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Low-Resolution Prototyping: Ideation Tool and Implementation of Structured Methodology

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Low-Resolution Prototyping: Ideation Tool and Implementation of Structured Methodology

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Dedication

This thesis is dedicated to my family who have instilled in me the tools and passion necessary to follow my dreams.

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I would like to thank all of my professors at The University of Texas at Austin, foremost Dr. Richard Crawford. His ability to creatively guide me through my studies was paramount to my success as a student. I would also like to thank my colleagues, whose intellect and grit have inspired me.

Abstract

Low-Resolution Prototyping: Ideation Tool and Implementation of Structured Methodology

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Low-resolution prototyping is acknowledged as a critical step in the engineering design process, but when and how physical representations of early conceptual models should be produced is often convoluted. In this research, two studies were conducted using low-resolution prototypes and materials. In the first study, student teams were tasked with generating potential solutions to a broad-scoped engineering design task. The use of physical artifacts was studied as it relates to both ideation as well as team communication. Building upon this, teams were then assigned to construct a concept they developed, and quantitative measures were taken to assess system performance. Teams with access to physical artifacts during ideation produced a higher number of concepts as well as better performing systems.

In the second study, a systematic tool was created to guide engineering teams through the low-resolution prototype design and evaluation processes. This tool is designed to have a broad application, and to assist teams in outlining a specific approach to constructing and evaluating early-stage physical models. The tool itself was evaluated to determine its effect, if any, on designers' decisions to iterate and improve concepts, as well as their decisions to conduct further concept generation based on the results of prototyping. The design and evaluation guides were then provided to undergraduate design teams and any effects due to student exposure to the guides were analyzed. Teams used them throughout their design process. Results were gathered regarding the teams' subjective views on the guides as well as their overall low-resolution prototyping process.

Low-resolution physical prototyping is becoming more accessible to engineering teams of all types, and decisions on when and how resources should be allocated to this process still remain somewhat unstructured. Implementation during the ideation phase, as well as development of a systematic method for embodiment following concept generation, are two stages of design in which low-resolution prototyping appear to be effective towards achieving a successful design outcome.

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Chapter 1: Background and Motivation: The Need for a Methodology for Low-Resolution Prototyping

1.1 BACKGROUND

From well-established design firms to undergraduate engineering students, the practice of prototyping concepts throughout the design process is an integral component in the development of successful and innovative products (1, 2). However, this process is often led more by experience and qualitative measures than by systematic methodology. Prototyping can serve many useful purposes, though is often seen as hindrance to production of the final design, as it requires a commitment of financial, human and time resources (2, 3, 16, 66, 67, 68).

A lack of structure and planning in the prototyping process has led to wasteful and ineffective use of available resources. Designers are tasked with developing innovative, efficient solutions to what are normally loosely structured problems (4, 5). A team is initially challenged with developing a solution to an abstract goal. The final product functions are outlined, yet the roadmap to embodiment is left to the designers' creativity. Prototypes fill a role in which the teams can reduce uncertainty as the desired product functions become finalized. With concrete planning and execution, especially in the initial stages of physical embodiment, prototyping can be especially useful.

In this thesis, the implantation of early-stage, or low-resolution, prototypes is investigated. These prototypes are used during or immediately after the design teams have outlined desired product functions and have begun to generate solution concepts.

Low-resolution prototypes provide a lower cost and time efficient approach to extracting necessary information to progress to the subsequent design phase. Often constructed of basic materials or using rapid prototyping methods, these physical embodiments of the design team's conceptual progress have many studied benefits. Through experimentation, the application of low-resolution physical prototypes is shown to improve communication amongst design team members (26, 27, 30). Internal communication is paramount in mitigating design fixation, a common detriment of group concept generation (62). In addition to studies showing groups may be more prone to design fixation, there are elementary studies which show exposure to a particular design (especially a physical representation) will also lead to design fixation. By providing access to another avenue of communication, teams can avoid fixation and develop more innovative solutions.

Much of the literature has shown the importance of early low-resolution prototyping, yet a systematic approach for design teams has not been fully developed. A classic example of this is from Tom Kelley, creator of Palo Alto's world-renowned design firm IDEO, who extols the power of prototyping and testing early concepts (22). He encourages his designers to "never go into a meeting without a prototype." However, what is absent from his writing is a concrete strategy for implementation. This may go back to the uncertain, open-ended nature of many engineering design problems. Loosely formed constraints and design objectives create a difficult environment for a one-size-fits-all method.

The first part of this thesis describes a study conducted with the planned use of low-resolution prototypes intended to mitigate group design fixation during the concept generation period. Especially prevalent in less experienced designers, group dynamics lead to fixation around examples of products and solutions the designers are already aware of. Connectivity to these designs, often subconsciously, inhibits innovate solutions from being created. There exist many methods for concept generation which attempt to solve this issue by directing the team to think outside the proverbial "box" and use unconventional methods to generate a broad spectrum of diverse ideas. However, all of these methods are entirely textual, graphical or spoken. By introducing basic physical materials for the design team to use throughout the process, it is hypothesized that a greater number of innovative solutions can be generated.

Secondly, the products of this research is a low-resolution prototyping guide and evaluation tool to assist undergraduate design teams through the prototype decision-making process. The tool prompts the team to think critically about the intended purpose of the prototypes, which product functions they were intended to demonstrate, and how they can used to provide feedback to the end user.

1.2 BENEFITS OF PROTOTYPING

An investigation into the systematic implementation of low-resolution prototypes was necessary because designers, especially less experienced teams such as engineering students, often discover much too late in the design process the problematic features of their designs. These mistakes can be costly, both from a time and financial perspective. The second key area where teams often struggle is eliciting critical customer and user feedback early in the engineering design process. Technical explanations accompanied by graphical representations or CAD designs are often hard to grasp by a non-technical audience. Concepts can be tested and validated by future users much more easily if there is a physical representation available to communicate design intent. In the following sections, the benefits of implementation of a systematic prototyping strategy are discussed. The focus of the discussion is on physical renditions; however, the value of virtual prototyping is also discussed.

1.2.1 Improved Understanding of Design Outcome

The most basic and straightforward purpose of the development of a prototype, low-resolution or otherwise, is to gain a better understanding how a concept or design satisfies customer needs. A prototype is simply a physical representation of the concept at one point in its evolution toward the final artifact (7). Often prototypes are classified into three different groups: fit, form or function. Fit prototypes are created to test assembly, interfaces, and manufacturing complications. Form prototypes, sometimes referred to as “look and feel” prototypes, provide understanding of the aesthetic design of final products. Finally, function prototypes are developed to test the specific functionality of entire systems of individual sub-systems. It is clear these three categories are not mutually exclusive, as many prototypes overlap two or all three categories.

Following the engineering design cycle outlined by Otto and Wood (71), design teams follow a phase of concept generation by creating early-stage prototypes. The first benefit of these is the ability of the artifact to supplement the designer’s limited design memory, or RAM, to make the analogy to a computer. As the designers are discussing possible ideas with one another, embodiment of their conceptual designs allows them to quickly share and build upon progress they have already made. Ullman et al. (6) showed that sketching designs aided in creating this extended memory system, as textual communication is insufficient in fully defining form. With physical prototypes serving as more tangible and concrete representations than sketches, Jang (5) arrives at the plausible explanation that these too also aid in extending both the individual designer's and the team's collective memory and understanding of the design.

Further evidence shows sketching is not entirely sufficient, as studies with undergraduate engineering students highlight their difficulty visualizing a structure from graphical representations alone (37). By creating a physical model, designers can better understand the functions associated with a prototype of any of the three categories described above.

Physical prototypes allow design teams to create concrete representations of design concepts, bringing them out from both the conceptual space of their minds and graphical representations. These prototypes, even rudimentary representations, also give design teams a chance to form their ideas into physical models. Often these basic physical representations are more time-efficient to produce than CAD models and more representative than hand-drawn graphical depictions. Throughout the concept generation and embodiment phases of the design process, design details can be examined and the designer's memory is freed up to build upon ideas already generated. This interplay between mental and physical representations of the design allows the most efficiency, as prototypes ease the burden on a designer's limited cognitive system (12).

1.2.2 Prototyping for Concept Generation and Communication

The second major function of physical prototyping is the ability for embodiment to spark new ideas and assist with concept communication, both amongst and outside the design team (27, 31, 32). Several studies demonstrate the effects of both sketching and physical prototyping on a designer's cognitive processes (1, 8, 9, 10, 11). The use of physical prototyping during the design process shows greater mental stimulation and the use of analogous concepts, often associated with more innovative concepts. However, designers can also be limited by this same application. If only presented with a limited set of prototyping tools (materials, manufacturing methods, etc.), fixation can occur, leading the team to simply mimic an existing design solution (2, 13). Design fixation is discussed in depth in a later chapter. However, it is worth mentioning now that in some cases physical embodiment can lead designers to only search for near-domain analogies (59, 60). If the team commits to a specific design space early because of a physical prototype, often it is challenging for designers to broadly search the entire spectrum of possible solutions (12). Though beneficial in reducing uncertainty, near-domain analogies can constrain the design space and lead to less innovative solutions (59, 60).

Used as a communication tool within a design team, the most significant benefit of physical prototypes is the ability for the team to mutually understand a shared representation of the design (26, 27). These physical artifacts serve as more concrete examples for shared discourse than discussion or graphical representations alone (28). Teams can comprehend the status of the design, and effectively communicate to team members their vision for future design changes. By having team members synchronized in design understanding, the prototypes serve to reduce uncertainties and improve the confidence and bonding of the team (29). With the team sharing a mutual understanding of design progress, Dow et al. (30) also assume a positive effect on both "individual emotions and team dynamics." This is clearly beneficial in promoting continued motivation and engagement in the design challenge.

As the design process progresses from early-stage concept generation into low-resolution embodiment, the vague mental model of the final deliverable can begin to be further detailed. Prototyping forces some design decisions to be made, and vague sketches and verbal communication can become a shared physical understanding of the design status. Having all team members clear on overall project direction is vital to utilizing individual input and efficient progress.

1.2.3 Improved Understanding of Customer Needs

Providing customers with physical prototypes in order to understand the design team's current thinking and design direction is very beneficial to producing a final design that meets their needs (18,19). Much like the use of prototypes within a design team, prototypes serve as ideal communication props for use with customers (29). The designers can more clearly understand the wants of the customer. Likewise, the customer can use the physical prototype to communicate potential changes and ideas. The physical prototype also gives the customer the ability to better understand the capabilities of the design team, and align their requests with those capabilities. During this feedback process, it is important for the team to receive feedback both individually and collaboratively (30). The designers learn together and can better outline their collective skillset, helping form a team identity (30). Further, when communicating with a non-technical audience, physical artifacts often convey ideas better than verbal explanations or graphical methods alone. Often, for users unfamiliar with the interface, CAD representations are difficult to understand. A physical representation is an effective way for the design team to communicate their proposed direction and to receive feedback.

Prototype interactions with customers and end users promote deeper understanding of behavioral use. With a prototype, designers can quickly and reliably understand the product user's behavior and the context in which the problem occurs (2, 16). Effective innovation necessitates an understanding of the challenges the user is facing and ways they can be overcome. Prototypes aid the design team in developing an empathic understanding of how the products they are developing will be used (25, 17).

1.2.4 Functional Validation and Iterative Design

Additionally, physical prototypes can be used for functional experimentation and testing. Often, early in the design process, several concepts must be compared and validated, without excessive resources being committed to a single design. This frequently involves creating a number of prototypes of different ideas in parallel. By constructing low-resolution prototypes, functional validation can be completed on complex designs, which may otherwise be very difficult to complete computationally. Even with the improvements in such design tools as computational fluid dynamics and finite element analysis, computing power and detailed solid models are still needed. Especially in customer use cases, physical models are ideal for testing ergonomics. Product aesthetics are also easily validated with "form prototypes," as demonstrated by the large number of companies that produce clay or foam models for customer feedback for design problems as diverse as kitchen appliances to automobiles.

Developing multiple concepts in parallel as a means for validation and selection can be an effective method of resource allocation. By comparing two prototypes against one another, designers have a better idea of product maturity long before large amounts of money and time have been committed (24). Concept selection with the use of prototypes avoids the common mistake of making decisions “based largely on paper proposals that provide inadequate knowledge of technical risk and a weak foundation for estimating development and procurement costs,” as noted by Dupont (24), who quotes John Young, the Director of Defense Research and Engineering for the United States Department of Defense.

One technology that lends itself well to early stage design embodiment is rapid prototyping, also known popularly as 3D printing. The cost and time needed to bring a concept to the physical prototype phase can be drastically reduced through the use of rapid prototyping (21). Inherent to the prototyping process is developing a concept into physical forms that can be evaluated for feedback (22). Rapid prototyping is a catch-all term for the rapidly growing and evolving field of manufacturing processes which quickly convert CAD designs into physical artifacts (23). One of the main benefits of rapid prototyping is for designs to be modified and iterated upon in a timely and cost-effective manner. As the prototypes are principally a means for feedback and validation, many more evolutions of the product can be generated and improved upon as the design process progresses.

1.2.5 Experiential Learning Opportunity for Designers

Developing a physical manifestation of a conceptual design also serves as a strong learning tool for designers, both novice and experienced alike. Not only does fabrication of the artifact come with its own set of experiential lessons, but the prototyping process follows Kolb and Fry’s Experiential Learning Process very closely (33, 34).

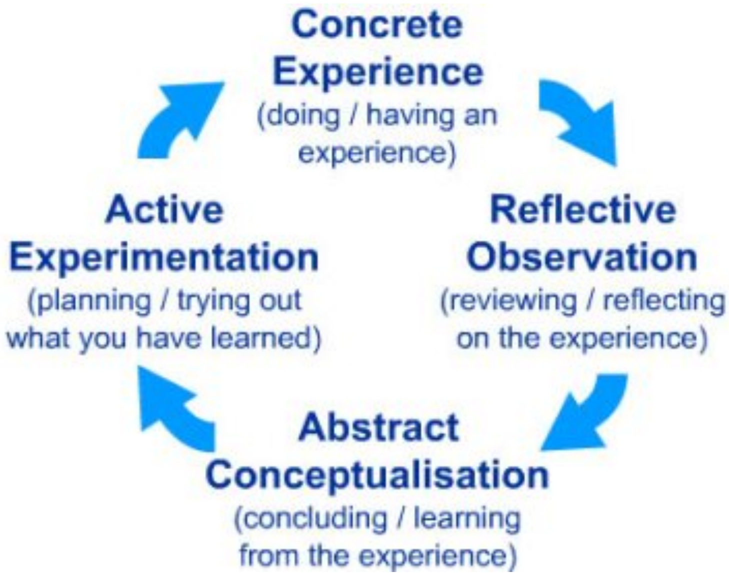


Figure 1: Kolb’s four stage learning cycle (75).

In Kolb et. al (33, 34), a four stage learning cycle is proposed, in which a complete learning experience is completed by initially starting with a real experience, reflecting upon that experience, learning and developing new ideas from the experience, and finally testing. Figure 1 contains a graphical depiction of this model. All of the stages feed into the next, and the process is iterative, as the experimentation leads to a new experience to begin again. Research shows including all four parts of the Kolb cycle dramatically enhances the learning experience (33, 34).

First, by constructing a physical prototype, whether using rapid prototyping techniques from CAD data, or from basic sketches, the design team becomes aware of design complications that have not emerged from conceptual discussions or graphical representations alone. Design assumptions in the conceptual phase can become apparent challenges when embodiment takes place. These challenges can either be validated, or reflected upon for redesign opportunities and re-examined concepts (35, 36, 37). In addition, the most valuable component of physical prototype construction is the exposure to “real-world engineering” and the associated non-idealities (38). There often exists a significant difference between the predicted behavior of a conceptual design (and associated functions), and the real behavior of an embodied prototype.

Second, as an experiential learning tool, prototyping is a catalyst for improved and more innovative designs, even as the design process is taking place. Kolb emphasized the importance of concrete experiences in improving specific skillsets, and the importance of testing ideas and receiving feedback. It is in the experimentation phase where prototyping fits, both in developing the design through iteration and validation, as well as in the engineer’s approach to the design challenge. Exclusion of this concrete experience or direct involvement may lead to sterile, recycled solutions (38, 73). Missed observations may lead to uneducated selection of concepts, flawed construction and faulty conceptual frameworks. Finally, by failing to actively validate prototypes through experimentation, the design team may never discover innovative solutions, and may remain in a conceptual rut (39).

Experiential learning, and knowledge creation, can also be thought of as movement between concrete experiences and abstract conceptualization, reflective observation and active experimentation (40). Engineering knowledge is formed when a designer creates a solution for a particular problem in a specific setting, reflects on those efforts, attempts to fully understand the concept, then modifies the design to accommodate new ideas (34).

1.3 LOW-RESOLUTION PROTOTYPING

Low-resolution prototyping, sometimes referred to as throwaway, low-fidelity, or early-stage prototyping, takes place concurrently or immediately following the ideation phase. Low-resolution prototypes are simple, low-cost representations of initial concepts intended to validate certain features of the design (69, 70). These may be functions, aesthetics, ergonomics, or manufacturing/assembly methods. Many of the design constraints are relaxed for low-resolution prototyping, as the embodiments are constructed from basic materials including wood, foam core board, piping, cardboard or other low-cost materials. Sometimes these initial low-resolution prototypes use a commercial off-the-shelf (COTS) product as a starting point and alter it to show how the new product may look or function. These prototypes are not meant to require a heavy investment of time for the teams either, but rather serve as a stepping stone to furthering the design process.

With the rise of rapid prototyping, it has become much easier for designers to convert a CAD design to a physical representation. Methods such as fused deposition modeling (FDM, known colloquially as 3D printing) printers, selective laser sintering (SLS), as well as computer numerical control (CNC) cutters, mills and lathes are often used. Access has even expanded to undergraduate engineering curriculums, with many programs offering free access to all of these systems. (74)

The ability for a designer to embody a virtual prototype in minutes has tremendous value for communicating design intent to both other team members as well as potential customers and end users. The rapid nature of this production also allows for easy iteration, a valuable avenue as many problems surface with early-stage prototyping.

1.4 HYPOTHESIS AND THESIS ORGANIZATION

Based on literary review and research, the use of low-resolution prototypes provide a clear benefit to designers. This research aims to show:

If the prototyping process is initiated during the ideation phase, a greater number of concepts will be generated. Additionally, a clear prototyping strategy for early-stage physical prototypes immediately following concept generation results in a more efficient product design cycle.

The second chapter of this thesis describes a study that was performed to demonstrate the effect of physical design tools during the ideation process. Teams were provided with basic building materials and tasked with generating solutions to an open-ended design challenge. These teams' results were then compared to teams who completed ideation solely using verbal and graphical forms of communication.

Chapter three describes a longer-term study in which student teams were provided guides for both making prototyping decisions and evaluating low-resolution physical prototypes. The motivation for this study stemmed from a lack of concrete methodology practiced by engineering design teams. The design guide was created to assist in analysis and awareness of critical decisions required during the low-resolution prototyping process. In conjunction, the evaluation guide was provided to teams to assess how well the constructed prototype met design objectives, and how it compared to concepts developed in parallel. Both the design and evaluation guides were provided to be used after concept generation had occurred, and were intended to enhance final design success. This is in contrast to the study covered in Chapter 2, which utilized physical prototyping as an ideation aid.

The research has been constructed to evaluate the outcome of increased usage and implementation of low-resolution prototyping in the early phases of the engineering design process. By examining the effects on both concept generation and low-resolution prototype development and evaluation, design teams can now start to more comprehensively understand how early-stage prototyping is beneficial to final product success.

Chapter 2: Design Fixation Mitigation through Ideation with Physical Prototyping

2.1 EXPERIMENT MOTIVATION

In developing an effective strategy for low-resolution prototyping in the product design cycle, an apparent benefit is the use of physical artifacts and materials as the designers develop and evolve their concepts. Designers use physical representations to overcome limitations in memory capacity (41, 42), to effectively represent and communicate concepts (43, 43) and to explore alternative solutions (45, 46, 47). Prototypes give designers a means of communicating concepts and opinions, and embodiment often elicits information about the design context that does not exist in the designer's head (30).

Following in the theme of physical manifestations giving rise to inspired design solutions and improved communication, an experiment was developed to test the concept generation and low-resolution prototyping outcome when engineers have access to basic materials during ideation. Our study seeks to determine if the presence of physical artifacts during concept generation promotes creativity and active communication, thus leading to more innovative solutions and a better performing low-resolution prototype. Jang and Schunn studied this topic with undergraduate engineering students (5). They observed, over the course of a semester-long design class, the use of physical prototyping tools by the teams. Their results suggest that the prevalence of physical manifestation of design concepts was highly dependent on materials provided to the students. A related study was conducted at Stanford University (30). Once again, undergraduate engineering students were tasked with completing a design challenge, but in 40 minutes in this study. The results show that designers who were encouraged to iterate on their designs scored much better, as opposed to those who only constructed a single iteration after the conceptual design.

2.2 DESIGN FIXATION

As discussed earlier, the use of physical prototypes can be effective in expanding the design space during concept generation. Design fixation occurs when a designer creates a new product or solution only with features similar to an existing design they have been exposed to (12, 48, 49, 50, 51, 52, 53, 54, 55, 56, 57, 58). The most challenging aspect of design fixation arises from the associative nature of human memory. Designers often think of a common or successful example solution which is currently on the market when tasked with a new design challenge. Design instructors often report that students commit to the first concept they develop (53). Much of concept generation methodology is developed to expand the design space, and to create possible design solutions which may branch into less apparent avenues. Design-by-Analogy (DbA) (59, 60) is a method which challenges design teams to form connections across different design domains, in which specific product functions may be shared. DbA therefore has potential to mitigate this fixation.

An important component of design fixation is that the engineer is rarely aware of being beholden to a constrained design space (53, 61). Associative memory leads designers to solutions they have been exposed to before (63). By operating within a spectrum of concepts subconsciously replicating prior designs, innovation is hindered.

2.2.1 Relevant Studies in Low-Resolution Prototyping

Several related studies examine the use of low-resolution prototypes as a ideation and design fixation mitigation tool. Jang and Schunn (5) tracked upper-level engineering students from a variety of disciplines throughout a product realization course. Students self-reported on usage of different artifacts, including computers, notes, SMART boards (data recording whiteboards) and physical prototypes, throughout the design process. Student teams' products were then rated for success at the end of the term by their respective professors. One clear result was teams that employed tools which promoted collaborative work more often produced more successful deliverables. SMART boards and physical prototypes "promoted productive group discussion with accurate and flexible updating of a shared mental model…" (5). Second, late adoption of prototyping was a trademark of unsuccessful teams. Lastly, teams shared design experience associated with the use of various tools. The study verified that students with industry experience understand the value of collaboration.

Youmans investigated whether physical prototyping was an effective tool for avoiding design fixation (12). The basis of this study was the hypothesis that designs employ prototypes to ease the mental workload and cognitive burden of complex conceptual designs. He also investigated whether designers working in groups to produce physical representations provided another avenue in design fixation avoidance. In this study, participants were exposed to a poor example solution prior to beginning a design task. Participants who were able to work in a full design environment (access to physical prototyping tools during conceptualization) performed much better in avoiding the design flaws present in the example. This result, however, conflicts with other research suggesting that through physical prototyping, designers can become fixated on their own designs. The investment of time and financial resources may lead a team to latch onto a particular solution, even when there is feedback showing it may not be optimal (8,9).

In a similar study conducted by Viswanathan and Linsey (65), one group of students was presented with an exemplary product which served the design task, and another group received a poor example of a design solution. The hypothesis was once again that when engineers design and test physical representations, they will discover flaws in the design caused by the fixation on negative features and resolve them. Once again, the results showed that teams who validated their designs through physical testing became aware of flaws adopted from the example solution. They were able to address and alter these, thus avoiding fixation on the provided model.

In a study of idea generation techniques, Linsey found that use of graphical representation during ideation produced a higher number of concepts than using words alone (64). It was also shown that the highest number of concepts produced during a given session occurred with techniques utilizing individual work (6-3-5, gallery viewing) as well as group collaboration (brainstorming). Both of these components in unison yield a greater number of concepts, as team members are able to generate ideas alone, then use them together to "spark" new solutions.

The 6-3-5 (or C-Sketch) method is a concept generation method in which six (signifying '6' in 6-3-5) participants are each given a large sheet of paper and different colored pen. They are then allowed time to individually draw three (the '3') concepts (71). After the set time, the papers are rotated and the next team member adds on or modifies the original sketch. This continues four additional times (for '5' total rotations). Finally, time is provided at the end for team members to discuss and explain their ideas, as well as work out modifications which occurred during the rotations. The 6-3-5 method allows team members to work independently to avoid bias by other group members. However, the process of rotating the sheets allows them to become inspired and build upon other team members' designs. A critical component is the discussion immediately following the graphical ideation. Team members are able to work as a cohesive unit to explore designs generated during the process. Another benefit of 6-3-5 is that it allows for an efficient concept generation session in only 30-60 minutes.

Brainstorming as used for this study consisted of very loosely constrained free-flowing ideation. The teams were asked to choose one moderator who would record ideas and serve to allow all members an opportunity to participate in sharing their ideas. It was reinforced that during this stage, no ideas are "bad ideas" and the goal was to generate a high number of concepts. Team members were allowed to communicate orally as well as graphically on paper provided.

2.3 METHOD

In this study undergraduate engineering students from the Department of Mechanical Engineering at The University of Texas at Austin were grouped into teams of four and divided into one of four experimental conditions. The goal was to test the effects of not only use of physical artifacts throughout the ideation process but also which concept generation method produced the highest number of concepts.

The design task had four conditions:

- Groups who used the brainstorming method in conjunction with physical artifacts and graphical tools during concept generation.

- Groups who used the 6-3-5 method in conjunction with physical artifacts and graphical tools during concept generation.
- Groups who used the brainstorming method and graphical tools during concept generation but no physical artifacts.
- Groups who used the 6-3-5 method and graphical tools during concept generation but no physical artifacts.

The following hypotheses were tested:

- Groups who have access to physical artifacts during concept generation generate both a higher net number of concepts as well as a high number of more innovative concepts.
- Groups using the brainstorming method produce a greater number of concepts during the initial generation period.
- Groups who generate a higher number of net concepts perform better during the embodiment stage of the experiment.

In this experiment, the control groups worked through the concept generation phase of the experiment using exclusively graphical and oral methods of communication. The experimental group had access to basic physical artifacts, and were informed these were exclusively for use during concept generation. Both groups then worked through an embodiment phase in which they were required to construct one of their solutions to complete the design task.

2.3.1 Materials and Design Task

For this study, the design task was developed to lend itself to two conditions: the ability for a broad range of design solutions to be generated, and the ability for one solution to be embodied and tested in a very short timeframe (approximately 30 minutes in an activity that would last 1 hour total). Also, avoidance of common engineering challenges was critical so that students who had attempted the challenge before would not have an unfair advantage. Examples of these include an egg-drop experiment or a load-bearing bridge made from thin wood sticks or paper. Also, the design task should lend itself to a broad range of solutions, meaning there was not one clear "best" answer. A design task that could be approached from many different energy domains and was novel, and therefore did not have an exemplary solution already on the market, was selected.

The study was divided into two distinct phases: a concept generation phase (Phase 1) and an embodiment phase (Phase 2). The students were not informed of Phase 2 until the completion of Phase 1.

The student groups were tasked with designing a system capable of moving a ping pong ball down an 8 ft. wide tiled hallway (such as those in the Engineering Teaching Center on The University of Texas at Austin campus). The following constraints were imposed during the concept generation phase:

- The apparatus must begin fully behind the "start" line.
- The measurement for distance was taken when the ping pong ball either directly touched the ground or stopped moving.
- The ball could not be propelled *directly* with human energy. This was clarified with the explanation that human energy could enter the system, but the constraint was meant to avoid such solutions as simply throwing or kicking the ball.

No further clarification was given on resources available, time, budget constraints, or methods for propulsion.

During the concept generation phase, the control groups were provided exclusively with six sheets of 12”x18” butcher paper (for recording ideas, not for prototype construction), 4 colored pens, and a concept documentation form. The experimental groups were provided with identical materials as the control group, as well as a wide variety of physical artifacts they could use as they saw best fit. Because the concept generation period was constrained to a short timeframe, the materials were selected to accommodate quick and efficient concept embodiment. The chosen materials could quickly be coupled together, as well as combined to form a wide range of design solutions. A toolkit consisting of a broad range of supplies that can easily be combined and changed allowed the teams to embody mental images and convey them to other teammates. The goal in this phase was not complete functionality, but physical representations improving information flow and inspiration.

With this in mind, each experimental group was provided with a set of K’NEX® (K'NEX Industries, Inc., Hatfield, PA, USA) assorted building materials, modeling clay, rubber bands and wooden dowels. These materials can be seen in Figure 2. The K’NEX® set consisted of assorted lengths of plastic rods and a mixture of different types of rod connectors. Also included in the set were plastic pulleys, wheel rims, and rubber tires. These are fast and easy to join and take apart, and many students are familiar with materials from previous use. The modeling clay also served to affix materials together, or to be formed into more complex shapes which the linear K’NEX® and dowels could not accommodate. Finally, the rubber bands came in various lengths and thicknesses.

The quantities of each material given to the teams was sufficient for quick model-building, but not enough for them to expand into full scale embodiments. This decision was made in an effort to maintain the focus on concept generation.

Figure 2: Ideation physical materials.

Though the students were not given details of the second phase of the experiment, they were encouraged to use the physical materials as a communication aide and source of design inspiration, rather than to focus on building a functional prototype during Phase 1. Avoidance of large amounts of time committed to building functional models was important, as the quantity of concepts generated in the initial phase was the explicit priority.

In Phase 2, all teams had access to the same material built kit, which consisted of expanded and more robust materials than the experimental teams used in Phase 1. Materials were selected to once again provide a broad range of possible design solutions. In Phase 2, all teams were provided with: ½" PVC pipe cut to 3 ft. lengths, corner and

“T” PVC joints, assorted bungee cords, duct tape, twine, 2 oz. clear plastic cups, and square wooden dowels. These materials can be seen in Figure 3. Teams were also provided with 4 ping pong balls (Figure 4) for testing. Experimental groups had to return their supplies from Phase 1, as now all teams had access to the same set of materials for system construction.

Figure 3: Construction materials for phase 2.

Figure 4: Ping pong balls.

2.3.2 Participants

The participants for this study were all fourth-year mechanical engineering students at The University of Texas at Austin. These students have had both formal exposure as well as practical application of the concept generation methods used in this study (brainstorming and 6-3-5). All of the students were enrolled at the time of the study in an introductory design methodology course, which is a prerequisite for the semester-long capstone design course. A total of 80 students volunteered for the study, with participants receiving course credit for participating. The 80 students were divided randomly between the experimental and control groups, as well as between the two concept generation techniques.

In the design methodology course, students are organized into groups to complete a semester-long product redesign project. There may have been groups which had previously worked with one another, and others who were meeting for the first time.

This was not explicitly controlled. During the study, students were assigned to teams based on order of appearance. Because this was consistent for all students arriving at the study, the likelihood that group members had worked together before was likely consistent between the control and experimental groups.

2.3.3 Procedure

To successfully address both of the experimental hypotheses, a novel design task was developed with the potential for a large number of design solutions that could be constructed and tested in a short period of time. There was a strict one-hour time limit on the study.

2.3.3.1 Pilot Experiment

In preparation for the study with the undergraduate students, two pilot experiments were conducted to test procedures and gain feedback on the design task. These pilot studies were conducted with graduate mechanical engineering students who had exposure to the concept generation techniques. They filled out a brief survey at the end of the experiment, asking for comments on the time allowed and the adequacy of the prototype materials provided.

Originally, the students were tasked with moving a US quarter coin down the hallway, but this proved very dangerous. Also, in the first pilot experiment, the team affixed their system to the ground using copious amounts of duct tape, as well as supporting it with their own bodies. Allowing for fixturing to walls and the floor narrowed to the design space to mainly catapult and slingshot solutions. Feedback from the students indicated that allowing these method leads to a simple slingshot as the clearly optimal solution. A photograph of a solution from the pilot study is shown in Figure 5.

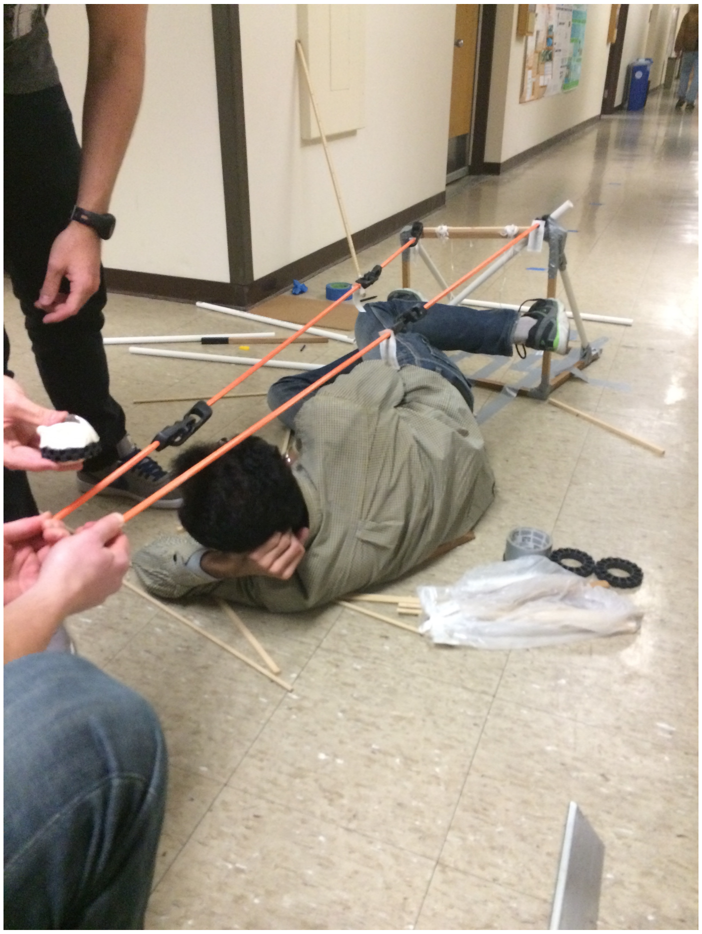


Figure 5: Pilot experiment testing.

In the subsequent pilot experiment, modifications were made to time allotments for both the concept generation phase as well as the construction phase. Limited to one hour, concept generation was shortened from 30 minutes to 20, allowing for a full 30 minute construction period. Organization of the students and materials, and providing directions all had to be accomplished during the actual implementation. Feedback from the graduate students showed that around the 15 minute mark during Phase 1, the focus began to shift from concept generation to selection. This was not the goal, so limiting

Phase 1 to 20 minutes allowed the team to more concretely focus on generating as many solutions as possible.

2.3.3.2 Experimental Study Procedure

The experiment was conducted in two sessions based on the class section the students attended. The participants were divided into groups of four based on arrival time, and half of the groups were directed to an adjacent room. In the first session, both the control and experimental group used brainstorming during the concept generation phase. In the second session, both the control and experimental groups used the 6-3-5 technique.

With the participants organized into their groups, directions for Phase 1 were read aloud. The teams were given 20 minutes to generate as many concepts as possible. These were recorded on a provided form. The participants were asked to keep the concept representations brief, with very brief written description if needed for differentiation.

The design task as read to the participants was:

> Develop a system to move a ping pong ball as far as possible. The entire system must not extend past a starting line and distance will be measured from this line. The following constraints apply:
>
> 1. The ping pong ball cannot directly touch the ground.
> 2. Movement cannot be "directly" powered by human (i.e. throwing ball, kicking ball, etc.)"

At the conclusion of the first 20 minutes, all teams submitted their forms. Then directions were read for Phase 2. In this embodiment phase, the teams were provided with the building materials and shown the testing area, which consisted of a starting line and lines designating every 3 feet. The oral instructions to the participants were:

> In the second part of today's experiment, you will be provided with basic materials and tasked with constructing one of your designs in 30 minutes. The challenge is still the same, to move a ping pong ball as far as possible from a starting line. However, there are some additional constraints:
>
> 1. The system must be self-supporting.
> 2. The system may not attach to anything in the room and should be easily moved.
> 3. The ball cannot be permanently modified in any way.

Students were then left to construct a concept of their choosing. They were able to test their systems at any time, and to complete as many iterations as desired. Each attempt was to be recorded on a provided form.

The experiment was conducted in exactly the same way for both sessions, save the concept generation method used during Phase 1. In the first session, both the control and experimental groups used the brainstorming technique. In the second session, both the control and experimental groups used the 6-3-5 technique.

For the teams using 6-3-5, guidance was given on how to best manage the 20 minute timeframe. They were advised to do three rotations of sketching, the first five minutes in length and subsequent two rotations each 3 minutes in duration. During the concluding nine minutes, the groups were asked to rejoin and discuss the concepts they had developed, with one group member recording concepts on the provided form. It was during this time that the experimental group utilized the physical artifacts provided to them.

2.4 OBSERVATIONS

Within the four-person teams, it was often the case that not all of the members engaged with the physical artifacts during concept generation. More often, one or two team members began constructing and discussing concepts, while the others listened or worked graphically. Small-scale basic models were quickly constructed and deconstructed, and often led to tangential concepts based on initial design inspiration. Figure 6 below shows one team utilizing the materials during concept generation.

Figure 6: Participants utilizing materials during concept generation.

The most commonly used artifacts were the K’NEX pieces. Several possible explanations for this are the inherent integrity of the connectors and joints, the ability to quickly assemble basic forms, or familiarity by participants. Though the groups were informed that the models constructed during the concept generation phase would not be tested, many of them gravitated towards embodiments which could become functional with further work. This is to say, very few “form” or aesthetic concepts were embodied, based on the materials used.

For the groups instructed to use the 6-3-5 method, interaction with the physical artifacts was reduced. By following the prescribed schedule for sketching and rotating, there were only 9 minutes available for idea communication and recording. A portion of this time was used to decipher the sketches, and to orally communicate what had been contributed to the graphical representations.

As stated earlier, all participants had prior formal instruction as well as practical application of both concept generation methods. While 6-3-5 is not as well-known as brainstorming, the students possessed a sufficient understanding of the method. They were able to effectively employ the method during Phase 1. See for example the 6-3-5 output in Figure 7.

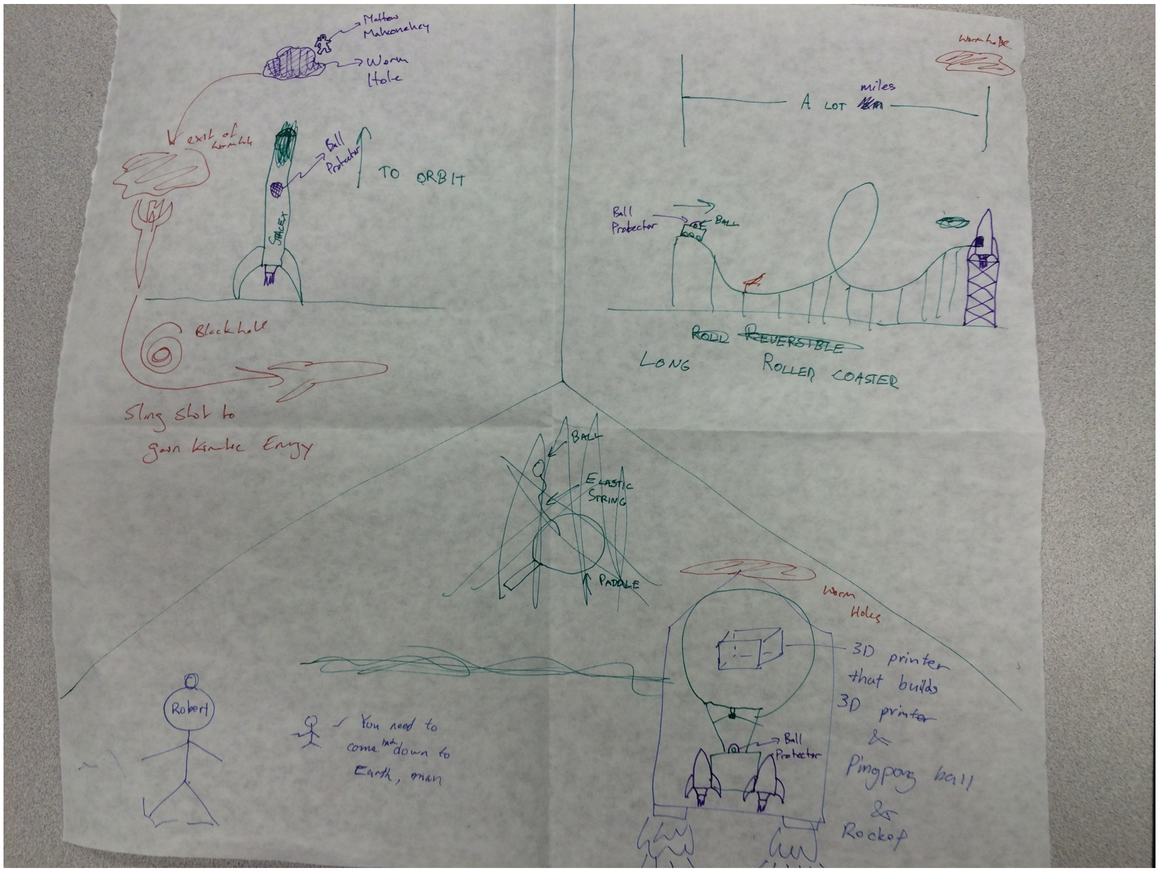


Figure 7: Example of one participant's 6-3-5 sketches after three rotations.

2.5 RESULTS AND DISCUSSION

Using the submitted forms following Phase 1 and Phase 2 of the study, results were compiled using objective measures. The metric analyzed was the quantity of concepts produced, as generation of a broad design space has been shown to lead to a higher likelihood of innovation (1). Records for attempts and distance were self-reported by the teams for Phase 2 of the study. Statistical analysis was conducted using a two-tailed Student's t-test.

2.5.1 Influence of Physical Artifacts on Concept Generation

First, results were analyzed with both Phase 1 concept generation methods combined. The hypothesis was that groups with access to physical artifacts would generate a higher number of concepts. As seen in Table 1 and Figure 8, results from the concept generation phase display a statistically significantly higher number of concepts generated by the groups with access to the physical materials during ideation (p = 0.0431). The data provide clear evidence that participant teams who used the set of physical artifacts generated more concepts during the concept generation phase, regardless of the ideation method used.

	Concepts	**Max.**	**Min.**	**Std. Dev.**
Control (no physical artifacts)	15.50	29	5	6.92
Experimental (physical artifacts)	21.63	30	14	4.75

Table 1: Combined results from phase 1.

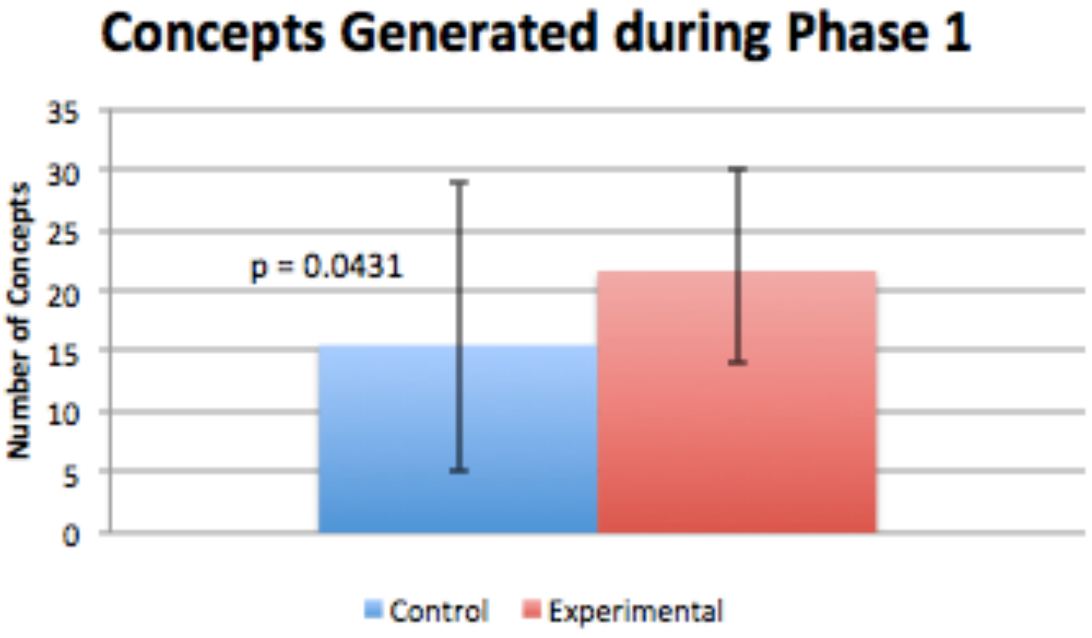


Figure 8: Combined results from phases 1 and 2.

Analysis of the results by ideation method during Phase 1 indicates that the brainstorming control group generated a significantly higher quantity of concepts than the 6-3-5 group (Figure 9). Limitation to oral and graphical communication may have led to the brainstorming group to work more efficiently during Phase 1. Due to recent exposure to the 6-3-5 method before the study, participants may have felt more comfortable with the unrestrictive nature of brainstorming. In addition, the 6-3-5 method was run on a shortened time schedule, as normally each rotation would be allowed a full five minutes and team members would be provided the opportunity for each concept page to complete a full rotation.

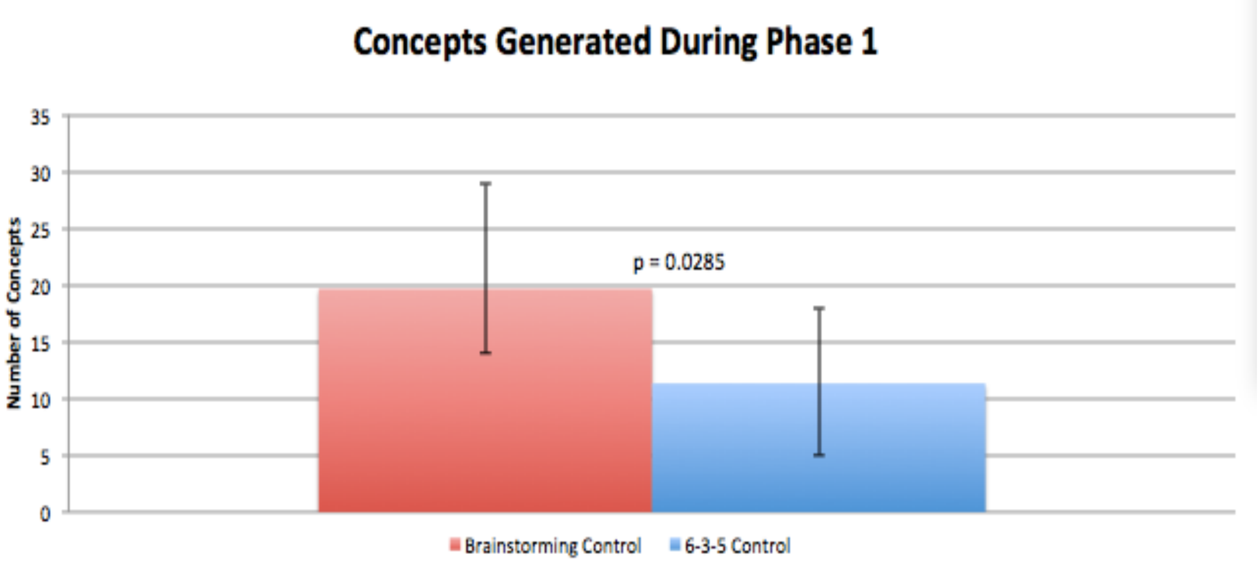


Figure 9: Phase 1 results from control groups.

No statistically significant difference was shown for the number of concepts generated between both groups with access to the physical toolkit. Both groups using the brainstorming method as well as the 6-3-5 method generated a similar quantity of concepts (Figure 10).

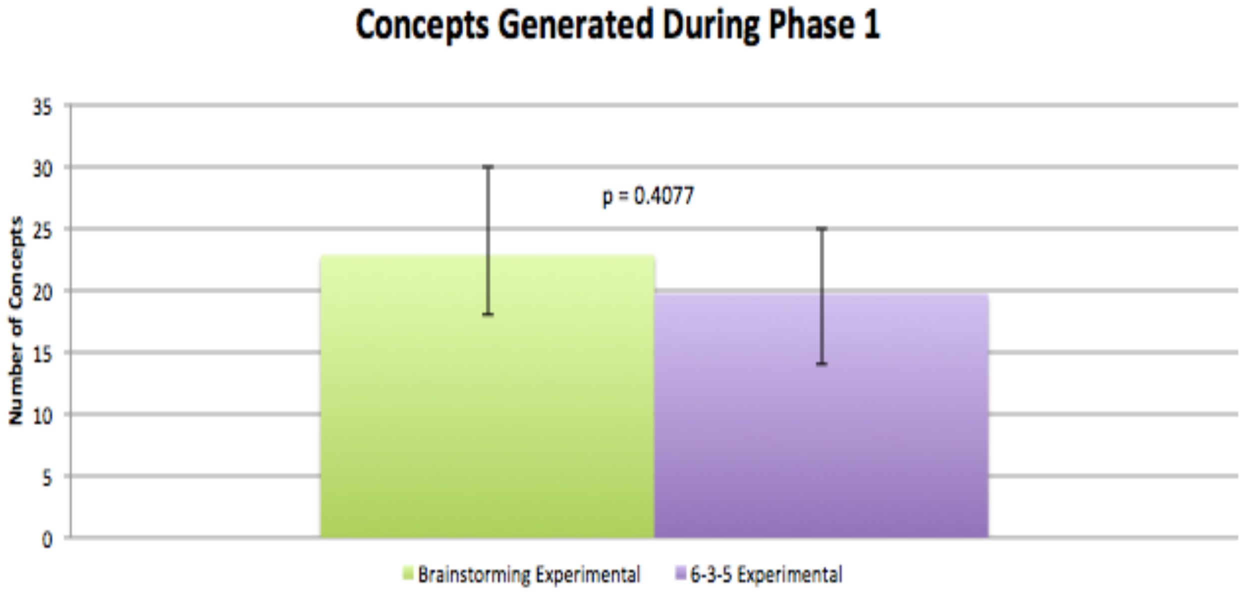


Figure 10: Phase 1 results from experimental groups.

Finally, the ideation methods were isolated and experimental and control groups were compared against each other. Once again, though the experimental groups proved to generate a higher number of average concepts, the difference was not statistically significant (Figures 11 and 12). This may be attributed to limited sample size, and further experimentation is recommended to more fully explore this question.

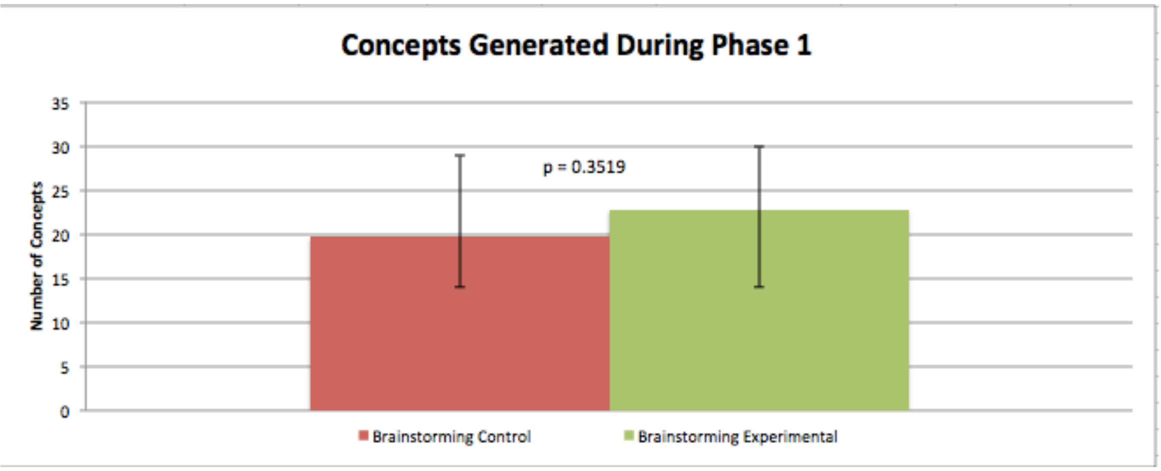


Figure 11: Results from brainstorming groups.

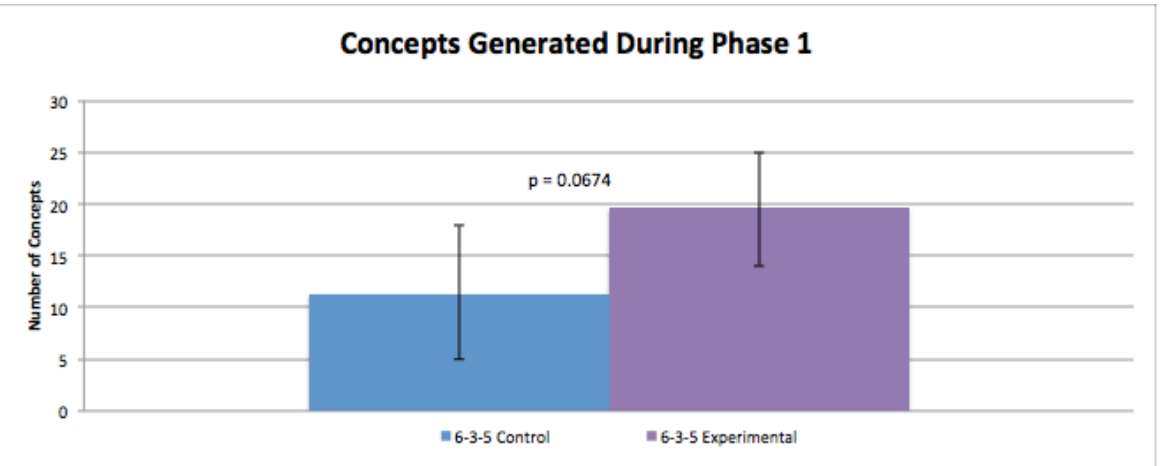


Figure 12: Results from 6-3-5 groups.

To summarize, when experimental and control groups were separated, a statistically significant improvement was not shown in the distinct ideation groups. When combined, a statistically significant improvement was seen for both ideation methods together when teams had access to physical materials during concept generation. One explanation for this is the relatively small sample size. For example, the experimental group for the 6-3-5 technique consisted of only 3 teams (12 students). However, out of these three teams the highest performing group in terms of maximum launch distance emerged (40ft.). Also, the variance in performance among these three teams was very large.

When ideation methods are combined for statistical analysis, an improvement is shown for teams with access to physical modeling tools, but further research is needed with more subjects to validate results. A statistically significant improvement for each ideation method independently is a possibility with a larger number of teams in future studies. It is important to note that analyzing both ideation methods together showed statistically significant improvement from teams who did not have access to physical materials compared to those who did.

2.5.2 Influence of Physical Artifacts during Concept Generation on Physical Embodiment Performance

By first analyzing the maximum distance travelled by the ping pong ball when launched by each team's embodied system, it can be seen that groups with access to physical artifacts during concept generation performed better (Figure 13). The systems developed by experimental groups reached a distance of 7.98 ft. further than the control groups (Table 2).

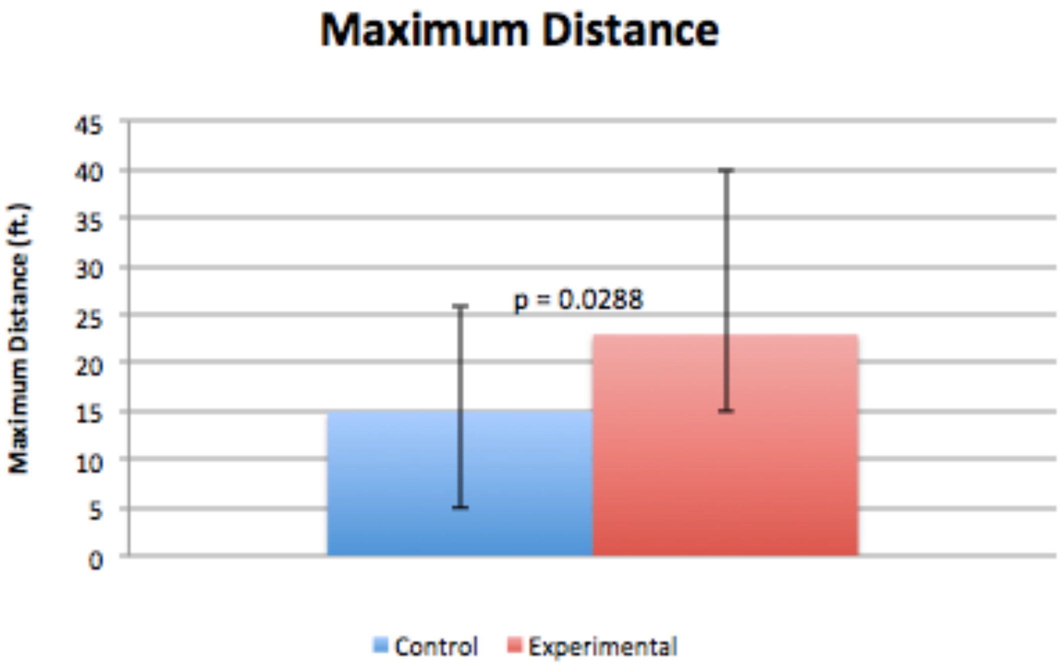


Figure 13: Phase 2 maximum distance results.

	Average max. Distance (ft.)	**Max.**	**Min.**	**Std. Dev.**
Control	14.96	25	5	6.93
Experimental	22.94	40	15	7.98

Table 2: Phase 2 maximum distance results

There was no statistically significant difference between the control and experimental groups for the number of launch attempts during Phase 2 of the study (Figure 14). Due to the limited time groups had for embodiment during Phase 2 (30 minutes), testing multiple concepts was not conducive to completion. Teams selected one of their concepts and after a test, made incremental modifications. Also, prolific testing did not have an effect on maximum distance (Figure 15).

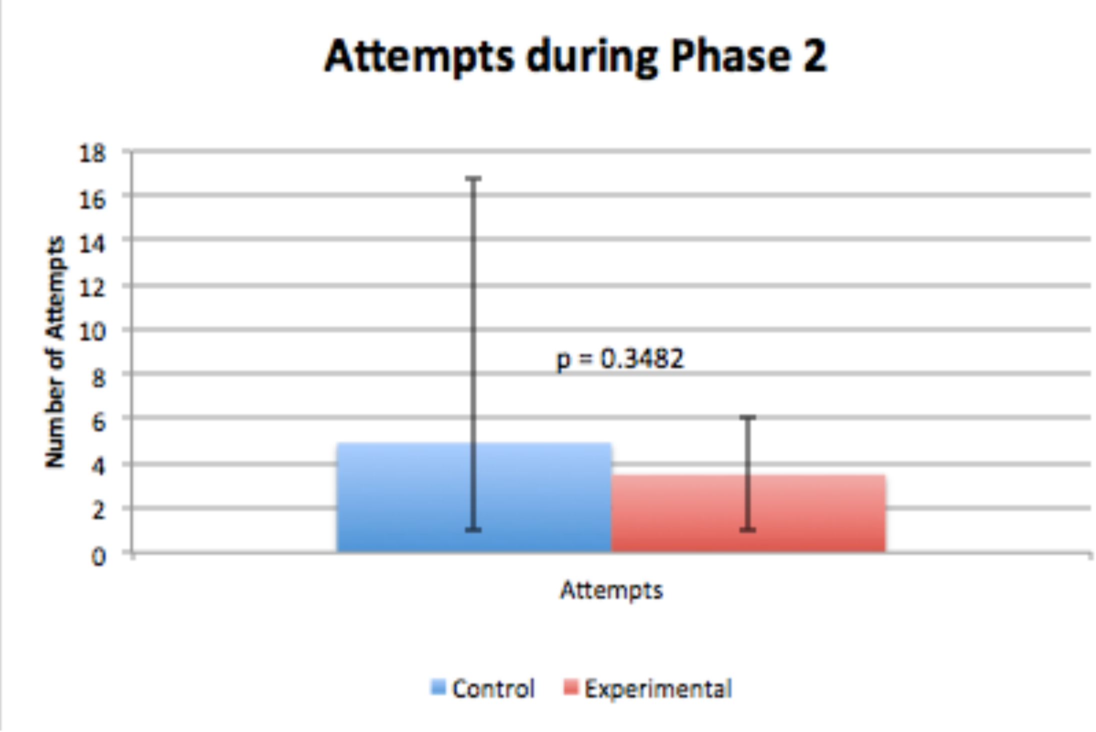


Figure 14: Phase 2 attempts results.

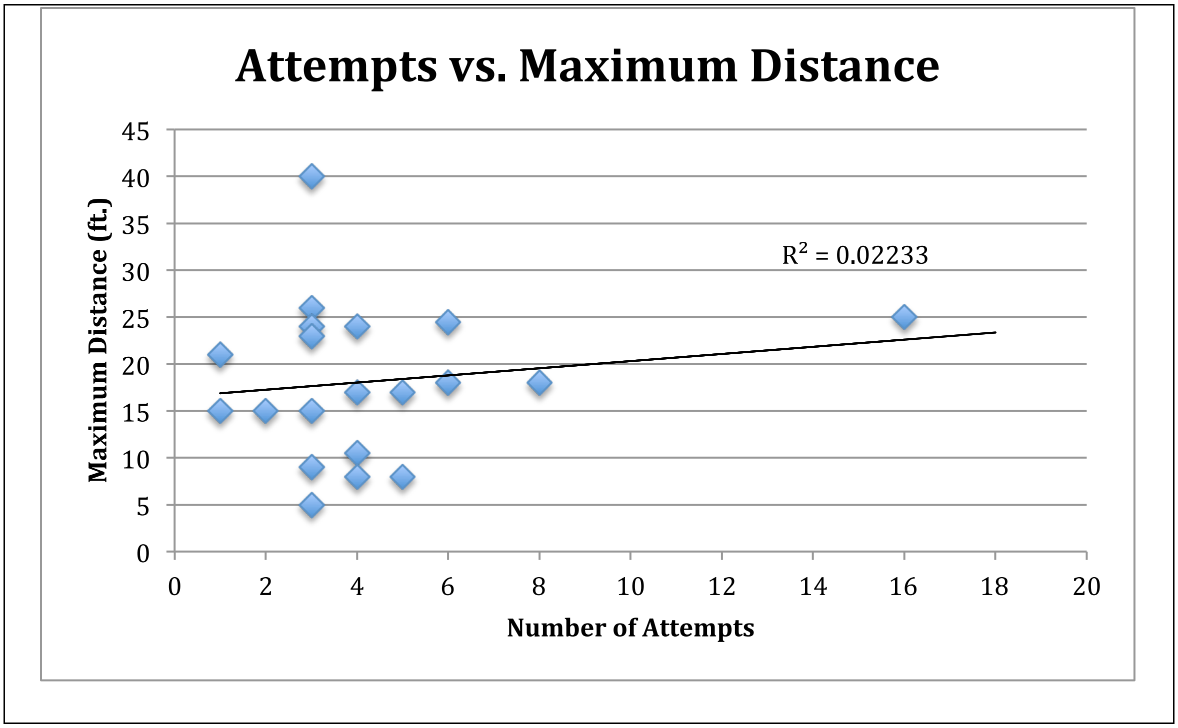


Figure 15: Attempts vs. maximum distance for phase 2.

2.5.3 Influence of Concept Generation on Physical Embodiment Performance

By comparing the number of concepts generated by a team with their final value for maximum distance, it was possible to deduce if teams that generated a higher number of concepts performed better. This however, was not the case (Figure 16). There was very little correlation between the number of concepts generated and maximum distance ($R^2 = 0.0114$). The data in this case is not a good fit for a linear line of best fit. One explanation is that teams using the physical artifacts during ideation exited that phase of the study with a more concrete shared mental image of possible embodiment solutions.

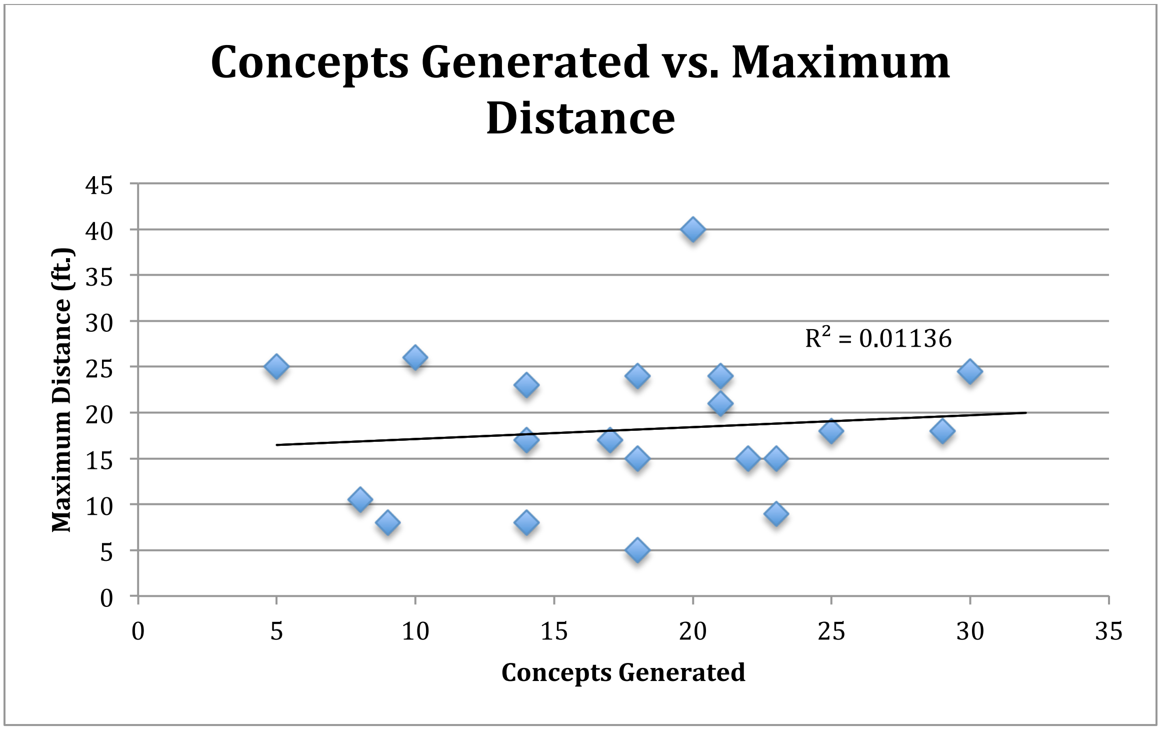


Figure 16: Number of concepts generated vs. maximum distance.

When experimental and control group data were separated, neither shows a strong correlation between the number of concepts generated and the maximum distance (Figures 17 and 18). However, a positive slope is displayed on with the trend line for the experimental group.

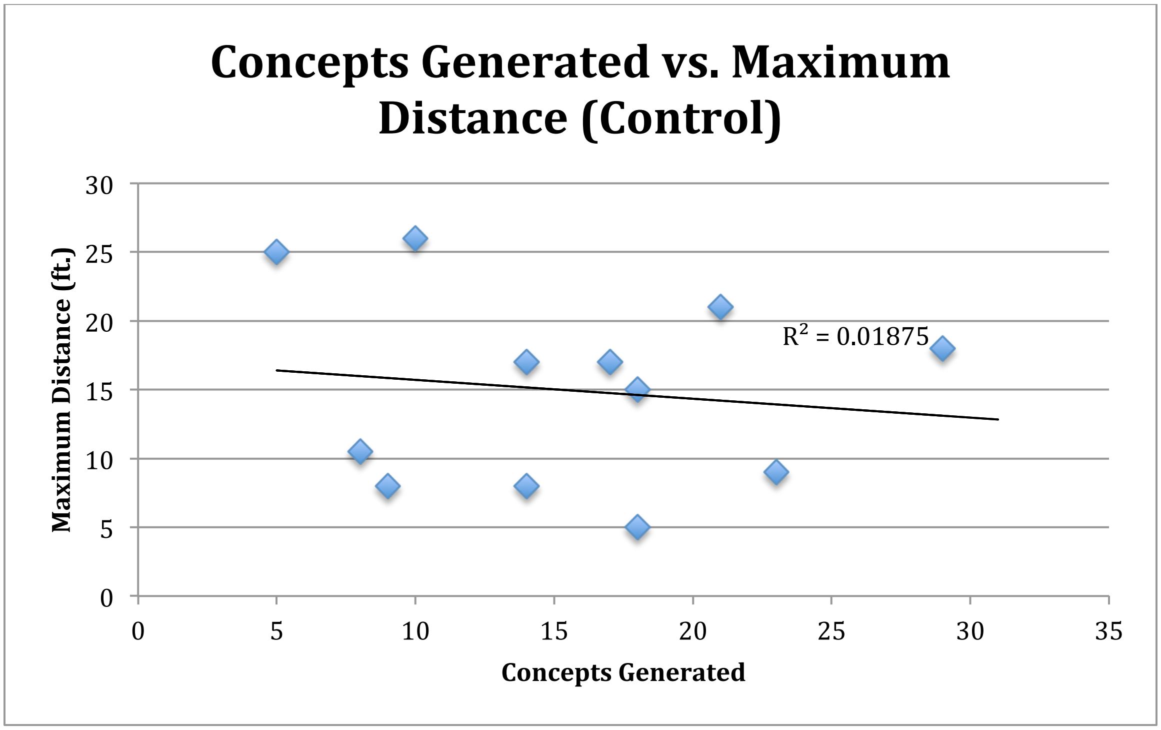


Figure 17: Control group concepts generated vs. maximum distance.

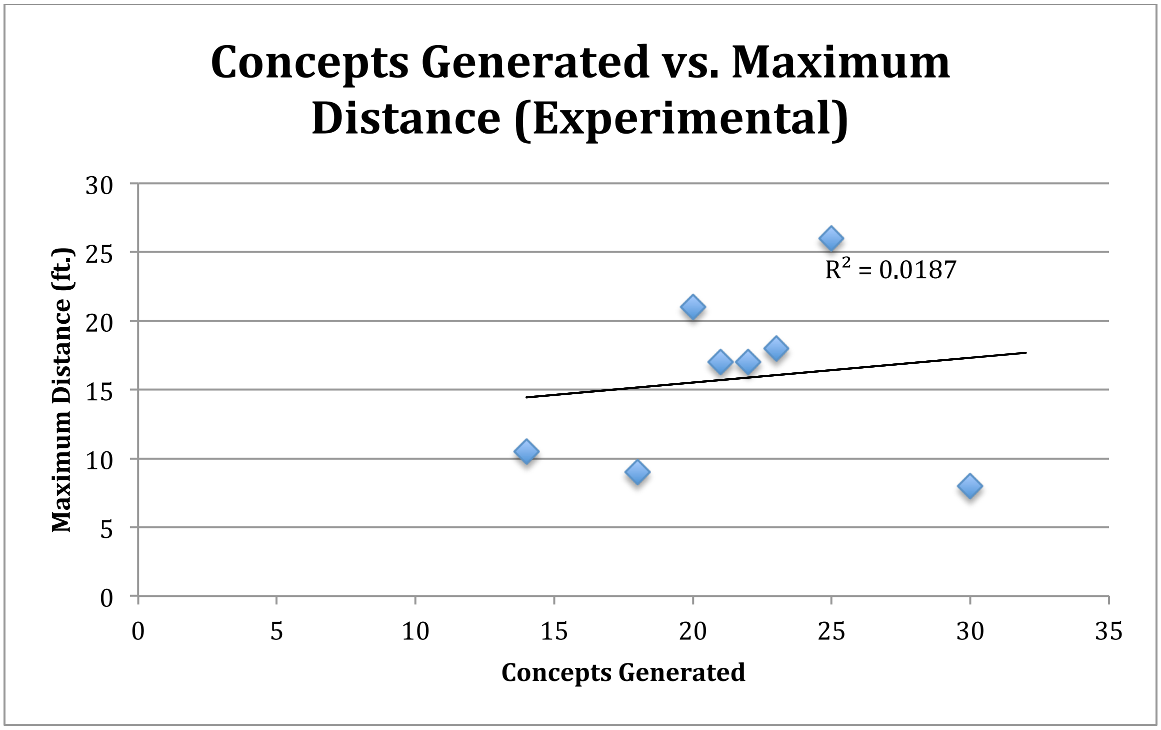


Figure 18: Experimental group concepts generated vs. maximum distance.

2.6 PARTICIPANT EMBODIED SOLUTIONS

During the 30-minute embodiment phase of the experiment, many of the teams decided to employ a slingshot system to propel the ball down the hallway. With the diversity of ideas created during Phase 1, it was interesting to see such convergence during prototyping. While there were adaptations such as guidance rails for the ball, many designs consisted of a pouch affixed to two bungee cords, which were then affixed to a base constructed of PVC pipe. One rather innovative solution was a system in which a wooden rod was loaded elastically into a PVC guide tube, with the ping pong ball loaded at the end. The rod was released, accelerating up the tube and impacting the ball, causing both to fly down the testing area. A second innovative solution was a catapult in which the arm was elastically loaded with wound bungee cords (Figure 19). Both of these approaches were very consistent. Once these designs were finalized, their repeatability was much better compared to other teams. The final 3 launches of the rod solution all landed within 4 ft. of one another, while the catapult maintained the final 3 launches to within 6 ft. While the more common solution produced launches which travelled a longer distance, they were not as consistent. Students who generated more innovative ideas (other than a catapult or slingshot) seemed to invest more in the proper design of their final system, leading to a more robust and consistent solution. The rod solution provided an unusual approach which was very repeatable and allowed the team to launch quickly and with very little set-up between attempts (see Figure 19).

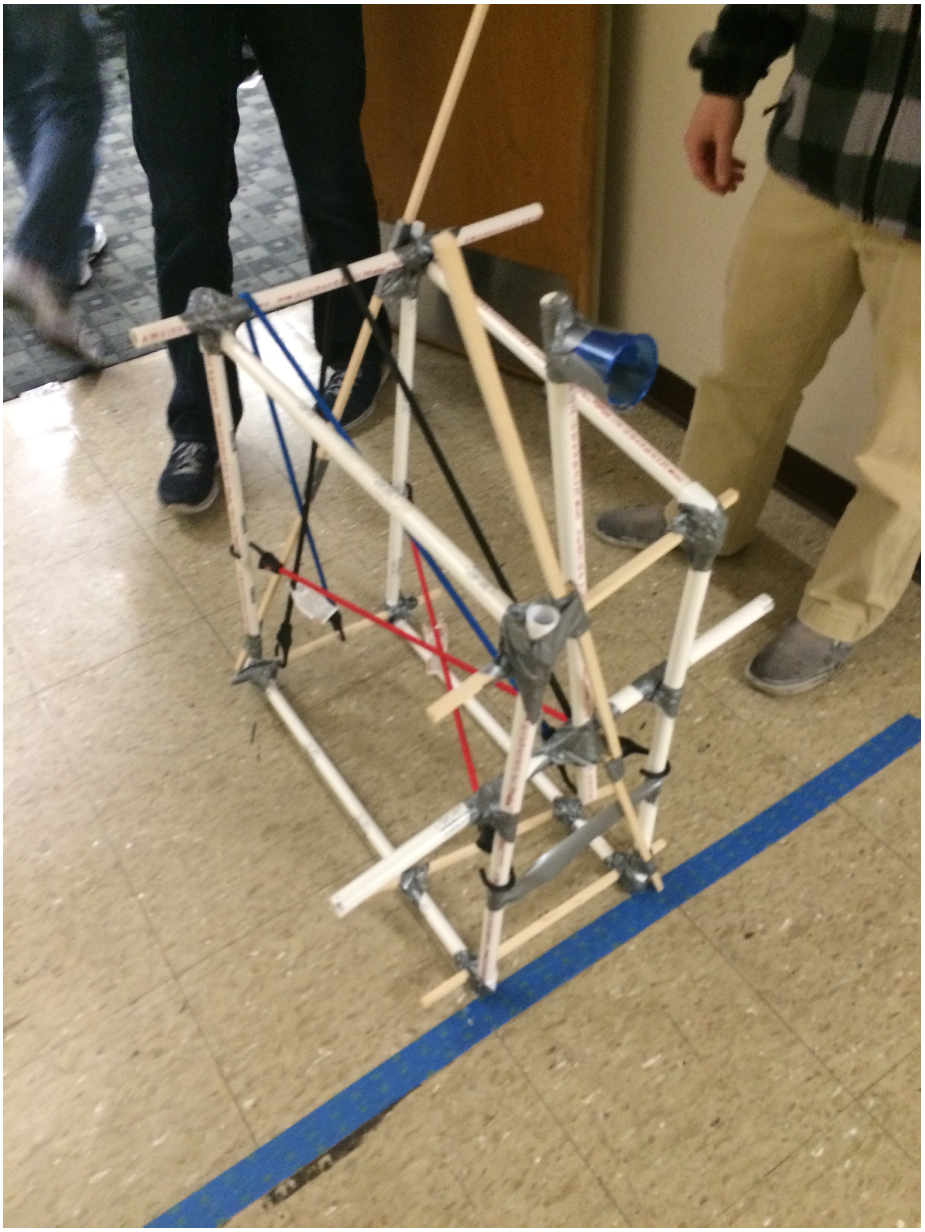


Figure 19: Catapult system.

2.7 SUMMARY

In this study it was shown that teams provided with physical materials to use during concept generation produced a larger number of concepts. In addition, the teams who used brainstorming as an ideation technique, both those with and without physical materials, also produced a higher number of concepts during the ideation period. However, the result for the experimental groups was not statistically significant. This may have been due to familiarity with the method, or the free flow of ideas was better suited for the limited concept generation time.

In addition, neither the number of attempts a team made nor the number of concepts they initially generated correlated strongly with final performance of their systems. The constraint of limited embodiment time could be a possible explanation, as construction and testing had to take place in a short 40 minute window.

The following chapter discusses how the introduction of a more structured approach to low-resolution physical prototyping and evaluating these constructed prototypes affects the design process as a whole. There has been little structured methodology in prior literature to assist design teams in making critical decisions concerning physical manifestations of their initial concepts.

Chapter 3: Low-Resolution Prototyping Design and Evaluation Guide

This chapter describes the development of guides for making prototyping decisions in the early stages of design and for evaluating the resulting prototypes. In the first section, the need for these guides is established. Following this, the design guide and evaluation guide are explained, as well as typical usage in a generic setting. Next, an explanation of the guides provided to undergraduate engineering students is given, with corresponding results from this application. Students were surveyed on both their subjective thoughts on the implementation of the design and evaluation guides, as well as the results of how their early-stage design process progressed.

3.1 BACKGROUND AND MOTIVATION

Undergraduate capstone design teams often struggle through the early stages of the design process, either due to lack of experience or strict budgetary and time constraints. Many teams forgo any type of physical prototyping and validation altogether during these stages (76). This is seen not only at the undergraduate level, but in design teams in a wide variety of scenarios.

Development of guides allowing teams to critically analyze prototyping decisions both during embodiment as well as after, during the evaluation phase, will enable teams to better incorporate low-resolution physical prototyping in the design process. As discussed earlier, physical prototyping leads to an increased understanding of final design outcome (5, 7, 29). Another major benefit is improved communication of conceptual designs. In the Department of Mechanical Engineering at UT Austin, the capstone design class is a one-semester project. Due to the accelerated nature of the course, a short four month window, teams often divide work among the members. This hampers collaboration and can often lead to integration problems later in the process.

Both the design guide and the evaluation guide were intended to be used after the concept generation phase, when one or more concepts had been selected for embodiment. Though iteration and inspiration are intended components of the prototyping process, the team should have already completed initial ideation.

3.2 LOW-RESOLUTION PHYSICAL PROTOTYPING DESIGN GUIDE

The low-resolution prototyping design guide was created for designers to more critically analyze methodology decisions made early in the design process. The guide assists designers in making decisions in several areas with respect to early stage, low-resolution prototyping. The first area for designers to analyze was the product functions to select for validation. Using the method explained by Otto and Wood (71), these functions are derived from identified customer needs. The initial requirement of creating a successful low-resolution prototype is a concrete understanding of which product function(s) will be validated.

The next section of the guide prompts the design team to identify which performance metrics (or design requirements) are associated with the pre-selected product functions. Just as in the final embodiment, these performance metrics can be used to evaluate how effectively the design satisfies the customer needs.

The guide then focuses on prototype architecture. Based on prior research on prototyping strategy guides (72, 77), the designer is asked to address three critical design considerations:

1. Will the prototype be scaled from its original size?
2. Will a specific sub-system of the final design be isolated for validation?
3. Will certain design constraints be relaxed to ease production?

By having the designer directly address these areas, production of a low-resolution prototype may become more time and cost efficient.

The guide then continues by prompting the designer to identify the most effective materials and manufacturing techniques for their prototype(s). Access to rapid-prototyping equipment such as FDM printers, laser and waterjet cutters, and CNC mills provides teams with a broad variety of fabrication options. Engineers are typically trained extensively on CAD design, and the ability to quickly generate physical prototypes these designs has lowered the barriers to production greatly. With a clear perspective on product functions and customer needs the prototype will need to satisfy, as well as discourse on optimal architecture and manufacturing method, the teams are better equipped for implementation of low-resolution prototyping in the design process.

To study the effectiveness of this design guide, it was provided to senior level engineering students who were enrolled in a capstone design course at The University of Texas at Austin. While these students were formally instructed on current approaches to low-resolution prototyping in their prior semester design methodology course, they still lacked practical application of these techniques. Prior to distribution, the benefits of physical prototyping were explained to all the teams. They were also instructed on how the guide could be applied to their particular design challenges. The design guide was developed in a way to provide student teams with guidance while maintaining a broad application for many different design challenges. The guide can be found in its entirety in Appendix A.

3.3 LOW-RESOLUTION PHYSICAL PROTOTYPING EVALUATION GUIDE

As a complement to the low-resolution physical prototyping design guide, the student teams were then provided a tool for evaluating their solutions. Initially, the teams are directed towards analyzing a specific prototype against competing solutions also prototyped in parallel using techniques they learned in the undergraduate curriculum, such as a Pugh chart. The first metric with which to compare competing designs is the degree to which the prototype satisfies the intended customer need(s). They are directed to use quantitative testing, as well as user/customer feedback and surveys.

Following a comprehensive analysis of how well the prototype satisfied intended customer needs, the guide opens a dialogue on any useful functions which may have arisen during the development and testing of the prototype. Very often, important use considerations as well as manufacturing and assembly issues will surface, even with very low-resolution prototyping.

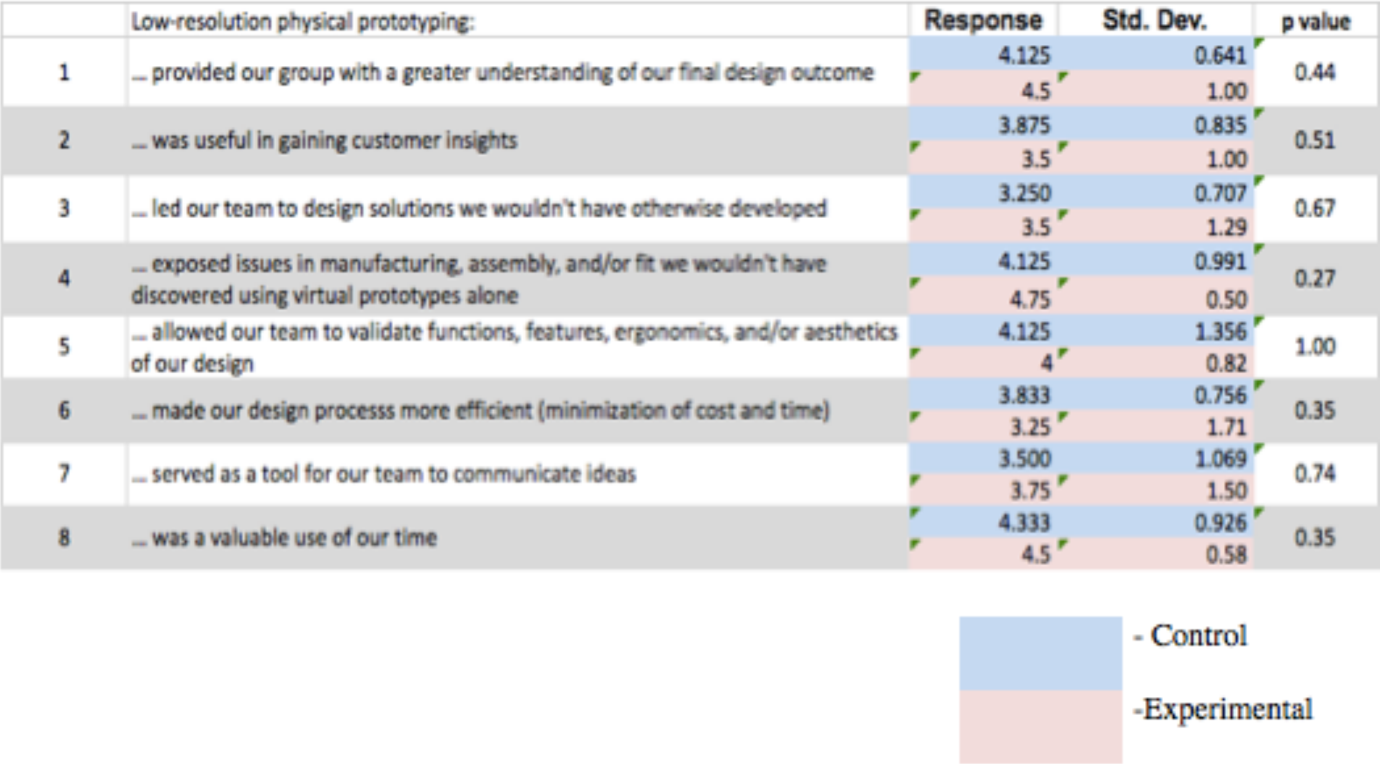
Finally, teams are prompted to discuss whether or not the design solution will be further investigated and iterated upon. Adjustments to the overall design, materials used, and manufacturing methods can all be addressed. Using the physical model as a communication tool for potential improvements allows team members to more effectively share ideas (26, 27, 28, 29).

This evaluation guide was also provided to the same student teams from The University of Texas. They were instructed on best practices for use, as well as how the evaluation guide serves as a complement to the design guide. Also, they were encouraged to approach low-resolution prototyping as an iterative process, as this evaluation guide could lead them to new and improved variations of current ideas they were developing. The evaluation guide can be found in its entirety in Appendix B.

3.4 SURVEY RESULTS AND DISCUSSION

To gain feedback on the low-resolution physical prototyping design and evaluation guides, two groups of senior design students were given surveys to complete immediately following the prototyping phase of their project. The control group was required to complete low-resolution physical prototypes, but was not exposed to the low-resolution physical prototyping design or evaluation guides. The experimental group was provided with both the guides, as well as a brief tutorial on best practices for implementing them.

The hypothesis was that with exposure to the design guide and evaluation guide, student teams would see low-resolution prototyping as a valuable phase of the design process, as they now could approach it systematically. The survey was administered with students answering a series of eight questions, with responses recorded on a Likert Scale (1-Strongly Disagree, 5-Strongly Agree). P-values were once again obtained by running a two-tailed T-Test.



	Low-resolution physical prototyping:	Response	Std. Dev.	p value
1	... provided our group with a greater understanding of our final design outcome	4.125 4.5	0.641 1.00	0.44
2	... was useful in gaining customer insights	3.875 3.5	0.835 1.00	0.51
3	... led our team to design solutions we wouldn't have otherwise developed	3.250 3.5	0.707 1.29	0.67
4	... exposed issues in manufacturing, assembly, and/or fit we wouldn't have discovered using virtual prototypes alone	4.125 4.75	0.991 0.50	0.27
5	... allowed our team to validate functions, features, ergonomics, and/or aesthetics of our design	4.125 4	1.356 0.82	1.00
6	... made our design processs more efficient (minimization of cost and time)	3.833 3.25	0.756 1.71	0.35
7	... served as a tool for our team to communicate ideas	3.500 3.75	1.069 1.50	0.74
8	... was a valuable use of our time	4.333 4.5	0.926 0.58	0.35

🟦 - Control

🟥 -Experimental

Table 3: Low-Resolution Physical Prototyping Survey Results

As seen in Table 3, though student teams (n=29) reported stronger agreement in questions pertaining to understanding of design outcome, an expanded design space, understanding of manufacturing and assembly challenges, use as a communication tool, and value of physical prototyping, none of the results were statistically significant. The hypothesis that teams who used the design and evaluation guides and implemented a structured low-resolution prototyping strategy would find the process more beneficial seems to hold. On a 1-5 Likert scale, teams who used the guides reported a score of 4.5, compared to a value of 4.33 for teams who did not. One explanation for the high score even within the control group is that, during the lecture component of their undergraduate design coursework, the students were taught that prototyping is a critical component of any design cycle. Therefore, they may have felt as though responding that low-resolution prototyping is inherently valuable, with or without a systematic methodology.

An additional observation is teams who followed the guides reported a higher agreement with discovery of assembly or manufacturing issues during low-resolution prototype construction. These teams, through the use of the guides, may have been acutely aware and watchful for these types of issues. As discussed in Chapter 1, often complications with embodiment become apparent quickly even though the conceptual design may have seemed sound (7).

3.5 SUMMARY

In this chapter, the need for straightforward methods for generating early-stage prototypes was first outlined. A solution to this was developed through both a low-resolution prototype design guide as well as evaluation tool. Teams can implement these two guides sequentially in order to approach their resource allocation and prototyping objectives in a more organized fashion. The design and evaluation guides were provided to undergraduate engineering senior design teams who chose to either proceed to their prototyping phase with the assistance of the guides or not. Results were discussed, and teams who chose to use the guides displayed a higher confidence in the information they derived from construction and testing of their prototypes. They also felt the prototyping phase was of more value to the overall design process.

Chapter 4: Conclusions and Future Work

This chapter summarizes the research presented in this thesis. Conclusions from the low-resolution prototyping experiment are presented first, along with suggestions for future work. Following this, the results of student experiences with the low-resolution prototyping guide are summarized, along with suggested directions for future work.

4.1 USE OF LOW-RESOLUTION PROTOTYPING DURING CONCEPT GENERATION

The results of this research show that access to a set of physical artifacts during the concept generation phase of design proved to generate a higher number of concepts within design teams. Also, these teams as a whole progressed to develop more successful embodiment designs. However, when comparing teams who produced the highest number of concepts and those with the best performing systems, no correlation was found. One reason for this may have been that while the teams were able to produce a high number of concepts, the study procedure limited them with both time and resources during the embodiment phase. The teams that produced a higher number of concepts often had concepts that were very innovative, requiring materials not available to the teams. Also, these innovative concepts were impractical or impossible to fabricate in the allotted 30-minute timeframe.

A possible reason for the observed elevated performance in both concept generation and system performance may be that experimental teams with access to the physical artifacts were able to more effectively work as groups. By using the physical materials to communicate ideas, they began developing a collective idea of the best application of specific concepts during embodiment. Again, it is important to note that the materials used during ideation were completely different than those during the embodiment phase, and teams had no knowledge they would actually be building a system when they were generating concepts.

4.1.1 Future Work

A logical next step in this research is a longer-term study on the use of physical materials during concept generation. By providing teams with both more time and a broader set of materials for embodiment (potentially of their choosing), a clearer understanding of the effects of low-resolution prototyping during ideation will be achieved.

This approach is clearly applicable for undergraduate teams, but it should be evaluated by more experienced designers as well. The literature review uncovered no widely accepted methodology on low-resolution prototyping best practices. With the increased availability of rapid prototyping equipment, implementation of low-cost physical representation of early-stage concepts should be used more widely.

4.2 LOW-RESOLUTION PHYSICAL PROTOTYPING DESIGN AND EVALUATION GUIDE

Work at The University of Texas at Austin has continued on development of a general prototyping strategy guide (72, 76, 77), and results from the development of a low-resolution component are promising. Statistical significance was not seen in the results from a post-use survey to compare decisions of student teams who were exposed to the guides and those who were not. Also, on average students rated the guides as useful and helpful. Also, further investigation into how low-resolution prototypes were implemented and validated can help guide the development of the methodology taught in the university curriculum.

4.2.1 Future Work

By analyzing not only self-reported responses to the low-resolution physical prototyping design and evaluation guides, but evaluation of the teams' final deliverables, the effectiveness of the guides can be better understood. By using the undergraduate teams' supervisors as assessors of project success, a study on teams with exposure to the guides as compared to prior years can be conducted.

For the study conducted in this research, the control group which had no exposure to the guides was required by course commitments to complete low-resolution physical prototyping. The experimental group, to whom the guides were provided, were not under the same requirement. Only groups who completed some sort of physical prototyping were administered the survey. In the majority of the cases, teams were not required to produce any type of prototype, low-resolution or otherwise. Through interviews, teams concede that time constraints as well as inexperience with manufacturing techniques restrained them from pursuing physical prototypes. The future study can be expanded to include a comparison between the two groups, those with required low-resolution prototypes and those without, on success of their final deliverables and how effectively the team worked together.

Appendices

APPENDIX A: LOW-RESOLUTION PHYSICAL PROTOTYPING DESIGN GUIDE

Low-Resolution Physical Prototyping Design Guide

Name of Concept to Prototype: ________________________________

Iteration #: __________

Customer Needs to be Validated:

These are the main product functions, which the prototype will be constructed to demonstrate.

-
-
-
-

Performance Metrics associated with Customer Needs:

Associated performance metrics will be used to evaluate how effectively the prototype satisfies the selected customer needs.

-
-
-
-

Prototype Architecture:

With basic prototype design, there are several approaches in which the prototype differs from final design intent. Give a brief explanation if this prototype will implement:

Scaling? ____

____

____

Sub-System Isolation? ____

____

____

Constraint Relaxation?

Material selection:

Readily available, inexpensive materials serve best for low-resolution prototyping. Repurposed materials can save on cost, while sometimes even allowing for iterative designs. Simple building materials such as wood, cardboard, PVC tubing and foam are easy and quick to work with. Which materials will be used to construct this prototype?

Manufacturing Technique:

Rapid prototyping techniques are well suited for low-resolution prototyping. FDM, laser cutting, and CNC can create quick models, which possess aesthetic qualities appropriate for customer feedback. Which manufacturing methods will be used to create this prototype?

APPENDIX B: LOW-RESOLUTION PHYSICAL PROTOTYPING EVALUATION GUIDE

Low-Resolution Physical Prototyping Evaluation Guide

Name of Prototype:______________________________________
Iteration #: ________

Other Prototypes Developed in Parallel:

Were other prototypes designed to address the same product function? During the evaluation phase these will be compared directly against one another.

Did the prototype satisfy the intended customer need(s)?

Experiment design must be considered here. How will you go about validating the prototype? Common methods are quantitative testing, user surveys and feedback.

A Pugh Chart can be used to compare multiple prototypes aimed at satisfying the same customer need or product function.

Did any other unintended (but useful) product functions arise from testing?

What feedback on the product was generated within the design team?

What feedback on the product was generated by potential customers, end users, and other teams?

Will you iterate on this design?

Considerations at this stage can include design, material or manufacturing adjustments. Sub-system integration for validated prototypes must also be accounted for. Did the prototype adequately satisfy the performance metrics? What can be improved?

References

1. Yang, Maria C. “A Study of Prototypes, Design Activity, and Design Outcome." *Design Studies* 26.6 (2005): pp. 649-69.

2. Schrage, Michael. *Serious Play: How the World's Best Companies Simulate to Innovate*. Boston, Mass.: Harvard Business School, (2000).

3. Austin, R. and Devin, L. *Artful Making: What Managers Need to Know About How Artists Work* . Financial Times Press, (2003).

4. Simon, Herbert A. *The Sciences of the Artificial: (3. Print.)*. Cambridge, Mass.-London, (1972).

5. Jang, Jooyoung, and Schunn, Christian D.. "Physical Design Tools Support and Hinder Innovative Engineering Design." *ASME DC*., 6 Mar. (2012).

6. Ullman, D., Wood, S., and Craig, D., “The Importance of Drawing in the Mechanical Design Process,” Computer Graphics, 14(2), pp. 263–274. (1990).

7. Lim, Y.-K., Stolterman, E., and Tenenberg, J. The anatomy of prototypes: Prototypes as filters, prototypes as manifestations of design ideas. ACM Transactions on Computer-Human Interaction, 15(2), Article 7, pp. 1-27. (2008)

8. Christensen, B., and Schunn, C., “The Relationship of Analogical Distance to Analogical Function and Preinventive Structure: The Case of Engineering Design,” Mem. Cognit., 35(1), p. 29. (2007).

9. Christensen, B., and Schunn, C., “The Role and Impact of Mental Simulation in Design,” Appl. Cognit. Psychol., 23(3), pp. 327–344. (2009).

10. Ball, L., and Christensen, B., “Analogical Reasoning and Mental Simulation in Design: Two Strategies Linked to Uncertainty Resolution,” Des. Stud., 30(2), pp. 169–186. (2009).

11. Ahmed, S., and Christensen, B., “An In Situ Study of Analogical Reasoning in Novice and Experienced Design Engineers,” J. Mech. Des., 131, p. 111004. (2009).

12. Youmans, Robert J. The effects of physical prototyping and group work on the reduction of design fixation, University of Illinois, (2010).

13. Finke, R. Creative Imagery: Discoveries and Inventions in Visualization, Lawrence Erlbaum Associates, Hillsdale, New Jersey, USA. (1990).

14. Leonard, D., and Rayport, J.F. Spark Innovation through Empathic Design. Harvard Business Review, pp. 102-113. (November December 1997).

15. Verplank, W., Fulton, J., Black, A. and Moggridge, W. Observation and invention: The use of scenarios in interaction design. CHI Tutorial, ACM Press. (1993).

16. Wagner, A. Prototyping: A day in the life of an interface designer, Reading, MA: Addison-Wesley, pp. 79-84. (1990).

17. Buchenau, Marion, and Jane Fulton Suri. "Experience Prototyping." *Experience Prototyping*, (2000).

18. Ehn, P., and Kyng, M. Cardboard computers: Mocking-it-up or hands-on the future. In Design at work: Cooperative design of computer systems (ed. Greenbaum, J., and Kyng, M.). Hillsdale, NJ: Lawrence Erlbaum, pp. 169-195 (1990).

19. Muller, M.J. Retrospective on a Year of Participatory Design Using the PICTIVE Technique, in Proceedings of CHI '92 ACM Press, 455-462. (May 1992).

20. J. Verlinden, Van den Esker, W., Wind, L., and Horvath, I. Qualitative Comparison of Virtual and Augmented Prototyping of Handheld Products, (2004).

21. Jensen, Randell, and Feland, Bowe. A Study of Rapid Prototyping for Use in Undergraduate Design Education. USAFA, Stanford, Perry School District, (2002).

22. Kelley, Tom, and Littman, Jonathan. *The Art of Innovation: Lessons in Creativity from IDEO, America's Leading Design Firm*. New York: Currency/Doubleday, (2001).

23. De Beer, DJ, Barnard, LJ, and Booysen, GJ. “Rapid Prototyping (through SLS) as Visualisation Aids for Architectural Use. “ (May 2012).

24. Dupont, Daniel G. "Proactive Prototypes." *Scientific American Global RSS*., (17 Jan. 2008).

25. Buchenau, M. and Suri, J.F. Experience Prototyping. Proceedings of the 3rd conference on Designing Interactive Systems: Processes, Practices, Methods, and Techniques, ACM, pp. 424-433. (2000).

26. Goldschmidt, G. "To See Eye to Eye: The Role of Visual Representations in Building Shared Mental Models in Design Teams'. CoDesign, pp. 43–50. (2007).

27. Pei, E., Campbell, R.I. and Evans, M.A. "A Taxonomic Classification of Visual Design Representations Used by Industrial Designers and Engineering Designers." The Design Journal, 14: pp. 64-91. (2011).

28. Rhinow, Holger, Koppen, Eva, Moritz, Josephine, Jobst, Birgit, and Meinel, Christoph. "Prototypes for Innovation – Facing the Complexity of Prototyping." *Prototypes for Innovation – Facing the Complexity of Prototyping*. (4 September 2013).

29. Dow, S. P., Glassco, A., Kass, J., Schwarz, M., Schwartz, D. L., and Klemmer, S. R. 2010. Parallel Prototyping Leads to Better Design Results, More Divergence, and Increased Self-Efficacy. ACM Trans. Comput.-Hum. Interact. 17, 4, Article 18, pp. 1-24. (December 2010).

30. Dow, S. P., Heddleston, K., & Klemmer, S. R. The Efficacy of Prototyping Under Time Constraints. Proceeding of the seventh ACM conference on Creativity and cognition CC 09, 165, Berkeley (USA). ACM Press. (2009).

31. Scrivener, S. A. R., Ball, L. J. and Woodcock, A. . Collaborative Design – Proceedings of Co-Designing 2000. London: Springer-Verlag, (2000).

32. Eckert, C. and Boujut, J.-F. 'The Role of Objects in Design Co-operation: Communication through Physical or Virtual Objects'. Computer Supported Cooperative Work 12: pp. 145–51. (2003)

33. Fry, Ronald, and David Kolb. "Experiential Learning Theory and Learning Experiences in Liberal Arts Education.", (January 1979).

34. Kolb, D. A. "Experiential Learning: Experience as the source of learning and development." Englewood Cliffs, NJ: Prentice Hall (1984).

35. Helbling, J. and Traub, L. "Impact of Rapid Prototyping Facilities on Engineering Student Outcomes." American Society for Engineering Education Conference and Exposition, Pittsburg, PA (2008).

36. O'Neill, R., Geiger, C., Csavina, K., and Orndoff, C. "Making statics dynamic! Combining lecture and laboratory into an interdisciplinary, problem-based, active learning environment." American Society for Engineering Education

Conference and Exposition, Honolulu, HI (2007).

37. Schumucker, D. “Models, models, models: the use of physical models to enhance the structural engineering experience.” American Society for Engineering Education Conference and Exposition Seattle, WA (1998).

38. Lemons, Gay, Carberry, Adam, Swan, Chris, Jarvin, Linda, and Rogers, Chris. "The Benefits of Model Building in Teaching Engineering Design." *Design Studies* 31.3: pp. 288-309. (2010).

39. Zerbe Enns, C. “Integrating Separate and Connected Knowing: The Experiential Learning Model.” The Teaching of Psychology, 20(1), pp. 7-13. (1993).

40. Beckman, Sara L., and Barry, Michael. "Innovation as a Learning Process: Embedding Design Thinking.", (2007).

41. Bilda, Z. and Gero, J.S. “The impact of working memory limitations on the design process during conceptualization.” Design Studies 28, pp. 343-367. (2008).

42. Miller, G.A. “The Magical Number Seven, Plus or Minus Two: Some Limits on Our Capacity for Processing Information.” Psychological Review 63, pp. 81-97. (1956).

43. Larkin, J. and Simon, H. “Why a Diagram is (Sometimes) Worth Ten Thousand Words.” Cognitive Science 11, pp. 65-100. (1987).

44. Zhang, J. and Norman, D. “Representations in Distributed Cognitive Tasks.” Cognitive Science 18, pp. 87-122. (1994).

45. Kirsh, D. and Maglio, P. “On Distinguishing Epistemic from Pragmatic Action.” Cognitive Science 18, pp. 513—549. (1994).

46. Maglio, P., Matlock, T., Raphaely, D., Chernicky, B., and Kirsh, D. “Interactive Skill in Scrabble.” Lawrence Erlbaum, (1999).

47. Maglio, P.P. and Kirsh, D. “Epistemic Action Increases With Skill.” In Proceedings of the Eighteenth Annual Conference of the Cognitive Science Society 16, pp. 391-396. (1996).

48. Dahl, D. W. and Moreau, P. “The Influence and Value of Analogical Thinking During New Product Ideation.” Journal of Marketing Research, 39, pp. 47-60. (2002).

49. Jaarsveld, S., and van Leeuwen, C. “Sketches from a Design Process: Creative

Cognition Inferred from Intermediate Products." Cognitive Science: A Multidisciplinary Journal, 29, pp. 79-101. (2005).

50. Jansson, D. G., and Smith, S. M. "Design Fixation." Design Studies, 12, pp. 3-11. (1991).

51. Marsh, R. L., Bink, M. L., and Hicks, J. L.. "Conceptual Priming in a Generative Problem Solving Task." Memory & Cognition, 27, pp. 355-363. (1999).

52. Marsh, R. L., Ward, T. B., and Landau, J. D. "The Inadvertent Use of Prior Knowledge in a Generative Cognitive Task." Memory & Cognition, 27, pp. 94-105. (1999).

53. Purcell, A. T., and Gero, J. S. "Design and other Types of Fixation." Design Studies, 17, pp. 363-383. (1996).

54. Smith, S. The Constraining Effects of Initial Ideas. In P. B. Paulus, & B. A. Nijstad (Eds.), Group creativity: Innovation through Collaboration. Oxford University Press, pp. 13-31. (2003).

55. Smith, S. M. *Getting Into and Out of Mental Ruts: a Theory of Fixation, Incubation, and Insight*. In R. Sternberg, & J. Davidson (Eds.), The nature of insight. Cambridge, MA: MIT Press. , pp.121-149 (1994).

56. Smith, S. M. *Creative cognition: demystifying creativity*. In C. N. Hedley, P. Antonacci, & M. Rabinowitz (Eds.), The Mind at Work in the Classroom: Literacy & Thinking, Hillsdale, NJ: Erlbaum. pp. 31-46. (1995)

57. Smith, S. M., Ward, T. B., and Schumacher, J. S. Constraining Effects of Examples in a Creative Generation Task." Memory & Cognition, 21, pp. 837-845. (1993).

58. Ward, T. B. "Structured Imagination: The Role of Conceptual Structure in Exemplar Generation." Cognitive Psychology, 27, pp. 1-40. (1994).

59. Moreno, D. P., Hernandez, A., Yang, M. C., Otto, K. N., Holtta-Otto, K., Linsey, J. S., Wood, K. L., and Linden, A. "Fundamental Studies in Design-By-Analogy: A Focus on Domain-Knowledge Experts and Applications to Transactional Design Problems," Design Studies, 35(3) , pp. 232-272. (2014).

60. Hey, J., J. Linsey, Agogino, A., and Wood, K. "Metaphors, Models, and Analogies in Social Science and Public Policy." *Analogies and Metaphors in Creative Design,* (2008).

61. Sachs, A. 'Stuckness' in the Design Studio." Design Studies, 20(2), pp. 195-209. (1999).

62. Kershaw, Trina, Holtta-Otto, Katja, and Lee, Yoon Soon. "The Effect of Prototyping and Critical Feedback on Fixation in Engineering Design." (2011).

63. Collins, A. M., and Loftus, E. F. "A Spreading Activation Theory of Semantic ." Psychological Review, 82, pp. 407-428. (1975).

64. Linsey, J. "An Experimental Study of Group Idea Generation Techniques: Understanding the Roles of Idea Representation and Viewing Methods." (2011).

65. Viswanathan, Vimal and Linsey, Julie. "Mitigation of Fixation to Negative Examples through Physical Modeling." (2011).

66. Schrage, M. *Cultures of Prototyping*. In T. Winograd (Ed.), Bringing design to software (pp. 10:1-10:11). ACM Press. (2006).

67. Karat, C. "Cost-Benefit Analysis of Usability Engineering Techniques. Human Factors Society." pp. 839- 843. (1990).

68. Michaelra, Ashwin. "Taxonomy of Physical Prototypes: Structure and validation." (2009).

69. Ehn, P., and Kyng, M. "Cardboard Computers: Mocking-it-Up or Hands-on the Future."Design at Work: Cooperative Design of Computer Systems (ed. Greenbaum, J., and Kyng, M.). Hillsdale, NJ: Lawrence Erlbaum, pp. 169-195. (1991).

70. Wong, Y.Y. "Rough and Ready Prototypes: Lessons from Graphic Design." Proceedings of CHI '92 Posters and Short Talks, ACM Press, pp. 83-84. (May 1992).

71. Otto, Kevin N., and Wood, Kristin L.. *Product Design: Techniques in Reverse Engineering and New Product Development*. Upper Saddle River, NJ: Prentice Hall, (2001).

72. Dunlap, Brock U. "Active Learning Module Assessment and the Development and Testing of a New Prototyping Planning Tool." *(*2014).

73. Erdogmus, H. "The Economic Impact of Learning and Flexibility on Process Decisions." IEEE Softw. 22 , 6 , pp. 76-83. (2005).

74. Forest, Craig R., Moore, Roxanne A., Jariwala, Amit S., Fasse, Barbara B., Linsey, Julie, Newsetter, Wendy, Ngo, Peter, and Quintero, Christopher. "The Invention Studio: A University Maker Space and Culture." (2014).

75. McLeod, Saul. "Kolb's Learning Styles and Experiential Learning Cycle | Simply Psychology." *Kolb's Learning Styles and Experiential Learning Cycle | Simply Psychology*. http://www.simplypsychology.org/learning-kolb.html (2013).

76. Gurjar, Tanmay. “Effects of a Structured Prototyping Strategy on Capstone Design Projects.” ASEE 2015. (2015).

77. Camburn, Bradley. “Transformational Indicators: Deciding When to Develop Transformable Products.” (2010).