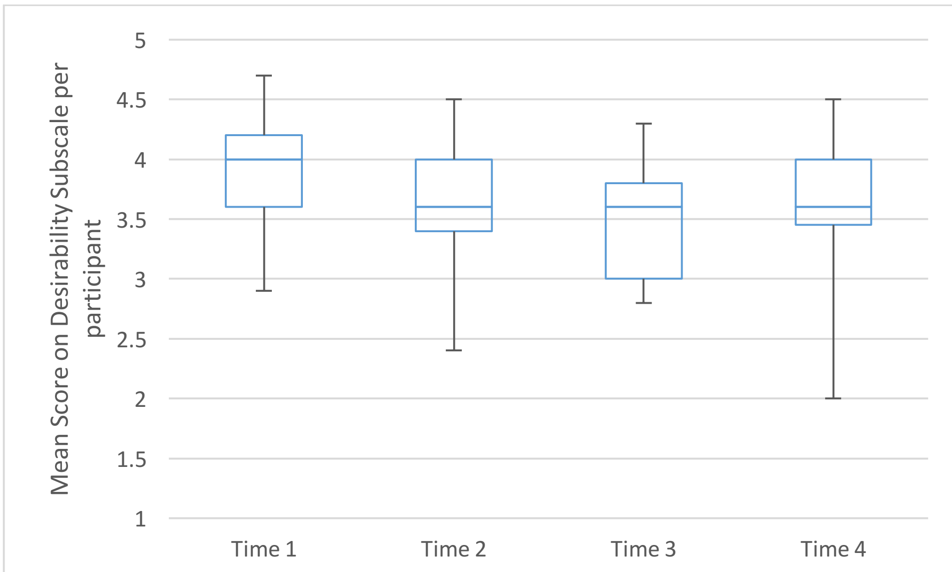

Figure 2: Mean Desirability Subscale Score at T1, T2, T3, and T4

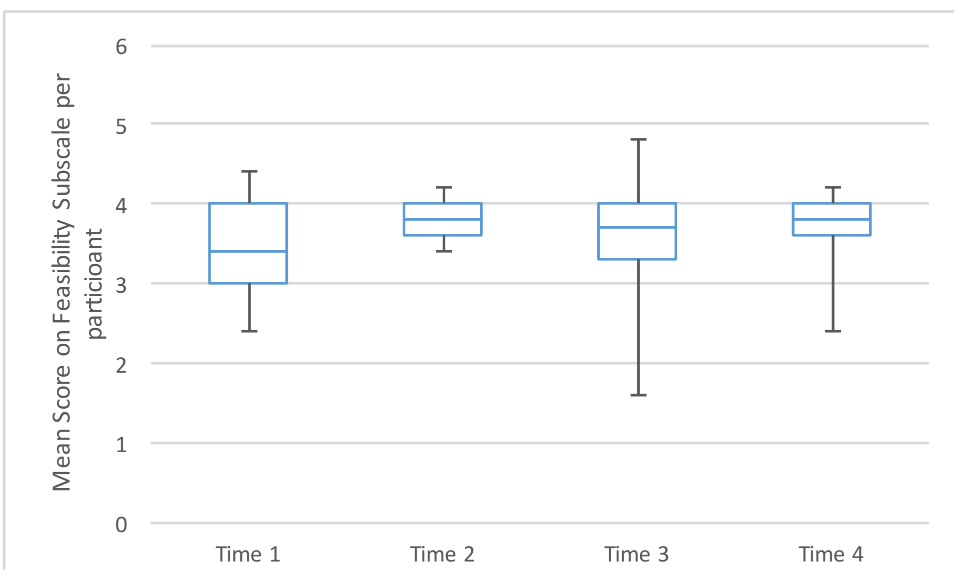

Figure 3: Mean Feasibility Subscale Score at T1, T2, T3, and T4

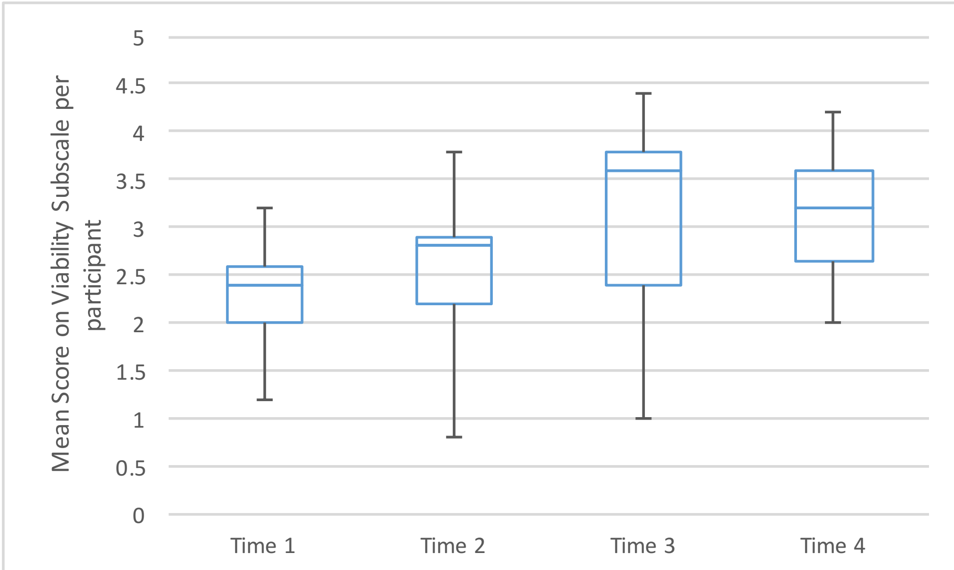

Figure 4: Mean Viability Subscale Score at T1, T2, T3, and T4

By reviewing Figures 2-4 along with the results from statistical analysis, the following observations can be made in relation to our first hypothesis:

- *H1a: We hypothesize that students will be more aware of desirability prototyping methods after being exposed to PFD.* There were statistically significant results comparing T1 (the time PFD was implemented) with T2 and T3, we did not see a statistically significant difference between T4 and T2 and T3. This means that students were more aware of desirability during the first prototype construction (T1) as compared with second and third alpha prototype construction (T2 and T3, respectively). **These findings support our hypothesis that students will be more aware of desirability prototyping methods after being exposed to PFD.** In other words students were able to successfully shift awareness from T2 and T3, and they focused on—or were more aware of—the desirability of their design at the first time (T1).

- *H1b: We hypothesize that students will be more aware of feasibility prototyping methods after being exposed to PFF.* We found statistically significant differences on the feasibility awareness subscale at T2 compared to T1 and T3. We also saw a statistically significant difference between T4 and T1 and T3. This means students were significantly more aware of feasibility during the second alpha prototype (T2) as compared with the first and third alpha prototypes (T1 and T3 respectively). This also means that students were significantly more aware of feasibility during the final prototype construction (T4) as compared with the first and third alpha prototypes. **These findings support our hypotheses that students will be more aware of feasibility prototyping methods after being exposed to PFF.** In other words students were able to successfully shift awareness from T1 and T3 and focus on feasibility during construction of the second alpha prototype (following the PFF learning module). Students were also able to shift back to feasibility for the final prototype.

- *H1c: We hypothesize that students will be more aware of viability prototyping methods after being exposed to PFV.* We found statistically significant differences on the viability awareness subscale at T3 compared to T1 and T2. We also saw a statistically significant difference between T4 and T1 and T2. This means students were statistically significantly more aware of viability during the third alpha prototype (T3) as compared with the first and second alpha prototypes (T1 and T2 respectively). This also means that students were statistically significantly more aware of viability during the final prototype construction (T4) as compared with the first and second alpha prototypes. **These findings support our hypotheses that students will be more aware of viability prototyping methods after being exposed to PFV.** In other words students were able to successfully shift awareness from T1 and T2 and focus on viability during construction of the third alpha prototype (following the PFV learning module). Students were also able to shift back to viability for the final prototype.

Reviewing T4 more closely reveals that students were statistically significantly more aware across all three dimensions—desirability, feasibility, and viability—during construction of the final prototype. This means that students used prototyping methods or practices from each of three previous alpha prototype phases throughout the construction of the final prototype.

5.2 Between Subjects Experiment

A Mann-Whitney U[70, 71] test was completed to determine if there were differences in desirability awareness sub-scores between the experimental class and the control class. This statistical method was chosen because it is a rank-based nonparametric test that is typically used to determine if there are differences between two groups on an ordinal dependent variable. Prototyping awareness was measured with a five point Likert-type scale, making it an ordinal dependent variable. This eliminated an independent samples t-test[70] as an option, as it requires a normal distribution and continuous dependent variable. Median prototyping awareness scores per item were not statistically significantly different between the experimental and control classes except on three items: 1) thought about the technical functionality of the design ($U = 953$, $p = .001$), 2) explored how subsystems would work ($U = 867$, $p = .040$), and 3) Was not concerned with the functionality of the prototype ($U = 502$, $p = .021$). All three items are within the feasibility subscale of the PAWS. This data indicates that students in the experimental group were significantly more aware about the technical functionality of their designs (with respect to these three items) as compared to the control groups.

The following observations can be made in relation to our second hypothesis:

- *H2: We hypothesize that students exposed to the PFX methods will be more aware of prototyping methods than students who are not exposed to these methods (control).* In general, we saw few statistically significant differences on PAWS items between the experimental and control classes. In particular, only three items yielded statistically different results across control and PFX groups. We know that the experimental group scored higher across these three items, however at this point we cannot say for certain why we saw these results. In future work we will attempt to parse this data out further and investigate the causes of these differences. We will collect more data in the next experiment to determine whether these differences might be due to a) course constraints

b) efficacy of student prototyping awareness c) social biasing or any number of other variables. We detected no differences in their awareness of desirability and viability but at this stage in the experiment are unable to define the reasons behind this finding. We will consider how these parts of PFX can be emphasized even stronger and more clearly next time, to see whether the way in which they are presented will yield different results. Further research is required to explore these findings and rule out alternative explanations.

6.0 Discussion of Results

The results of our analysis indicate that a statistically significant relationship exists between prototyping awareness, as measured by PAWS, and PFX methods. The purpose of this paper was to present preliminary findings on the relationship between the three prototyping lenses—desirability, feasibility, and viability—and students' prototyping awareness. Based on our statistical analysis, we found support for our first hypothesis, meaning that students were able to successfully shift their prototyping awareness to focus on either desirability, feasibility, or viability with respect to PFX methods. This is an important finding because it indicates that students can successfully engage with and implement new prototyping methods to develop more desirable, feasible, and viable end designs. In a separate study, the final designs from the control and experimental classes were compared, and the designs of students using PFX significantly outperformed their counterparts' designs in terms of user satisfaction, user perceived value, manufacturability, and technical functionality[19].

We found no statistically significant difference between the control and experimental groups in terms of prototyping awareness. This is an interesting and unexpected finding, as data from a separate experiment showed that designs from the control classes performed significantly lower in metrics related to desirability, feasibility, and viability; in other words, the students' design outcomes seem to show that the control group students are not as aware of the PFX lenses as the experimental group [74]. In this experiment we evaluated the final designs produced in both control and experimental classes across four categories of metrics, including user perceived value, user satisfaction ratings, technical functionality scores, and overall manufacturability of end designs. User perceived value and user satisfaction were evaluated by two independent raters, technical functionality was measured by the amount of rice each vacuum was able to collect in ten seconds, and manufacturability was evaluated by calculating the critical part ratio for each design. The disparity in the findings from these two experiments could indicate that some social bias is at play, with students answering items based on what they *think* their prototyping awareness levels should have been, as opposed to what they actually were. This finding could also indicate that students are not aware of their own knowledge gaps and feel that their prototyping behaviors and practices are at a mastery level. An initial prototyping knowledge survey would help to determine the bounds of students' knowledge surrounding prototyping and may help answer this question. Future work will incorporate a survey for post-hoc analysis such as this.

This work benefits design educators because it helps shed light onto the thought processes and behaviors student engineers engage in during the prototyping process. PAWS can be used to determine if students are focusing on desirability, feasibility, or viability, and it can help educators re-focus student teams onto problem areas or blind spots. Our work also helps students and educators take some of the guesswork and mystery out of the prototyping process. The PFX framework guides student teams to prototype and iterate on designs more effectively, ultimately leading to designs that are more desirable, feasible, and viable. Future work will help determine how generalizable PFX methods are by exploring how PFX affects designs and students within different design contexts and problems. Our goal is to create a set of prototyping methods that enhance traditional design courses and add to students' skill sets and tools for use in industry.

7.0 Limitations and Future Work

Our study was limited in its scope due to a lower internal consistency on the feasibility subscale and constraints placed on the experiment due to the nature and timing of the course. It should be noted that the Prototyping Awareness Survey (PAWS) is in its pilot stage, and the results of this work will help advance its development. Future work will include iterating and revising items on the feasibility subscale in an attempt to raise its internal consistency; the moderate internal consistency makes it difficult to attribute changes on that subscale to one larger construct, namely, feasibility. We will revise the items on that subscale so that they are related only to the feasibility construct by consulting the prototyping, design, and assessment literature.

Constraints placed on the experiment due to the nature and timing of the course include: a sample of convenience for the intervention class (N =30); PFX methods could not be randomized; and the lectures, materials, and instructions in control classes were outside the control of the primary researcher. The intervention sample was a sample of convenience, as the primary researcher was teaching this section; this means that the effect the lecturer had on the class could not be evaluated and may have influenced student and design outcomes. In future work, control classes and experimental classes will be randomized to remove this potential effect. Because the researcher only had control over one section, the order of the PFX methods was set to be (1) desirability, (2) feasibility, and (3) viability; future work will include a partial factorial experimental design to evaluate what (if any) effects the order of PFX methods has on student and design outcomes. Finally, lectures, materials, and instructions for the final prototype within the control sections were outside the control of the primary researcher; so, other methods may have affected the results from these sections. In future work, the course content will be controlled throughout each prototyping phase.

Engineering students are expected to develop innovative products that solve some of the world's toughest challenges as soon as they enter the workforce. The Accreditation Board for Engineering and Technology (ABET) requires engineering graduates to have "an ability to design a system, component or process to meet desired needs within realistic constraints such as economic, environmental, social, political, ethical, health and safety, manufacturability, and sustainability"[72]. A thorough understanding and mastery of the design process is necessary to solve these difficult challenges; however, one of the most critical stages of the design process, prototyping, has remained largely unstructured and unstudied. This work evaluated the impact on prototyping awareness of a guided prototyping framework. Future work will explore how PFX may help engineering students test and iterate on designs faster and more effectively.

Finally, our work aligns with the National Science Foundation's second strategic goal "stimulate innovation and address societal needs through research and education"[73]. By educating engineering students to develop products that incorporate societal, economic, and technical perspectives, we are encouraging the development of innovative solutions and individuals. Engineers and students exposed to this work will be able to design a technically feasible product or system that meets the needs of a complex global market and user base.

References

1. Yilmaz, S., Daly, S., Jablokow, K. W., Silk, E., & Rosenberg, M. (2014). Investigating Impacts on the Ideation Flexibility of Engineers. Proc. of 2014 ASEE Annual Conference and Exposition, Indianapolis, IN.
2. Neeley, W. L., Lim, K., Zhu, A., & Yang, M. C. (2013, August). Building fast to think faster: exploiting rapid prototyping to accelerate ideation during early stage design. In *ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers.
3. Shah, J. J., Smith, S. M., & Vargas-Hernandez, N. (2003). Metrics for measuring ideation effectiveness. *Design studies*, *24*(2), 111-134.
4. Toh, C. A., & Miller, S. R. (2014). The impact of example modality and physical interactions on design creativity. *Journal of Mechanical Design*, *136*(9), 091004.
5. Viswanathan, V. K., & Linsey, J. S. (2009, October). Enhancing student innovation: Physical models in the idea generation process. In *Frontiers in Education Conference, 2009. FIE'09. 39th IEEE* (pp. 1-6). IEEE.
6. Viswanathan, V. K., & Linsey, J. S. (2012). Physical models and design thinking: A study of functionality, novelty and variety of ideas. *Journal of Mechanical Design*, *134*(9), 091004.
7. Elsen, C., Häggman, A., Honda, T., & Yang, M. C. (2012, August). Representation in early stage design: An analysis of the influence of sketching and prototyping in design projects. In *ASME 2012 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. 737-747). American Society of Mechanical Engineers.
8. DeFranco, J., Jablokow, K., Bilen, S., and A. Gordon (2012). The Impact of Cognitive Style on Concept Mapping: Visualizing Variations in the Structure of Ideas. Proc. of the ASEE 2012 Annual Conference and Exposition, San Antonio, TX.
9. Liu, Linchuan, and Peter Khooshabeh. "Paper or interactive?: a study of prototyping techniques for ubiquitous computing environments." *CHI'03 extended abstracts on Human factors in computing systems*. ACM, 2003.
10. Stone, R. B., & Wood, K. L. (2000). Development of a functional basis for design. *Journal of Mechanical design*, *122*(4), 359-370.
11. Reimann, M., & Schilke, O. (2011). Product differentiation by aesthetic and creative design: A psychological and neural framework of design thinking. In *Design Thinking* (pp. 45-57). Springer Berlin Heidelberg
12. Skogstad, P., & Leifer, L. (2011). *A unified innovation process model for engineering designers and managers* (pp. 19-43). Springer Berlin Heidelberg.
13. Ulrich, K. T., & Eppinger, S. D. Product design and development. 2004.
14. Camburn, B. A., Dunlap, B. U., Kuhr, R., Viswanathan, V. K., Linsey, J. S., Jensen, D. D., ... & Wood, K. L. (2013, August). Methods for Prototyping Strategies in Conceptual Phases of Design: Framework and Experimental Assessment. In *ASME 2013 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference*. American Society of Mechanical Engineers.
15. Bandura, A. (1997). *Self-efficacy: The exercise of control*. New York: W. H. Freeman and Company.
16. Deci, E. L., & Ryan, R. M. (1985). *Intrinsic motivation and self-determination in human behavior*. New York: Plenum
17. Seligman, M. (1990). Learned optimism. New York: A.A. Knopf.

18. Gerber, E., & Carroll, M. (2012). *The psychological experience of prototyping*. *Design studies*, *33*(1), 64-84.
19. [Blinded Paper Currently in Review]. *The Prototype for X Framework: Assessing the Impact on Desirability, Feasibility, and Viability of End Designs.* Submitted to ASME 2016 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference. American Society of Mechanical Engineers, Under Review.
20. Youmans, R. J. (2011). The effects of physical prototyping and group work on the reduction of design fixation. *Design Studies*, *32*(2), 115-138.
21. Bucciarelli, L. L. (2002). Between thought and object in engineering design.*Design studies*, *23*(3), 219-231.
22. Yang, M. C. (2005). A study of prototypes, design activity, and design outcome. *Design Studies*, *26*(6), 649-669.
23. Perry, M., & Sanderson, D. (1998). Coordinating joint design work: the role of communication and artefacts. *Design studies*, *19*(3), 273-288.
24. Eckert, C., & Boujut, J. F. (2003). The role of objects in design co-operation: communication through physical or virtual objects. *Computer Supported Cooperative Work (CSCW)*, *12*(2), 145-151.
25. Gerber, E. (2011). The Psychological Experience of User Observation. In *DS 68-7: Proceedings of the 18th International Conference on Engineering Design (ICED 11), Impacting Society through Engineering Design, Vol. 7: Human Behaviour in Design, Lyngby/Copenhagen, Denmark, 15.-19.08. 2011*.
26. Eastman, C. (2001). New directions in design cognition: studies of representation and recall. *Design knowing and learning: Cognition in design education*, 147-198.
27. Kiriyama, T., and Yamamoto, T., 1998, “Strategic Knowledge Acquisition: A Case Study of Learning through Prototyping,” Knowledge-Based Systems, 11(7-8), pp. 399–404
28. Bucciarelli, L. L., 1994, *Designing Engineers*, MIT Press, London.
29. Andreasen, M. M., and Hein, L., 1987, *Integrated Product Development*, IFS (Publications), UK
30. Mckim, R. H., 1972, *Experiences in Visual Thinking*, Brooks/Cole Publishing Company, Belmont, CA
31. Brereton, M., & McGarry, B. (2000, April). An observational study of how objects support engineering design thinking and communication: implications for the design of tangible media. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems* (pp. 217-224). ACM.
32. Vidal, R., Mulet, E., and Go´mez-Senent, E., 2004, “Effectiveness of the Means of Expression in Creative Problem-Solving in Design Groups,” J. Eng. Des., 15(3), pp. 285–298.
33. Dow, S. P., Glassco, A., Kass, J., Schwarz, M., & Klemmer, S. R. (2009).*The effect of parallel prototyping on design performance, learning, and self-efficacy* (Vol. 10). Stanford Tech Report.
34. Dow, S. P., Fortuna, J., Schwartz, D., Altringer, B., Schwartz, D. L., & Klemmer, S. R. (2012). Prototyping dynamics: sharing multiple designs improves exploration, group rapport, and results. In *Design Thinking Research* (pp. 47-70). Springer Berlin Heidelberg.
35. Hartmann, B., Klemmer, S. R., Bernstein, M., Abdulla, L., Burr, B., Robinson-Mosher, A., & Gee, J. (2006, October). Reflective physical prototyping through integrated design, test, and analysis. In *Proceedings of the 19th annual ACM symposium on User interface software and technology* (pp. 299-308). ACM.
36. Viswanathan, V., & Linsey, J. (2011, October). Understanding physical models in design cognition: A triangulation of qualitative and laboratory studies. In *Frontiers in Education Conference (FIE), 2011* (pp. S3F-1). IEEE.
37. Christie, E. J., Jensen, D. D., Buckley, R. T., Menefee, D. A., Ziegler, K. K., Wood, K. L., & Crawford, R. H. (2012). Prototyping Strategies: Literature Review and Identification of Critical Variables. In *American Society for Engineering Education*. American Society for Engineering Education.
38. Kershaw, Trina C., Katja Hölttä-Otto, and Yoon Soo Lee. "The effect of prototyping and critical feedback on fixation in engineering design." *CogSci, Boston, MA* (2011).
39. Viswanathan, C., & Kumar, V. (2012). *Cognitive effects of physical models in engineering idea generation*. TEXAS A&M UNIVERSITY.
40. Liem, A. (2011). Using design education to survive in the 'corporate world' of higher learning and research. *Journal of Design Research*, *9*(2), 104-118.

41. Houde, S., & Hill, C. (1997). What do prototypes prototype. *Handbook of human-computer interaction*, *2*, 367-381.
42. Lim, Y. K., Stolterman, E., & Tenenberg, J. (2008). The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas. *ACM Transactions on Computer-Human Interaction (TOCHI)*, *15*(2), 7.
43. McCurdy, M., Connors, C., Pyrzak, G., Kanefsky, B., & Vera, A. (2006, April). Breaking the fidelity barrier: an examination of our current characterization of prototypes and an example of a mixed-fidelity success. In *Proceedings of the SIGCHI conference on Human Factors in computing systems* (pp. 1233-1242). ACM.
44. Maguire, M. (2001). Methods to support human-centred design. *International journal of human-computer studies*, *55*(4), 587-634.
45. Sefelin, R., Tscheligi, M., & Giller, V. (2003, April). Paper prototyping-what is it good for?: a comparison of paper-and computer-based low-fidelity prototyping. In *CHI'03 extended abstracts on Human factors in computing systems* (pp. 778-779). ACM.
46. Lin, J., & Seepersad, C. C. (2007, January). Empathic lead users: the effects of extraordinary user experiences on customer needs analysis and product redesign. In *ASME 2007 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. 289-296). American Society of Mechanical Engineers.
47. Genco, N., Johnson, D., Hölttä-Otto, K., & Seepersad, C. C. (2011, January). A Study of the Effectiveness of Empathic Experience Design as a Creativity Technique. In *ASME 2011 International Design Engineering Technical Conferences and Computers and Information in Engineering Conference* (pp. 131-139). American Society of Mechanical Engineers.
48. Kaulio, M. A. (1998). Customer, consumer and user involvement in product development: A framework and a review of selected methods. *Total Quality Management*, *9*(1), 141-149.
49. Boehm, B. W., Gray, T. E., & Seewaldt, T. (1984). Prototyping versus specifying: a multiproject experiment. *Software Engineering, IEEE Transactions on*, (3), 290-303.
50. Kimbell, L. (2011). Rethinking design thinking: Part I. *Design and Culture*, *3*(3), 285-306.
51. Johansson- Sköldberg, U., Woodilla, J., & Çetinkaya, M. (2013). Design thinking: past, present and possible futures. *Creativity and Innovation Management*, *22*(2), 121-146.
52. Gabrysiak, Gregor, Holger Giese, and Andreas Seibel. "Towards next generation design thinking: scenario-based prototyping for designing complex software systems with multiple users." *Design Thinking*. Springer Berlin Heidelberg, 2011. 219-236.
53. Reimann, M., & Schilke, O. (2011). Product differentiation by aesthetic and creative design: A psychological and neural framework of design thinking. In *Design Thinking* (pp. 45-57). Springer Berlin Heidelberg
54. IDEO.org | Home. (n.d.). Retrieved October 12, 2015.
55. dschool.stanford.edu | Home. (n.d.). Retrieved October 12, 2015.
56. Boothroyd, G. (1994). Product design for manufacture and assembly.*Computer-Aided Design*, *26*(7), 505-520.
57. Kuo, T. C., Huang, S. H., & Zhang, H. C. (2001). Design for manufacture and design for 'X': concepts, applications, and perspectives. *Computers & Industrial Engineering*, *41*(3), 241-260.
58. Ben-Arieh, D., & Qian, L. (2003). Activity-based cost management for design and development stage. *International Journal of Production Economics*, *83*(2), 169-183.
59. Tornberg, K., Jämsen, M., & Paranko, J. (2002). Activity-based costing and process modeling for cost-conscious product design: A case study in a manufacturing company. *International Journal of Production Economics*, *79*(1), 75-82.
60. Özbayrak, M., Akgün, M., & Türker, A. K. (2004). Activity-based cost estimation in a push/pull advanced manufacturing system. *International journal of production economics*, *87*(1), 49-65.

61. Qian, L., & Ben-Arieh, D. (2008). Parametric cost estimation based on activity-based costing: A case study for design and development of rotational parts.*International Journal of Production Economics*, *113*(2), 805-818.
62. Doke, E. R., & Swanson, N. E. (1995). Decision variables for selecting prototyping in information systems development: A Delphi study of MIS managers. *Information & Management*, *29*(4), 173-182.
63. Guimaraes, T., & Saraph, J. V. (1991). The role of prototyping in executive decision systems. *Information & management*, *21*(5), 257-267.
64. Chen, C., J. Kasof, A.J. Himsel, J. Dmitrieva, Q. Dong, and G. Xue, Effective of explicit instruction to "be creative" across domains and cultures. Journal of Creative Behavior, 2005. 39(2): p. 89-110
65. Frisch, D. (1993). Reasons for framing effects. *Organizational Behavior and Human Decision Processes*, *54*(3), 399-429.
66. Tversky, A., & Kahneman, D. (1981). The framing of decisions and the psychology of choice. *Science*, *211*(4481), 453-458.
67. Silk, E. M. The Design Problem Framework: Using Adaption-Innovation Theory to Construct Design Problem Statements.
68. Wright, M. S. M. Exploring the Effects of Problem Framing on Solution Shifts: A Case Study.
69. Higgins, J. J. (2003). Introduction to modern nonparametric statistics.
70. Mann, H. B., & Whitney, D. R. (1947). On a test of whether one of two-random variables is stochastically larger than the other. *The Annals of Mathematical Statistics*, *18(1)*, 50-60.
71. Hollander, M., & Wolfe, D. A. (1999). *Nonparametric statistical methods*(2nd ed). Hoboken, NJ: Wiley.
72. Abet.org | Home. (n.d.). Retrieved October 12, 2015.
73. Begin, W. D. (2015). National Science Foundation
74. [reference removed]
75. Cooper, R. G. (2001). *Winning at new products: Accelerating the process from idea to launch*. Basic Books.

Appendix A: Prototyping Framework used in Experiment

Context: ACME Tool Company has a product family of 18V cordless drills, saws and sanders that have been very successful in the consumer market. Their marketing department recommends expanding the product line to include a cordless handheld vacuum. **Need:** Design and build a prototype of a handheld vacuum. ***Your prototype should focus on solving a customer need and you should work to create a positive customer experience.*** **Goal:** A jury consisting of corporate executives, typical	**Context:** ACME Tool Company has a product family of 18V cordless drills, saws and sanders that have been very successful in the consumer market. Their marketing department recommends expanding the product line to include a cordless handheld vacuum. **Need:** Design and build a prototype of a handheld vacuum. ***Your prototype should focus on solving a key issue in functionality or technical feasibility.*** **Goal:** A jury consisting of corporate executives, typical customers and investors will	**Context:** ACME Tool Company has a product family of 18V cordless drills, saws and sanders that have been very successful in the consumer market. Their marketing department recommends expanding the product line to include a cordless handheld vacuum. **Need:** Design and build a prototype of a handheld vacuum. ***Your prototype should focus on creating an economically viable solution that is ready for mass manufacture.*** **Goal:** A jury consisting of corporate executives, typical customers and investors will

Appendix B: The Prototyping AWareness Scale

Please answer each of the following questions based on your mindset or thought process as you prototyped. No response is “right” or “wrong.” Please consider the full range of responses for each of the items and avoid bunching your responses down either side or down the middle, since these patterns will make it difficult to interpret the results. *Your answers are confidential and your participation is voluntary.*

When developing my prototype I...

	Strongly Disagree (1)	Disagree (2)	Neither Agree or Disagree (3)	Agree (4)	Strongly Agree (5)
Empathized with users	❍	❍	❍	❍	❍
Thought about the user's needs	❍	❍	❍	❍	❍
Reflected on user feedback about the design	❍	❍	❍	❍	❍
Built features I felt would increase user value	❍	❍	❍	❍	❍
Did not care about the aesthetics of the design	❍	❍	❍	❍	❍
Thought about the technical functionality of the design	❍	❍	❍	❍	❍
Explored how subsystems would work	❍	❍	❍	❍	❍
Used technical knowledge to layout or design the prototype	❍	❍	❍	❍	❍
Determined one or more technical functions to test	❍	❍	❍	❍	❍
Was not concerned with the functionality of the prototype	❍	❍	❍	❍	❍
Thought about the manufacturability of my design	❍	❍	❍	❍	❍
Contemplated how my design would fit in the market	❍	❍	❍	❍	❍
Considered the expected return on investment my design would produce	❍	❍	❍	❍	❍
Thought about which available resources could be used to bring the design to market	❍	❍	❍	❍	❍
Did not consider mass manufacture of the product	❍	❍	❍	❍	❍