INFLUENCE OF FORMAL TECHNIQUES AND DESIGN FIXATION ON IDEA GENERATION TASKS IN ENGINEERING PRACTICE

by

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Abstract

The outcome of the idea generation process often lays the groundwork for the overall success of an engineering project, which highlights the need for an effective process. However, the factors that impact this stage of engineering problem solving are often not considered by practicing engineers, who generally do not often use formal idea generation techniques, and instead usually conform to what is considered best practice at their respective organizations.

This thesis is structured to answer two research questions. Does a formal technique improve idea generation performance over the informal best practice in an engineering organization? Also, do example solutions hinder the idea generation process by artificially constraining the perceived design options, known as design fixation, when using either the formal or informal techniques? The formal technique used was a modified version of C-Sketch. The results of the experimental groups were compared across four metrics: quantity, variety, novelty, and quality of functional ideas.

The results showed that using a formal idea generation technique statistically outperformed the de-facto approach on all metrics, whereas the negative effect of design fixation was not seen. From experimental observation it is surmised that the formal approach was superior to the de-facto approach because it reduced social loafing, used time more efficiently, reduced the need for group consensus, mitigated premature idea evaluation, and increased the positive effects of peer evaluation.

Thesis Supervisor: Maria Yang

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Since I began working in Massachusetts as a mechanical engineer, it has been a dream of mine to attend MIT. It was a dream that I've been able to obtain in large part from the encouragement of my friends and family, the financial support of Draper Laboratory, and help from my colleagues at Draper Laboratory, members of the SDM cohort, and teaching assistants and professors. I'd like to thank Katy O'Brien, my Draper colleague and SDM companion in the trenches with me since day one, Team6! A special thanks goes to my thesis advisor, Professor Maria Yang, whose guidance, positive attitude, and love for engineering design is infectious and pushed me to write this thesis. A special thanks also to over forty of my colleagues at Draper Laboratory who participated in this research experiment. Finally, to my wife Michelle, who has supported me both vocally, and quietly, always selflessly, throughout this journey, and our little daughter Nava, who will only remember this time as when "Daddy go to school".

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1 Introduction to Thesis

Few would deny that developing a strong idea to solve a particular problem is the cornerstone for a successful engineering project, yet understanding how organizations and individuals actually conceive these ideas is a much less clear. While the disciplines of engineering are not given to the abstract, instead governed by equations, and the laws of physics, their most successful practitioners need the ability to develop good ideas into successful concepts to effectively ply their trade. The factors that impact this stage of engineering problem solving are often not considered by practicing engineers who, in my experience, generally having little training in formal idea generation techniques, usually conform to what is considered the best practice at their respective organizations.

It is within this context that this thesis works to understand how a particular company performs idea generation, and what impact various factors have on its success. While the experiment looks at one organization in particular, the lessons learned from this research are applicable more broadly. It is hoped that this research continues to add to our understanding of how we more effectively generate ideas for the design problems we face today.

1.1 Thesis Motivation

I've spent my professional life as a mechanical design engineer tasked with creating solutions to customer problems in organizations large and small. Looking back on my designs, I've created some that were innovative, while others seem trite, almost scripted. I've worked with some very creative engineers who were able to develop solutions that were extraordinarily elegant and well-tailored to the constraints of the needed solution and others who could never really develop any solutions outside those that we'd relied on for past projects. I've seen engineers reach out for novel solutions from the oddest places or just rely on the subject matter experts to provide the concept to push forward. I've seen prior solutions constrain current problem needs. I've been in hundreds of design reviews, built hundreds of concepts physically, developed an order of magnitude more in 3D design software, and attended brainstorming sessions, albeit most of them unstructured. However, until returning to school at MIT, I'd never really thought much how we actually generate ideas for engineering problems. This thesis is my attempt to that just that by studying the research into this important and often overlooked portion of engineering, by characterizing what my colleagues and my organization do to generate ideas, performing an experiment to see if some strategies are more effective than others, and sharing the knowledge gained with the wider community.

1.2 Thesis Objective

This work's principal objectives are to understand if the use of a formal method for idea generation outperforms the de-facto strategy currently in use at an engineering laboratory on the various metrics of idea generation and whether the use of an example solution creates a state of fixation for designers that inhibit their ability to generate many potential ideas. The effect of design fixation will also be studied as a function of the method of idea generation used.

This thesis structured to first discuss the motivations and objectives behind the research. Next, a literature review on research into idea generation and design fixation, including where gaps in the research currently exist is presented. This is followed by a case study on how idea generation is performed at a not-for-profit research and development engineering laboratory, Phase I, which is then compared through an experimental setup against a formal progressive idea generation technique with the conditions of design fixation also being examined, Phase II. Finally, the results of this experiment are analyzed and conclusions drawn from the work are shared as well as limitations of the experiment and possible future work.

This goal of this research is to answer several important research questions.

Q1: What does idea generation look like in practice at a not for profit research and development laboratory, defined as the de-facto approach?

Q2: Does a formal idea generation technique outperform the de-facto approach to idea generation on the metrics of quantity, quality, variety, and novelty of ideas generated?

Q3: Does a fixating example negatively impact the metrics of idea generation for the de-facto method or the formal method?

The hypotheses postulated and tested through this research are as follows:

H1: Idea generation will be an ad hoc approach that includes conceptual 3D modeling, peer evaluation, white board sketching, and engagement of subject matter experts.

H2: Formal idea generation techniques will outperform the de-facto approach on quality, variety, and novelty, but not on overall quantity.

H3: The fixating example will not reduce the quantity of ideas generated for either method, but variety, novelty and quality will be reduced in both cases, with the de-facto approach underperforming the formal idea generation technique on these metrics.

2 Literature Review

This literature review begins by examining the research into how we engage in creative problem solving, specifically how it affects engineering design. A taxonomy of different idea generation techniques is presented with an in depth review of one of the most popular and widely diffused techniques, Brainstorming, and a set of progressive idea generation techniques based on sketching. The research into fixation is then presented, including strategies that have been studied to reduce the impact of design fixation. The methods developed to measure both the impact of idea generation techniques and design fixation are presented. Finally, the gaps in the current research are identified that this work intends to address.

2.1 Creative Problem Solving and Design

Engineers are often tasked with designing novel products to solve problems presented by their customers. While the domain of expertise may vary, this basic task is germane to all engineering disciplines, yet the process and results of how engineers generate ideas for customer problems varies greatly. The importance of this idea generation task, often called Creative Problem Solving (CPS), should not be understated, as it is estimated that 70 percent or more of the life cycle cost of a product is determined during design [1].

Creative problem solving is often done in groups, they assist in exploring the problem space and generating a wide variety of novel ideas, thus obtaining an overview of potential design directions [2]. This conceptual phase is in essence divergent thinking, where ideas and concepts are to be free flowing and continually focused at opening up design options that have not yet been uncovered. Formal idea generation methods have been established as tools to help facilitate this divergent thinking phase. A key difference in many of these methods is how ideas are shared amongst the group, written word, spoken word, sketching or some combination of the three. Design engineering, especially those disciplines dealing with product development, often convey ideas through sketching, however a survey of formal idea generation tools available in the late 1980's showed very few have a graphical component [3].

2.2 Idea Generation Techniques Taxonomy

Formal methods of idea generation have been formulated only in the past fifty years, which have been roughly broken into a two broad method types: intuitive and logical methods [4]. Intuitive methods focus on increasing the flow of ideas and using the human subconscious to uncover novel ways to solve problems. Some well know intuitive methods include Brainstorming, Fishbone diagrams, and C-Sketch.

Logical methods presuppose a more scientific decomposition and analysis of the problem. Functional Analysis, FA, is a common logical method that breaks the problem down into functions, using a black box, block diagram approach and is often referenced in product design literature [5,6]. Other logical methods are often associated with matching problem attributes with prescribed solution sets through the use of design or functional databases. The "Theory of Inventive Problem Solving" TIPS, or TRIZ [7] is an example of this kind of logical method. The classification of idea generation techniques is given in Figure 1.

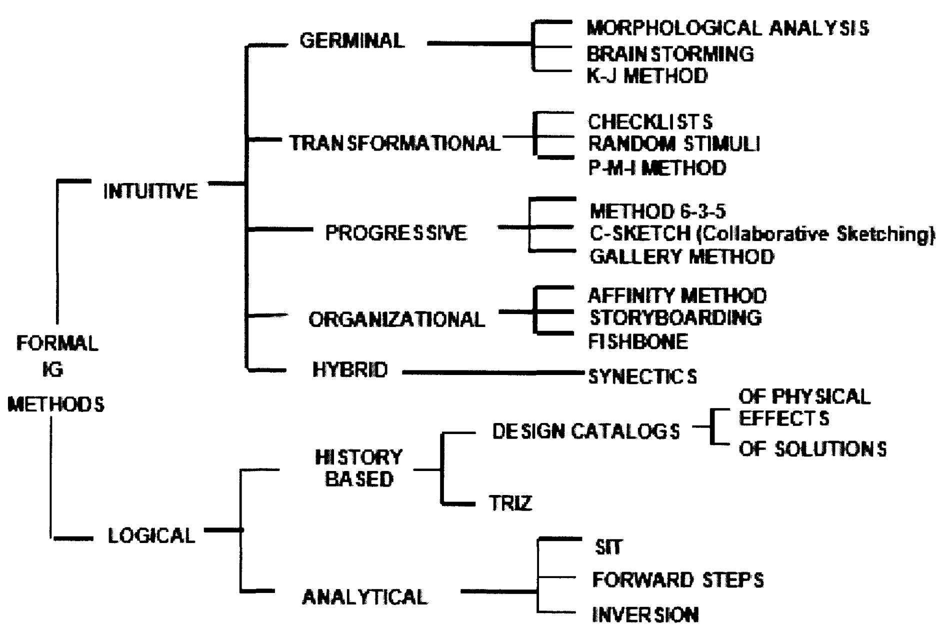

Figure 1: Classification of Idea Generation Techniques [4]

As these formal methods of idea generation were being developed and diffused through academia and industry alike, researchers became interested in many facets of this critical phase of design with much of this research straddling the boundary between Design Engineering and Cognitive Psychology, with both disciplines adding to the understanding of how idea generation is accomplished. One study that compared how participants allocated their time between understanding the problem and solving the problem using intuitive and logical approaches, showed that using a Functional Analysis, a logical method, users spent their time approximately equally split amongst the two, whereas using Brainstorming, participants spent almost 90% of their time solving the problem [8]. This thesis research resides in the intuitive branch of these formal methods, comparing Brainstorming, a commonly used germinal technique to a Progressive Idea Generation technique, C-Sketch.

2.2.1 Brainstorming

Engineering research into design has focused on studying the techniques that have been classified in Figure 1. Much of the research has centered on evaluating the method that is known to almost anyone who works in creative problem solving, even outside of engineering, Brainstorming [9]. A watershed moment in formalizing the techniques of idea generation is Alex Osborn's 1953 book that codified this group idea generation process. The basic rules of Brainstorming included: focus on quantity, withhold criticism, welcome unusual ideas, and combine and improve ideas [10]. The technique included a facilitator who would present the problem to be considered and write down ideas for all participants to see as they were being generated by the group. There was no sketching involved, only verbalization of ideas from the group.

Brainstorming was touted as being able to double to the number of ideas that an individual in a group setting could create versus the individual alone. Research by Yang, while not showing a causal link, between the quantity of brainstormed ideas and design outcomes, shows at least a correlation between the two [11]. Other research has also found that the process of Brainstorming has greater positive effects on the organization, outside of the quantifiable output of the process [12,13]. Sutton et al. found that successful engineering design organizations like IDEO, use Brainstorming as the cornerstone of their ideation process specifically because it supports the organizational memory of design solutions, provides skill variety, and supports an attitude of wisdom, acting with knowledge while doubting what one knows, among other benefits. While Henningsen found that another positive, often unquantified, outcome of Brainstorming is group cohesion which could be valuable in an organizational setting.

Brainstorming has continued to be a mainstay in many design circles as the ideation method of choice, even though various studies have called into question it efficacy as an ideation tool. Multiple studies have shown that Brainstorming groups create fewer ideas than "nominal groups" which are made up of individual who are working alone [14,15]. This difference which is called productivity loss is often explained by three attributes of the Brainstorming process, people interrupting each other or waiting for others to speak, a procedural mechanism, the effect of the group on the individual, social psychological mechanism, and self-interested laziness, or social loafing, defined as group members that are not actively participating to their full capacity since others are willing to shoulder the load. The attribute that has the largest effect was the procedural mechanism [16,17]. The delays that arise when group members wait for their turn to speak disrupted the organization of idea generation and reduced the flexibility of idea generation [17].   Recent research has called into question these findings stating that the productivity losses associated with having to wait for others to speak, while real, are overstated since most experiments were performed in a time constrained environment, usually less than 30 minutes, whereas when time is unconstrained Brainstorming groups approximate the number of ideas generated by nominal groups [13]. One of the rules of Brainstorming is that group members are expected to build upon others' ideas. The expectation is that one group member's ideas will act as stimuli for other group members and vice versa, with the outcome of having more ideas generated. This idea exposure during Brainstorming can both facilitate and interfere with the idea generation process

[18]. This cognitive interference could also be a factor in participants becoming fixated on certain ideas to the detriment of the idea generation process.

Variants of Brainstorming have also been developed that include sketching during the idea generation process, collectively called graphical Brainstorming, have been studied and compared the classical method of Brainstorming proposed by Obsorn to better match the desire of designers to use sketching as a medium to convey their ideas. The study showed that these graphical variants did not increase the number of ideas generated and showed less building off of other group members ideas, as compared to the traditional method [2].

2.2.2 Progressive Idea Generation Techniques

Another subset of intuitive idea generation techniques is based on progressive approaches. These involve groups but often individuals are working on ideas alone. The premise of this set of approaches is that is allows time for individuals to be creative, provides feedback from other designers without criticism or confrontation, and encourages designers to build off the ideas of others, and is productive because it allows designers to create ideas at the same time. These techniques are very similar, but they usually vary by how ideas are captures, written word or sketches, or both, and how and when other team members get to view and comment on other members work. The following is a discussion of three of these techniques that are well suited to product development, because they satisfy the designers desire to be able to sketch idea concepts.

2.2.2.1 Brainsketching

Brainsketching as a technique developed out of the desire by traditional Brainstorming users to express their ideas not just verbally, but visually [3]. The expected benefit of this method is that it allows members to build upon others ideas, but also allows them space to create their ideas individually. Traditional Brainsketching uses a small group of designers who sit and sketch and annotate their own ideas to a problem, then they share those idea, either by passing their sheet to another member, or by posting it on a wall for all members to see before another member receives their sheet. This is done for a set amount of time and all members are given a chance to view and sketch upon other's original sheets, see Figure 2 for details. Some variants of Brainsketching allow participants to explain their ideas to the group between sharing sketch sheets.

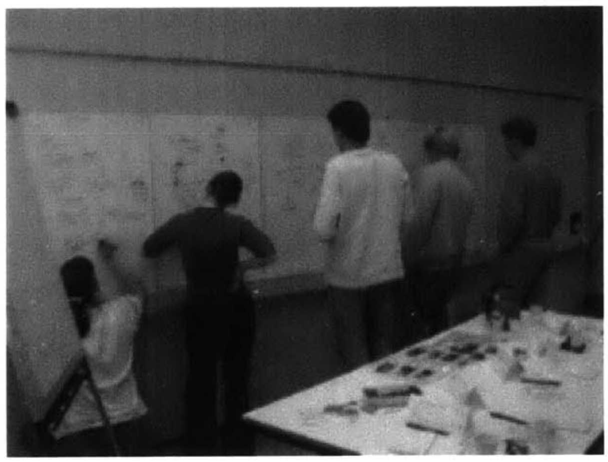

Figure 2: Group Participating in Brainsketching [19]

2.2.2.2 C-Sketch

C-Sketch, collaborative sketching, is a variant of a written word only method, 6-3-5. C-Sketch was developed based upon the premise that sketching is important to design, collaboration of ideas provides diversity in design, and that misinterpretations of ideas may prove to be catalysts in developing creative new constructs [20]. It was originally proposed at the Design Automation Lab at Arizona State University in 1993, under the name 5-1-4 (G), which stood for 5 designers, 1 idea at a time, 4 passes, Graphical. Each designer develops one conceptual solution and details it in sketches only for a fixed period of time. After that time has elapsed the sketch is passed to another team member who may alter the design by adding, subtracting, or modifying the design given to them, with the only caveat that the original design cannot be scrapped in its entirety. This continues in subsequent rounds until each designer has had a chance build on each original design, with the output of total ideas equal to the number of group members, see Figure 3 for an illustration of C-Sketch.

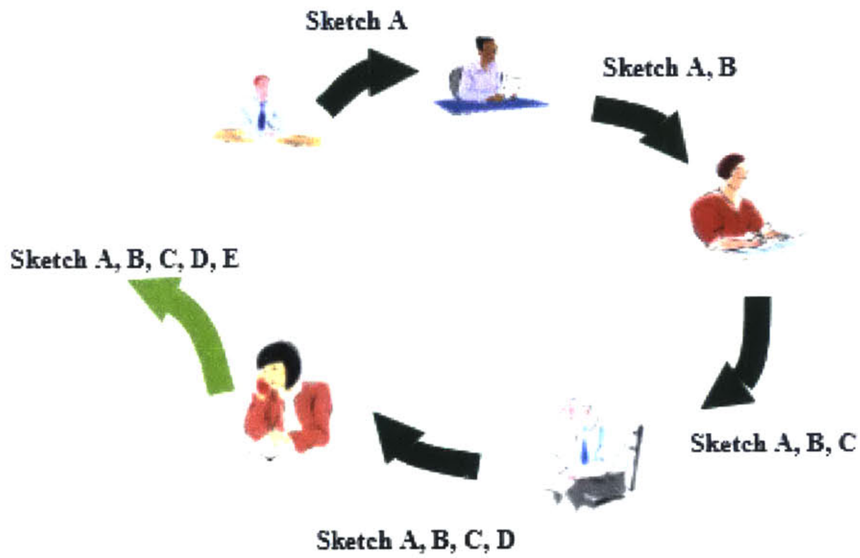

Figure 3: C-Sketch Method [20]

2.2.2.3 Gallery Method

The Gallery method was originally developed by Hellfritz in 1978 [6] which combines individual and group work and is well suited for the engineering idea generation in that is supported by the use of sketching. The protocol is as follows, the group is given the design problem and is then asked to sketch silently and annotate if needed for fifteen minutes. This allows them to develop their own ideas, intuitively and without procedural or social mechanisms of interference that are associated with Brainstorming. After this first period, group members post their ideas on a wall for fifteen minutes of display and discussion with other team members about their ideas. This gives the team the ability to solicit feedback on their ideas, an opportunity to discover new ideas, find complementary ideas, and potentially build off the ideas of others. Then group members take down their sketches and have another fifteen minute period to work on the ideas that were gathered during the display period. An illustration of the Gallery method is shown in Figure 4.

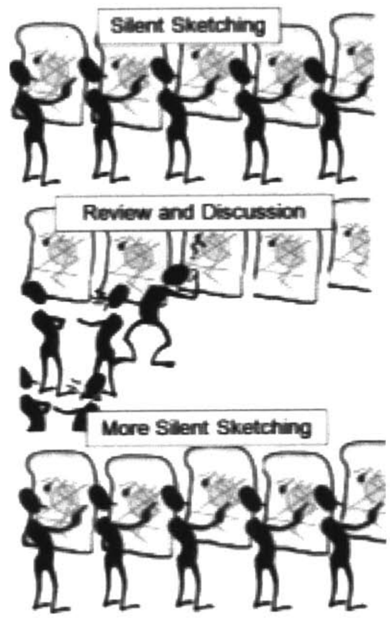

Figure 4: Gallery Idea Generation Technique [21]

2.3 Design Fixation

How humans develop ideas and concepts for creative problem solving tasks has been an active area of research, especially as it pertains to how humans develop new ideas and the negative impact of mental fixation. Cognitive psychology has focused on how designers create and use mental images, some have argued that these images are generally descriptive, not pictorial, while others believe mental images closely resemble pictorial representations [22]. Some of the earliest work sought to understand innovation and creativity in problem solving. It specifically studied conditions under which people find it difficult to produce innovative solutions. One famous study involved two pieces of string that were hanging from the ceiling of a room spaced far enough apart that they can't be walked toward each other and connected. There are various tools in the room and the solution is to use one of the tools, the set of pliers, as a weight to swing one piece of string like a pendulum so it can be caught and attached to the other string. This solution involved an innovative and unusual use of the pliers, which was often not considered by the subjects. This result hinted that well established uses of everyday objects prevent the problem solver from creating the innovative solution that the problem required [23]. Even though the term wasn't codified until much later, the phenomenon of mental fixation was being elucidated.

Research has shown there is an overwhelming role played by prior knowledge in structuring otherwise novel ideas, while the conceptual building blocks may vary between disciplines, the tendency to build novel ideas from domain-specific blocks is the same [24]. Even in completely creative, imaginary tasks, humans are usually unable to develop novel solution and instead default to, *structured imagination*, that is when subjects create a new member of a category for an imaginary setting, their imagination is structured by a particular set of properties that are characteristic of that category [25]. This inability to develop out of domain solutions, has also been characterized as *the path-of-least-resistance model*. Participants, when tasked to create something novel, hark back, either consciously or unconsciously to existing categories and concepts and incorporate those in some manner into their "new" creations. This was shown in an experiment by Ward which asked participants to imagine and draw creatures that might live on another planet in our galaxy. Overwhelming the creatures drawn had earthlike features, bi-lateral symmetry, sensory organs, appendages, even when participants were instructed to go beyond their "wildest imagination" extra-terrestrials continued to resemble something on the Earth. Novelty, it seems, is more difficult to generate than one might expect.

Prior experiences doesn't always benefit creative thinking, because it can constrain creative idea generation by leading people to base their ideas on the details of those earlier experiences. This was shown in a set of experiments where some participants were given examples, and even some were explicitly told to avoid the re-use of these examples. The results showed that recent experience can lead to unintentional conformity, thereby reducing novelty and constraining the generation of creative ideas [26].

The impact of these results for the engineering and design community are just as significant and worrisome as for other creative endeavors than rely on novel thinking. When designers are “stuck” on a narrow set of possible solutions, the result is often referred to as *design fixation*. Design fixation was defined by Jansson and Smith as a blind, and sometimes counterproductive, adherence to a limited set of ideas in the design process [27]. In their ground breaking 1991 work, four experiments all showed different elements of design fixation, see Figure 5 for details. In the first experiment, engineering students were given a probable solution to a design prompt and results showed that while the number of solutions generated between the control and experimental group were not statistically significant, more features of the given example were replicated in the experimental group’s solutions than the control group. The example in the second experiment had obvious design flaws, but again these flawed features showed up in solutions given by the experimental group. Even in a subsequent experiment, when the experimental group was explicitly told to avoid these flawed features, the features were replicated in the results. In the final experiment, professional engineers were the participants, and similar results showed the impact of design fixation in their proposed solutions.

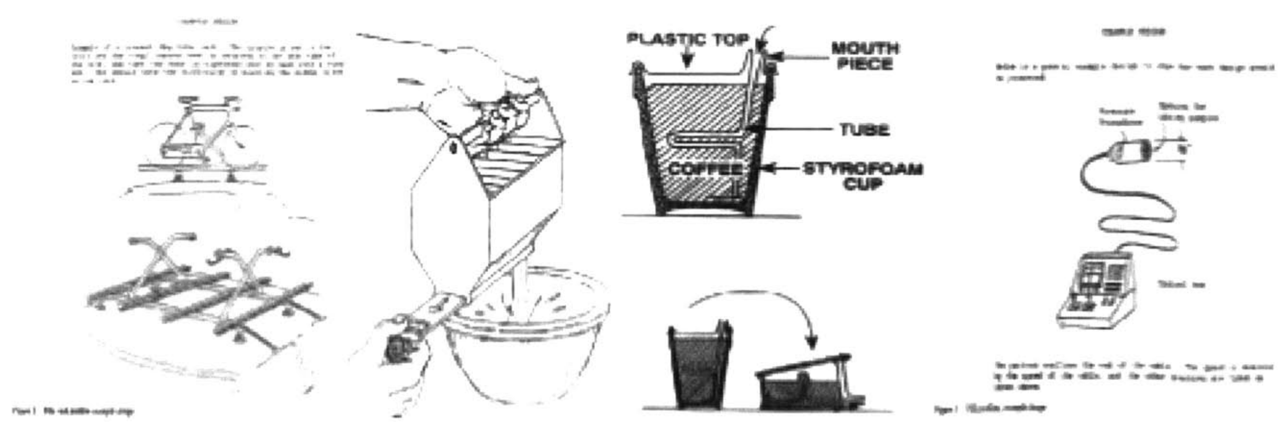

Figure 5: Design Fixation Examples [27]

Initial replication of these experiments was performed by Purcell and Gero and showed a relationship between the amount of design fixation shown as being a function of multiple variables:

familiarity, experience level, and extent of differences in the fixating example [28]. In later years, further research by Purcell and Gero ended up developing a more nuanced stance of design fixation [29]. Their experiments showed that design fixation was most probable in two scenarios. The first being that the fixation effect is not simply discipline specific but involves the use of an example that embodies principles that are specific to a particular domain of knowledge. For example, exposing a group of mechanical engineering designers to a pictorial representation of an example design which embodies typical principles of the discipline does appear to induce a fixation effect, by the reuse of features of the given example. Also, they found that fixation occurred with the absence of domain specific knowledge and a reliance on everyday knowledge activated by exposure to a picture of a familiar example.

Research has shown that not only are engineering students and practicing engineers susceptible to design fixation, engineering design faculty under similar experiments have shown similar results, even inaccurately perceiving that provided examples improve their idea generation outcomes [30]. Clearly, the evidence shows that examples have an impact on the idea generation process, often measured by the amount of replication of example features in proposed solutions. Another area of research that is germane to this thesis is how to more holistically evaluate idea generation process and the impact of design fixation than simply the number of replicated features.

2.4 Methods to Reduce Design Fixation

As designers search for inspiration of new and novel designs they often look to their own intentional learning in a particular domain and incidental knowledge they have acquired from daily experiences [28]. As explored previously, sometimes these sources of inspiration could actually hinder the creative problem solving process by fixating designers, reducing the range of potential options. To avoid the negative impacts of design fixation researchers have provided multiple strategies.

The use of prototypes was found to reduce design fixation in team's designing common tools and simple designs [31,32]. Viswanathan and Linsey found with rather simple design tasks, the use of prototyping showed no increase in design fixation. The authors though noted this effect could be due to the level of simplicity or complexity in the design problem. Youmans showed that since creative problem solving tasks demand a significant amount of our naturally limited cognitive resources and that prototyping was, in effect, a strategy to reduce this cognitive load by transferring the energy and effort needed to maintain a design internally into an external representation, that the now reduced cognitive load would allow designers to reapply these freed up resources to detect design fixation [32].

Conversely though, other research has shown that when designers refer to within-domain prototypes, they made very few between-domain analogies, significantly fewer than when sketching or referring to ideas without external representation [33]. These findings though are tabulating the effects of design fixation in distinct ways, the first correlates design fixation to the inability to identify and remove poor design choices from a fixating design, while the second study looks at design fixation as an inability to create a broad set of potential solutions that include out of domain options.

One interesting study looked at the impact of providing partial photos to designers in order to inspire new designs without inducing design fixation [34]. The results showed that relative to designers that were presented full pictures, designers with partial photos developed more designs that were judged to be original. They showed that presenting these partial photographs, even though they conveyed less information than the full photographs, did not hinder the design process. Potentially the improvements in idea generation outcome could be explained is similar terms to the benefits of ambiguous sketches. The ambiguity allows designers to rethink, re-imagine what is being conveyed, this interpretation step allows the designer to expand the potential design space.

Smith and Linsey [35] provide a three pronged approach to overcoming design fixation. They suggest forgetting fixation, by shifting contexts, which does not necessitate explicit identification of the fixating knowledge. An example of this is when ideas come to a designer outside of actively searching for solutions, often they occur as an insight outside of working directly on the problem at hand. Another approach suggested is redefining the problem, because the problem as originally defined might imply a particular, and therefore narrow solution set. Finally they using out of domain analogies or word trees to spark new ideas, consistent with previous work [21].

Other approaches discussed in the literature include stepping away the problem at hand and approaching in at another time, often called incubation [35,36]. Also, the strategy of providing explicitly de-fixating instructions reduced the instances of design fixation found in Jansson and Smith's original experiments [37].

2.5 Methods to Evaluate Idea Generation Techniques and Fixation

How to properly evaluate idea generation techniques and levels of design fixation has been an active field of research for many decades. Starting with Obsorn's Brainstorming, the evaluation of the efficacy of the process was based simply on the total quantity of ideas it produced [10]. Psychologists like Torrance in the 1970's developed a much more robust method of evaluating ideas along the lines of fluency, flexibility, originality, and elaboration [38]. Other attempts have surmised that it is not only the output of the process that matters, the benefits of doing the particular process itself should not be overlooked [12,13]. Evaluation of the degree of design fixation present has mostly been measured by number of ideas, and the number of elements that are replicated in the potential solution set by study participants [26]–[30].

Shah et al. [39] state that there are two fundamental values used in judging the worth of an idea generation technique, how effective it is in expanding the design space and how well does it explore this space. These values clearly and accurately characterize the idea generation process as a process of divergent thinking. In order to capture these values they propose four effectiveness measure: quantity, quality, novelty, and variety.

- *Quantity* is defined as the total number of ideas generated by a group when it uses a certain idea generation method.
- *Quality* is a measure of the feasibility of an idea and how close it comes to meeting the design specifications.
- *Novelty* is a measure of how unusual or unexpected an idea is compared to other ideas.
- *Variety* is a measure of the explored solution space during the idea generation process since generation of similar ideas would be a measure of low variety and therefore less exploration of the design space.

2.6 Gaps in our Current Understanding

Most of the current understanding of idea generation is centered on defining how idea generation is actually performed, from a social science or psychological perspective. While these fundamental aspects of idea generation are critical to developing a more complete picture of how humans perform these cognitive tasks, focusing on *how* idea generation is done in practice, is no less important. Studies involving students as participants are a common approach to characterize idea generation [20, 25–27], but research involving practitioners and idea generation methods is less common. There is some research that has characterized the idea generation tools that are commonly understood and their prevalence in industry, [11]. There has also been some research into idea generation through Design by Analogy amongst practitioners in service oriented industries, like finance [40]. In contrast, this work focuses its efforts on determining the idea generation technique used by practicing engineers in a research and development environment and comparing the effectiveness of that technique with a more formal approach across a variety of metrics.In Phase I, interviews will be done with practicing engineers at Draper Laboratory in Cambridge Massachusetts, a not for profit, Research and Development Laboratory, to characterize their idea generation process and identify the technique most representative of the one used in the organization, which will be called the de-facto approach. In Phase II, an experiment will be performed using practicing engineers at Draper Laboratory to determine the impact of using a formal technique, a Progressive Formal Idea Generation technique, modified C-Sketch, and design fixation on an idea generation task, as compared to the de-facto approach. A design problem and a detailed fixating example will be developed that is suitable for use in determining the efficacy of these techniques and the impact of design fixation. The results will be scored on the metrics of quantity, variety, novelty, and quality of ideas. At the end of the experiment, a short survey will be administered to capture any potential variables that are uncontrolled in the experiment which will then be analyzed to see if they might have had any influence on the experimental results.

3 Phase I: Current Practice of Idea Generation at Draper Laboratory

To better understand the current practice of idea generation at Draper Laboratory, five mechanical design engineers were interviewed. These interviews were done individually for approximately thirty minutes with open ended questions with the intent to elicit their perspective on how idea generation is commonly performed at the organization. The laboratory specializes in defense and national security projects for the US government. As a research and development organization, the laboratory is often working on projects that involve implementing or creating new technologies to meet their customer's requirements. The laboratory does not have a defined product line or manufacturing bias towards a few individual products, most projects are standalone, and for security reasons much of the design information is stove piped which inhibits some sharing of design concepts and strategies amongst the engineers. Usually, projects are done through a proposal mechanism, often solicited by a government institution, which includes a technical approach, costing, and a notional schedule. Often, these proposals include the initial solution concept. In total the Engineers interviewed have over 75 years of cumulative experience in mechanical design at the laboratory, have all worked on various proposals and design problems, are all mechanical engineers, but represent various organizational groups.

Preliminary findings from these five interviews pointed at some key components to idea generation strategy employed at the laboratory. There was consensus that there is no formal method of idea generation being used at the laboratory, instead idea generation generally continued until the internal development team, including the project manager, was satisfied that the proposed design would be satisfactory to the customer. The most and only cited technique by name was Brainstorming, albeit what was described would not fit Obsorn's definition although similarities did exist. The "Brainstorming" technique involved engineers coming together to discuss different design options to satisfy a particular problem. People would throw out ideas and others would often build upon them. However, the process was very unstructured with idea evaluation also a common aspect of the process. Implicitly the goal of the process wasn't to expand and define the design space, but get to the "right" idea. This idea generation process is always in context of a larger conversation, it is not purely an academic exercise in creativity. The goal is not the generation of 20 different concepts per se, but rather to come up with a producible design from an abstract vision the customer has of what they want their product to do. There is no specific interest in the idea metrics of quantity, variety, novelty, and quality. Often the theory of operation of the product has been defined by the customer and the job of the engineers is to realize that vision in hardware.

Many of the engineers noted the importance of the proposal process. Often if a proposal includes a hardware solution, a particular concept is generated usually under the guidance of the project manager who interfaces directly with the customer within a tight timeline of about a week. These conceptual designs are often driven by either perceived or known customer requirements and are usually more cosmetic in nature than technical. The engineers noted that they are rarely working on an "ill-defined" problem that allows them to do divergent thinking and explore a large design space. More often, they are implementing, realizing someone's vision for what the hardware should "look like" or "be like".

Once a contract is awarded, the concepts are further refined within the program team that usually includes a single mechanical engineer. Assessment of this design is often done within the project team, which spans multiple engineering disciplines. These designs are almost always presented as 2D images from 3D CAD models developed by the mechanical engineer. Feedback on the design is given to the engineer, who then incorporates it into the design where applicable. When asked about how they solve smaller detailed or component design issues the engineers said that first they will usually do some idea generation on their own, which includes some search for inspiration, sometimes on the internet, or through every day analogies. Once they have some ideas, some go straight into 3D CAD to flesh them out, while others begin by hand sketching their ideas or white boarding them. Most, at some point, seek out other mechanical engineers for feedback on their designs, with the majority of them seeking out subject matter experts, someone they know that has some expertise in the design area of interest. Eventually, these designs get refined to the point that they are ready for review with the customer at a Preliminary Design Review (PDR). Often in this phase, rapid 3D prototypes of the design are created to verify the design intent and to convey to the team and customer the essence of the design. Then, the final design in the form of 2D presentations, either as proper fabrication and assembly drawings or as a slide deck, are present to the customer at a Critical Design Review (CDR) when the project team believes their design is ready to go to fabrication, integration, and testing. It was noted however that in only approximately half of the projects, what is eventually developed as the final design is notionally the same as the concept that was submitted with the proposal.

Generally, it seems that how engineers and organizations generate ideas for potential solutions, is not a common aspect in the course work of most engineering students. For organizations as well, learning how to successfully generate ideas is often very ad hoc, with only a small minority of them employing a formal approach. Engineers often develop their own strategies for the ideation phase of the project, this often includes group Brainstorming sessions, concept peer reviews, talking with more senior subject matter experts, and depending on the discipline generating 3D computer models. The results of this study formed the basis of the de-facto technique used for the Phase II experiment.

4 Phase II: Controlled Idea Generation Experiment

4.1 Experimental Methodology

Forty participants were categorized by their experience level, Junior- less than 7 years industry experience, or Senior- greater than 7 years of industry experience, and their domain experience, mechanical, electrical, software, systems, or quality. Participants were distributed into eight balanced groups with respect to experience level, domain expertise, and gender. The experiment took place over eight, hour long, lunchtime sessions in a laboratory conference room where food was provided. After reviewing and signing the necessary consent forms, all participants were given the same written design prompt, detailing the problem, asking them to generate ideas, and informing them on how those ideas would be scored. Next, participants in half of the sessions received details on the current solution in the form of an image and a detailed description. This served as the fixating example. All participants were then given 5 minutes to think of potential solutions or study the given solution, individually. For purposes of the study, those participants receiving the example solution were be considered "fixated". Next, the participants were given an information sheet on the idea generation technique they were expected to use for the session. Half of the groups received a sheet detailing the approximation of the de-facto method of idea generation, these groups are considered the control, while the other half received details on the mechanics of a modified C-Sketch technique. The C-sketch technique is considered modified since participants are not constrained to developing a single idea as is the case in the traditional approach. All groups had 30 minutes to develop concepts that meet the requirements of the design prompt. Once time elapsed all material was collected for evaluation and participants filled out a short survey that sought to uncover any uncontrolled variables that might result in a strong correlation to the results such as the aggregated frequency of idea generation tasks performed by members of the group. Then, participants were debriefed on the intent of the experiment, with the reminder not to discuss the experiment with anyone until after the final session was completed. In summary there were four distinct groups in the experiment, with each group being replicated twice: (1) Fixated participants doing de-facto ideation (2) Fixated participants doing modified C-Sketch (3) Non-fixated participants doing de-facto ideation (4) Non-fixated participants doing modified C-Sketch. For a summary of the group configurations and the randomized run order, see Table 1.

Table 1: Experimental Group Configurations

Experiment Order	Group Number	Idea Generation Technique	Fixating Example Given	Number of Participants
1	1	De-Facto	No	5
8	2	De-Facto	No	5
2	3	De-Facto	Yes	5
7	4	De-Facto	Yes	5
6	5	Modified C-Sketch	Yes	5
5	6	Modified C-Sketch	Yes	5
3	7	Modified C-Sketch	No	5
4	8	Modified C-Sketch	No	5

4.1.1 Participants

Volunteers from the engineering staff at Draper Laboratory were solicited via an email request to participate in the experiment. As an incentive to participate, a complimentary lunch was provided for the experimental sessions and members of the group that had the best results were given $25 Amazon gift cards. A total of 43 staff members volunteered for the exercise, with participants spread amongst the various engineering disciplines with various experience levels. All participants filled out a survey after the experiment that cataloged their years of industry experience, domain of expertise, the frequency in which they participant in idea generation meetings, what, if any, idea generation techniques have they used for work, and an open ended question asking them to characterize idea generation strategies at the laboratory. The participant survey used can be found in the Appendix.

4.1.2 Description of the Design Problem

The selection of the appropriate design problem is critical to developing an effective experiment. To fully characterize the idea generation process the problem needs to be sufficiently complex such that a complete solution must incorporate multiple functions to meet the requirements. The problem must also allow for various design solutions, some which could be quite novel. The problem should be a real world issue, unique enough that participants feel motivated to solve it without having hypothesized potential solutions a-priori. The problem should lend itself to solutions that are sketch-able, with simple annotations for further explanation. To measure the impact of the fixating example, the given solution to the problem, should be well documented, practical, even commonplace, or obvious. With these constraints in mind, the design problem and fixating example were established. The problem statement given to all participants was as follows:

<u>Design Problem Statement:</u>

During the winter of 2015 Eastern Massachusetts was hit with approximately six feet of snow in a four week period, crippling the state's transportation infrastructure. Most notably, the public transportation system run by the Massachusetts Bay Transportation Authority, or MBTA, was severely hampered with service on rail and subway lines cancelled, reduced, or delayed for most of this period. There was so much snow that officials had to shut portions of the above ground system down for days as they used armies of workers, including the National Guard, to clear the tracks and the electrified third rail that the subway cars use for power, see Figure 6 for an image of a snowbound subway train.

Figure 6: A Snowbound Red Line Train South of Boston, February 2015 [41]

Your task is to generate ideas on ways to keep the rails clear so that in spite of the next major snowstorm event, the MBTA shall be able to provide adequate service to the commuting public. Out of the box thinking is encouraged, be creative! Scoring will be based on the quantity, quality, variety, and novelty of the ideas. Individuals on the team with the best overall score will each receive a $25 gift card from Amazon.com. See the following page for details on how to capture your team's ideas.

4.1.3 De-facto Idea Generation Groups

After the case study in Phase I was completed an idea generation approach was developed to represent the de-facto group idea generation technique most often employed by engineers at the laboratory. In loose terms this could best be described as un-mediated Brainstorming, where white board sketches are commonplace to clarify design ideas, and both divergent ideation takes place almost concurrently with convergent design evaluation. Usually the groups are rather small, 3-5 people, with the engineer responsible for the design calling on other colleagues with design experience to participate, often with multiple engineering domains represented. This experience is replicated in the experiment by having groups with both junior and senior engineers from across multiple domains, performing the experiment in a typical conference room setting with a white board. The deviations from normal practice, identifying ideas by numbers, segregating them in different quadrants of the paper and having a fixed performance period, were instituted in order to better evaluate the outcome of the experiment. This experimental setup is recorded in the following explanation that is given to the participants at the start of the session:

Group Idea Generation:

You have been assigned to a team of five people to generate product solutions for this problem and will be scored as a team. A product solution is defined as a complete concept that solves the problem posed in the design problem. You will be given 30 minutes to develop ideas as a group on the white board or on the provided paper as you see fit. For product solutions on the white board, please denote diverse solutions with numbers and use the printout mechanism to document before erasing the board. Product solutions should primarily be expressed as sketches, with annotations as needed for clarity. If you use the supply of 8.5x11 paper, segmented into 4 sections, please segregate diverse solutions in these quadrants. Teams are expected to self-organize if they feel the need, but must work as *a single entity. At the conclusion of the 30 minute idea generation period, all the product solutions on paper plus those captured from the white board will be collected for evaluation.*

4.1.4 Formal Idea Generation Technique Groups

The formal idea generation groups used a modified C-Sketch approach. In the traditional C-Sketch technique, six individuals each develop three sketches each then pass those ideas five times to others on the group. In this modified format there is no constraint placed on the number of sketches an individual can do, and there are only five group members. The total time of the exercise is 30 minutes broken up into five, 6 minute rounds to match the total time of the de-facto technique. The instructions for the modified C-Sketch groups that was given at the beginning of the session is as follows:

<u>Collaborative-Sketch Participants:</u>

You have been assigned to a team of five people to generate <u>product solutions</u> for this problem and will be scored as a team, but you will be doing work individually using a technique called Collaborative Sketch. A product solution is defined as a complete concept that solves the problems posed in the design problem. You will be given a supply of 8.5x11 paper, segmented into 4 sections, please segregate solutions in these quadrants. Please use sketches for your solutions, with annotations as needed. You will have 6 minutes to sketch on as many pieces of paper as needed. Then you will pass these solutions to your teammate on your left for them to look at and either modify (erase some portion), improve upon, or to generate new solutions altogether on blank paper. You will receive solutions from your teammate on your right to do the same task. After another 6 minutes, these ideas will be rotated again to the next team member, and so on, until all team members have a chance to sketch upon their other teammate's solutions. At the conclusion of the 30 minute idea generation period, all the product solutions will be collected for evaluation.

4.1.5 Experimental Fixation Group

As shown in Table 1, two groups using the de-facto group idea generation technique and two groups using the formal idea generation technique, modified C-Sketch, will also be given a fixating example with the design prompt. This example will be included on a separate sheet of paper and groups can study this solution in the 5 minutes they are allotted before the group activity begins. The fixating example given was as follows:

The Current Solution:

The MBTA currently employs "Snowzilla" after severe snow storms which is a rail mounted device with an operator on top that uses a large jet engine to blow and melt snow off the tracks of the Red line's Mattapan trolley branch. See Figure 7 *for an image of "Snowzilla". The engine is capable of generating 3,000 pounds of thrust and reaching a temperature of 1,000 degrees, and its exhaust is directed down a chute to blast snow. It sits on railroad wheels, weighs 26,000 pounds, and measures 8 by 12 by 27 feet — though most of that length is taken up by its elongated snout. Its thirst for fuel is so great — it guzzles 900 gallons in a single run — that a tanker truck must follow it from station to station. Snowzilla shoots a jet of gas that obliterates snow from railroad tracks, only occasionally belching fire if you use it wrong* [42].

Figure 7: MBTA "Snowzilla" Machine [42]

5 Phase II Analysis of Results and Discussion

5.1 Experimental Session Results

The groups involved captured their ideas in one of two ways. The modified C-sketch groups were constrained to capturing their ideas on shared pieces of paper, while the de-facto groups, as their preference dictated, could capture their ideas on the conference room white board or on the supplied paper. Modified C-sketch teams did not communicate during the session while, de-facto teams had to talk with each other. Three out of four of the de-facto groups decided to capture their ideas on white board, whereas one group captured all their ideas on paper. During the experimental sessions the color of the markers or pencils that each group was using was switched in order to allow for evaluation of when the ideas occurred during the session temporally. Green denoted the first ten minutes, red the next ten minutes, and black the final ten minutes. Groups were reminded that the ideas needed to be mainly sketched, but annotations were allowed for clarity. This was done for consistency amongst the experimental conditions, specifically because C-sketch is a sketched based idea generation technique.

Figure 8 shows representative ideas on the white board from a de-facto technique group, while Figure 9 is a good representative set of proposed solutions that were captured by a modified c-sketch group on paper.

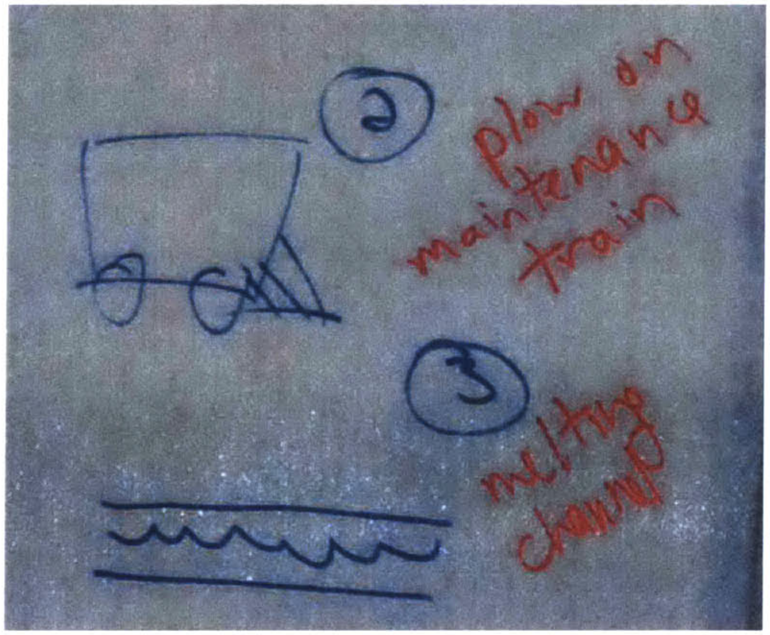

Figure 8: Group #1, De-Facto Group, Proposed Solutions

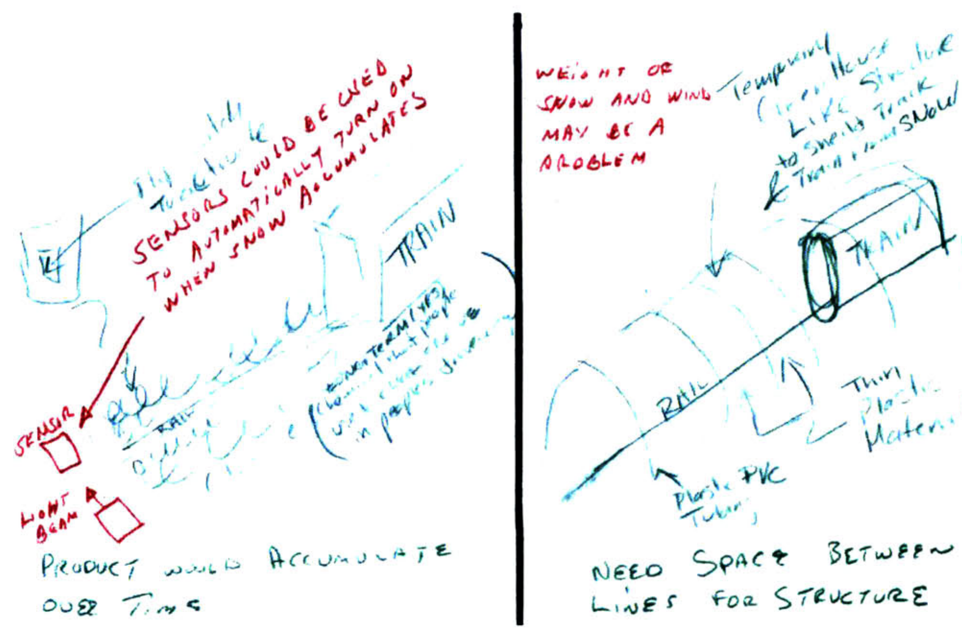

Figure 9: Group #5, Modified C-Sketch Group, Proposed Solutions

5.2 Metrics of Evaluation

To quantify the impact of the idea generation techniques used and to measure the effect of design fixation, several metrics were employed that were developed by Shah et al. [39]. To evaluate the impact of the idea generation technique used, four metrics were implemented: (1) quantity of functional ideas developed (2) novelty of functional ideas developed, (3) variety of functional ideas developed, and (4) quality of functional ideas developed. To assess the effect of the fixating example the metrics used to evaluate the idea generation techniques were employed. The expectation was that a group with a fixating example would have lower scores on all of the aforementioned metrics due to a solution space that is artificially constrained by the fixating example.

To accurately assess the experimental results it is important to define the difference between a functional idea and a product solution. The groups were specifically asked to generate product solutions, not functional ideas. This analysis bases these definitions on prior work done by Linsey et al. [21] where a functional idea is defined as a single idea to solve one of the product's functions and a product solution is defined as the sum of all functional ideas packaged as one solution and indicated as such by the experimental group.

To determine the quantity, quality, novelty, and variety of functional ideas, the overall product solutions generated by the groups were broken down into the discrete ideas that constitute the whole product. Each one of these discrete ideas counted towards the scores of the group. Some groups, especially those that used the white board often had only one or two functional ideas per product solution, Figure 10. In contrast, the modified c-sketch groups more often had multiple functional ideas in one product solution, Figure 11 shows an example of functional ideas and scoring.

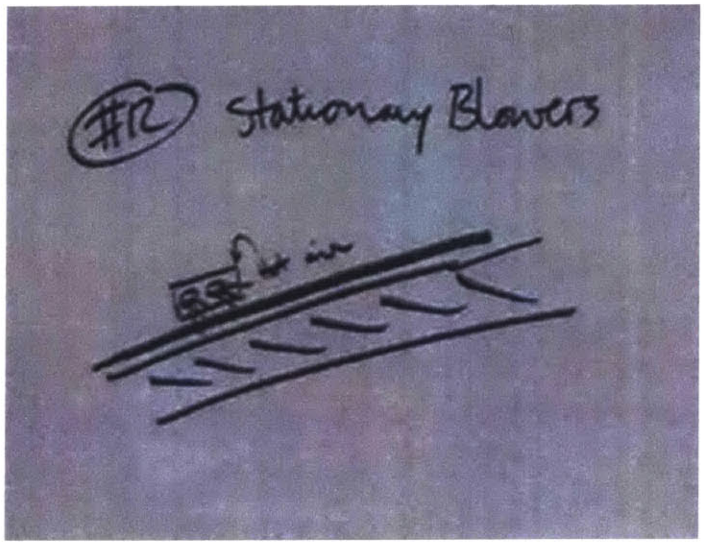

Figure 10: Single Functional Idea Product Solutionon a Whiteboard

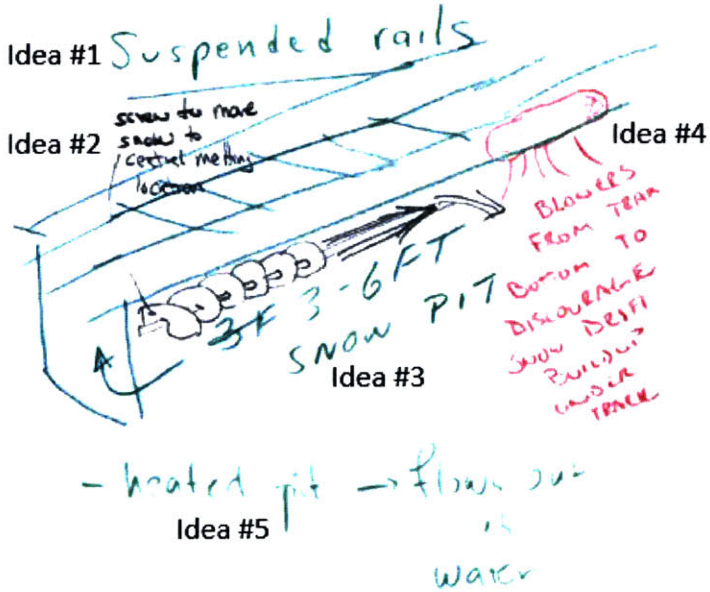

Figure 11: Product Solution with Multiple Ideas Using Modified C-Sketch, Note Iterations

5.3 Quantity of Functional Ideas

The quantity of functional ideas is assessed by simply counting the number of non-redundant functional ideas a group developed in all of their product solutions. The quantity score for each group was determined using (1)

$$Q = \sum_{x=1}^{p} Q_x \sum_{f=1}^{m} I_{1f} \quad (1)$$

where Q is the total group quantity score of p product solutions, Q_x is the quantity score for a product solution with *m* functions, and I_{1f} is the quantity of all non-redundant ideas for a particular function across all product solutions. The results for the quantity of functional ideas are given in Table 2.

Table 2: Quantity of Functional Ideas

Group Number	Idea Generation Technique	Fixating Example Given	Number of Ideas Per Team	Total Number of Ideas	Total Number of Non-Redundant Ideas
1	De-Facto	No	17	186	76
2	De-Facto	No	24		
3	De-Facto	Yes	17		
4	De-Facto	Yes	14		
5	Modified C-Sketch	Yes	29		
6	Modified C-Sketch	Yes	26		
7	Modified C-Sketch	No	30		
8	Modified C-Sketch	No	29		

Performing a one way ANOVA (analysis of variance) on the quantity score showed statistically significant effect (F=21.00, p=.0038) with respect to the use of the de-facto or formal technique. This difference in the quantity of functional ideas indicates that the formal technique was more effective at generating more ideas than the de-facto technique, see Figure 12.

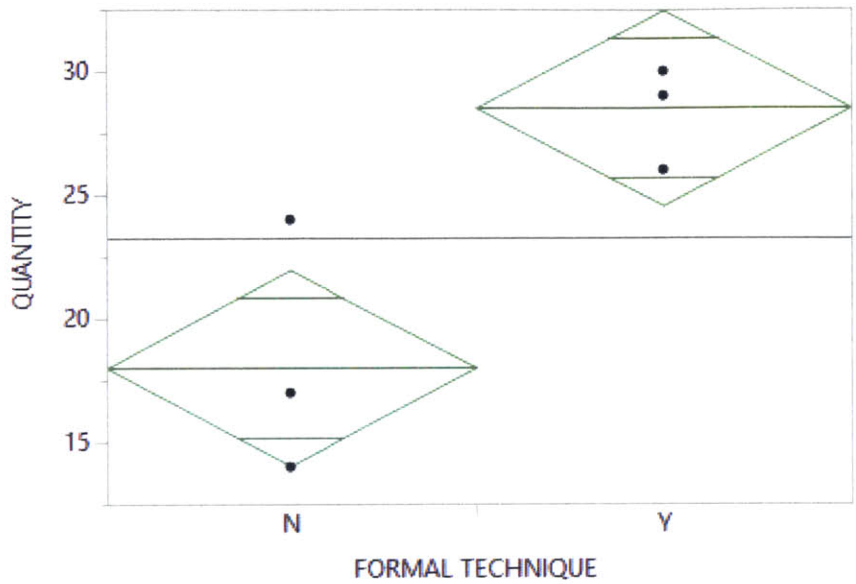

Figure 12: One-Way ANOVA Quality vs. Formal Technique

Performing a one way ANOVA on the quantity score with respect to the presence of a fixating example did not show a statistically significant effect (F=.578, p=0.48), however the trend shows that the fixating example potentially could have been detrimental to the quantity result, see Figure 13.

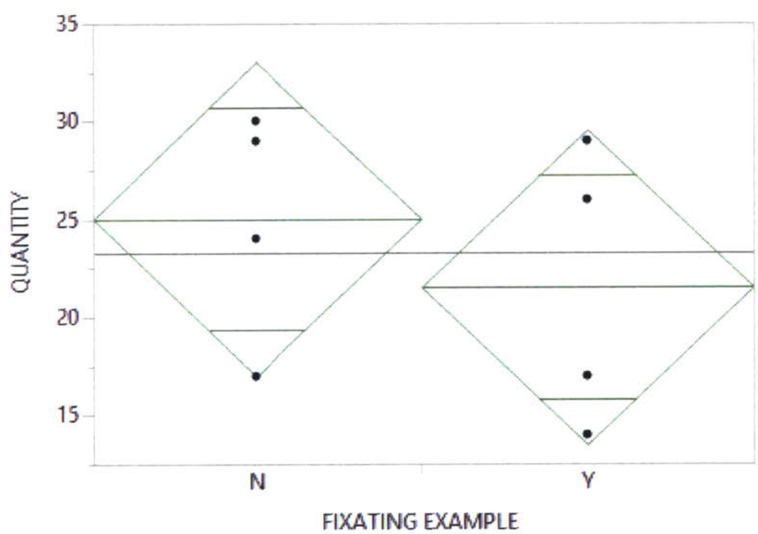

Figure 13:One-Way ANOVA Quality vs. Fixating Example

5.4 Novelty and Variety of Functional Ideas

Using the approach developed by Shah et al. [39] the novelty score for each group was determined using (2)

$$N = \sum_{x=1}^{p} N_x \sum_{f=1}^{m} f_f S_{1f} \quad (2)$$

where *N* is the total group novelty score of *p* product solutions, N_x is the overall novelty score for a product solution with *m* functions, the functional weightings are f_f, and S_{1f} is calculated using (3)

$$S_{1f} = \frac{T_f - C_f}{T_f} \times 100 \quad (3)$$

where S_{1f} is the novelty score for each function, T_f is the total number of ideas produced for a said function, and C_f is the count of the current ideas for that function. Multiplying by 100 normalizes the expression. No functional weightings were assigned in this analysis. The novelty results are given in Table 3.

Table 3: Novelty of Functional Ideas

Group Number	Idea Generation Technique	Fixating Example Given	Novelty Score
1	De-Facto	No	71
2	De-Facto	No	104
3	De-Facto	Yes	67
4	De-Facto	Yes	53
5	Modified C-Sketch	Yes	124
6	Modified C-Sketch	Yes	105
7	Modified C-Sketch	No	139
8	Modified C-Sketch	No	131

Performing a one way ANOVA on the novelty score showed statistically significant results ($F=15.36$, $p=0.0078$) with respect to the use of the de-facto or formal technique, Figure 14. This difference in the novelty of ideas indicates that the formal technique was more effective at generating more novel ideas than the de-facto technique.

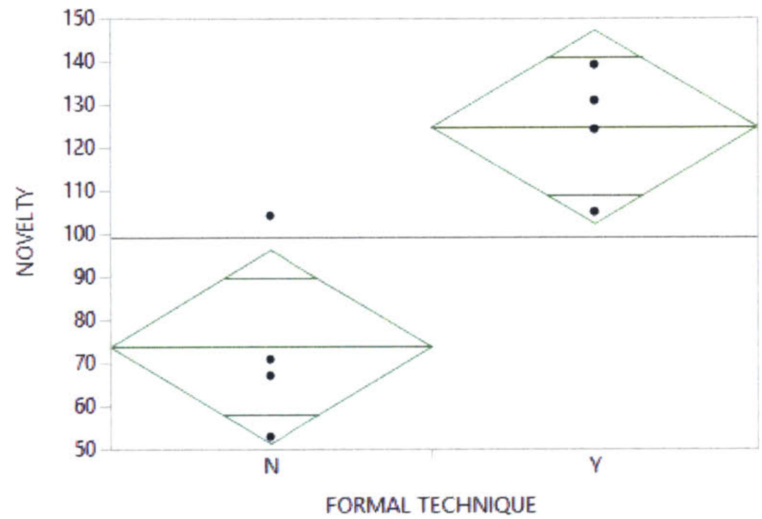

Figure 14: One-Way ANOVA Novelty vs. Formal Technique

Performing a one way ANOVA on the novelty score did not show a statistically significant results (F=1.14, p=0.327) with respect to the presence of a fixating example, see Figure 15. However, the results seem to show that for this design problem a fixating example likely reduced the novelty of the ideas generated.

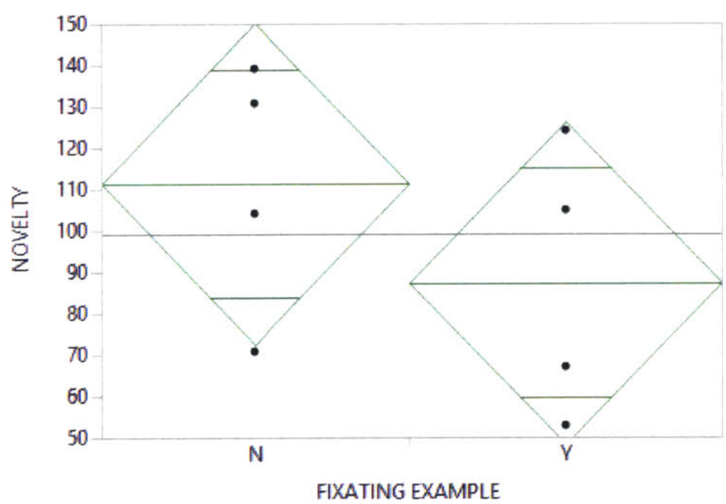

Figure 15: One-Way ANOVA Novelty vs. Fixating Example

The variety score for each group was determined using (4)

$$V = \sum_{x=1}^{p} V_x \sum_{f=1}^{m} f_f S_{2f} \text{ (4)}$$

where V is the total group variety score of p product solutions, V_x is the overall variety score for a product solution with m functions, the functional weightings are f_f, and S_{2f} is calculated using (5)

$$S_{2f} = \frac{B_c}{B_t} \times 100 \text{ (5)}$$

where S_{2f} is the variety score for each function, where functional ideas from all product solutions, from all groups, binned together by similarity with the total number of bins denoted B_t, and B_c is the number of bins occupied with at least one idea for the group. Multiplying by 100 normalizes the expression. No functional weightings were assigned in this analysis. The variety results are given in Table 4.

Table 4: Variety of Functional Ideas

Group Number	Idea Generation Technique	Fixating Example Given	Variety Score
1	De-Facto	No	22
2	De-Facto	No	32
3	De-Facto	Yes	22
4	De-Facto	Yes	18
5	Modified C-Sketch	Yes	38
6	Modified C-Sketch	Yes	34
7	Modified C-Sketch	No	39
8	Modified C-Sketch	No	38

Performing a one way ANOVA on the variety score showed statistically significant result ($F=18.63$, $p=0.005$) with respect to the use of the de-facto or formal technique. This difference in the variety of ideas indicates that the formal technique was more effective at generating a wider variety of ideas than the de-facto technique.

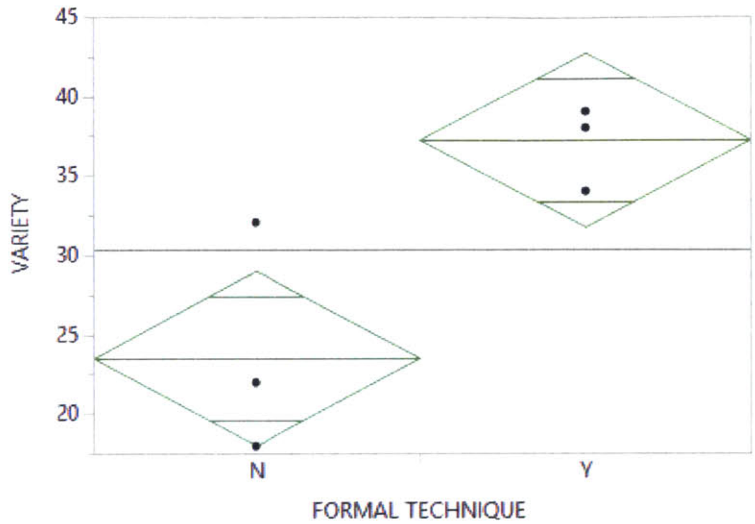

Figure 16: One-Way ANOVA Variety vs. Formal Technique

Performing a one way ANOVA on the variety score did not show a statistically significant relationship (F=0.6, p<0.47) with respect to the presence of a fixating example, see Figure 17. However, the results seem to show that for this design problem a fixating example potentially reduced the variety of ideas generated.

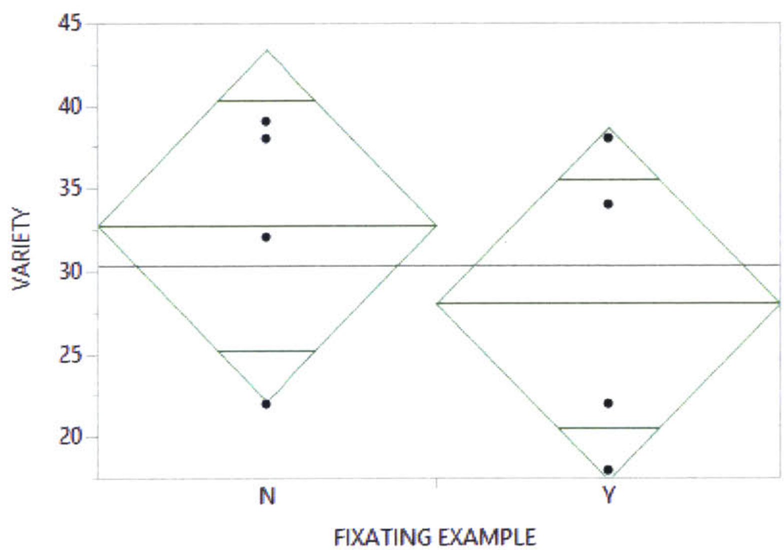

Figure 17:One-Way ANOVA Variety vs. Fixating Example

5.5 Quality of Functional Ideas

Quality scores for the group were determined by a panel of judges which included the author of the study and two engineers who were blind to the purpose of the experiment or hypotheses of the result. The quality of the standalone functional ideas were scored individually, not at the product solution level, using a new quality scale, see Table 5, that was inspired by a similar scale developed by Linsey et al. [21] and given in Figure 18. The quality scale was modified to provide more granularity and force a greater spread, specifically since functional ideas were being scored, not product solutions.

Table 5: Modified Functional Idea Quality Scoring

Functional Idea Quality Scoring		
Is the idea feasible?	No	0
	Yes	1
Does it solve the whole problem?	No	
	Yes	3
Is the idea efficient and reasonable?	No	
	Yes	6

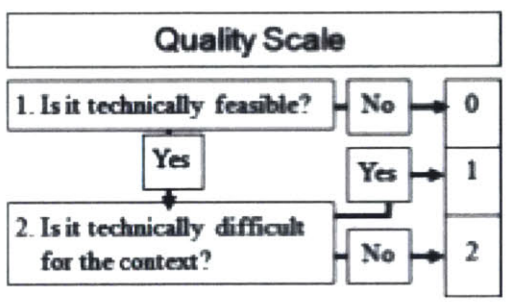

Figure 18: Product Solution Quality Rating Scale [21]

Scoring was done in a real time panel format and any discrepancies were discussed and resolved amongst the three by majority vote. The results are given in Table 6.

Table 6: Quality of Functional Ideas

Group Number	Idea Generation Technique	Fixating Example Given	Quality Score
1	De-Facto	No	40
2	De-Facto	No	45
3	De-Facto	Yes	35
4	De-Facto	Yes	36
5	Modified C-Sketch	Yes	61
6	Modified C-Sketch	Yes	48
7	Modified C-Sketch	No	66
8	Modified C-Sketch	No	50

Performing a one way ANOVA on the quality of functional ideas score showed a statistically significant result (F=12.25, p=0.012) with respect to the use of the de-facto or formal technique, see Figure 19.

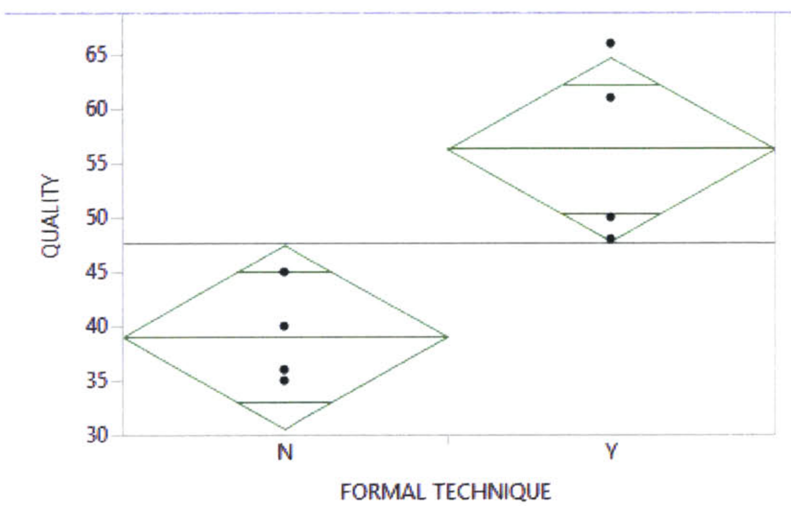

Figure 19: One-Way ANOVA Quality of Functional Ideas vs. Formal Technique

Performing a one way ANOVA on the quality of functional ideas score did not show a statistically significant relationship (F=0.4, p<0.55) with respect to the presence of a fixating example, see Figure 20. However, the results seem to show that for this design problem a fixating example potentially reduced the quality of ideas generated.

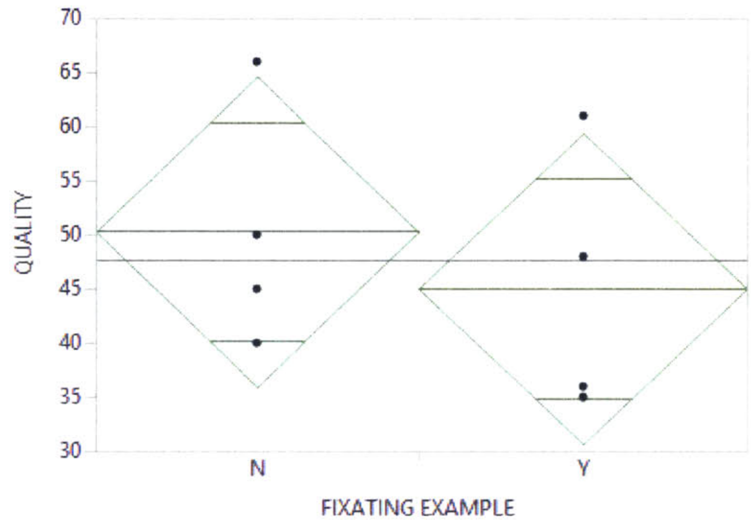

Figure 20: One-Way ANOVA Quality of Functional Ideas vs. Fixating Example

5.6 Evaluation of Uncontrolled Variables

The information gathered in the survey was used to determine if variables that were not specifically controlled in the experiment could be correlated to the results obtained. These variables were chosen because they might plausibly influence the experiment. Any correlations should not necessarily be considered causation of the results. However, efforts should be made to reduce any strong correlations found herein for any future extension of this research, or study whether these correlations could in fact be predictive of the overall results. The uncontrolled variables that were monitored and their multivariate correlations scores with respect to the functional idea metrics are given in Table 7. A score of 1.00 shows positive correlation, while a score of -1.00 shows a negative correlation.

Table 7: Multivariate Correlation of Uncontrolled Variables

Functional Idea	Industry Experience	Idea Generation Experience	Snow Removal Experience	Public Transportation Experience
QUANTITY	0.441	-0.171	0.423	-0.029
VARIETY	0.426	-0.161	0.437	-0.033
NOVELTY	0.477	-0.130	0.384	0.013
QUALITY	0.354	-0.231	0.397	-0.052

From the results in Table 7, there seems to be a slight positive correlation between industry experience and all performance metrics. Conversely, however, there seems to be a slight negative correlation between all performance metrics and the amount of idea generation experience of the group. There was a slight correlation between the performance metric results and the experience at snow removal and no correlation between the level of use of public transportation in the winter months and the performance metrics.

Participants were also asked questions to qualitatively assess the effect of having an example, if applicable, the perceived effectiveness, and level of comfort with the technique that they used.

The results of participants perception of the impact of receiving an example is given in Figure 21.

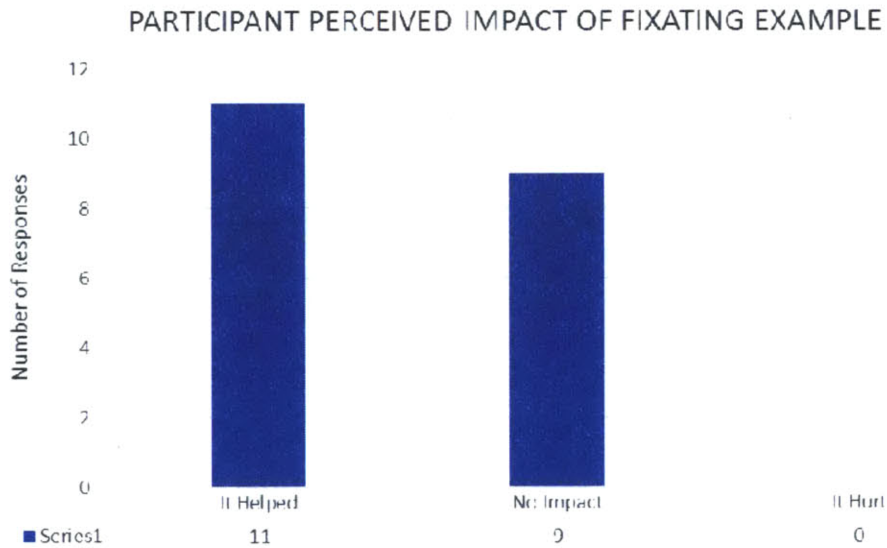

Figure 21: Results for Survey Question: What affect did the provided example have on your performance? N=20

The level of comfort and perceived effectiveness with the technique used varied across the two conditions. A one way ANOVA was performed for both comfort and effectiveness on the technique used and the results of showed a statistically significant higher level of comfort with the de-facto condition, than the formal technique (F=6.943, p=.039), Figure 22. The results are not shown to be significant for the effectiveness of the technique used, even though slightly more groups found the de-facto technique to be more effective (F=.46, p=.52), see Figure 23.

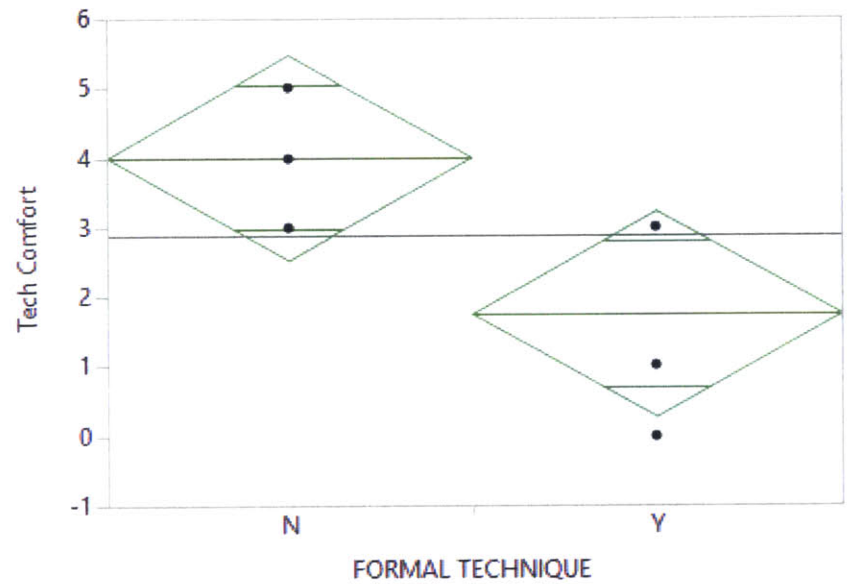

Figure 22: One-Way ANOVA Level of Technique Comfort vs. Formal Technique

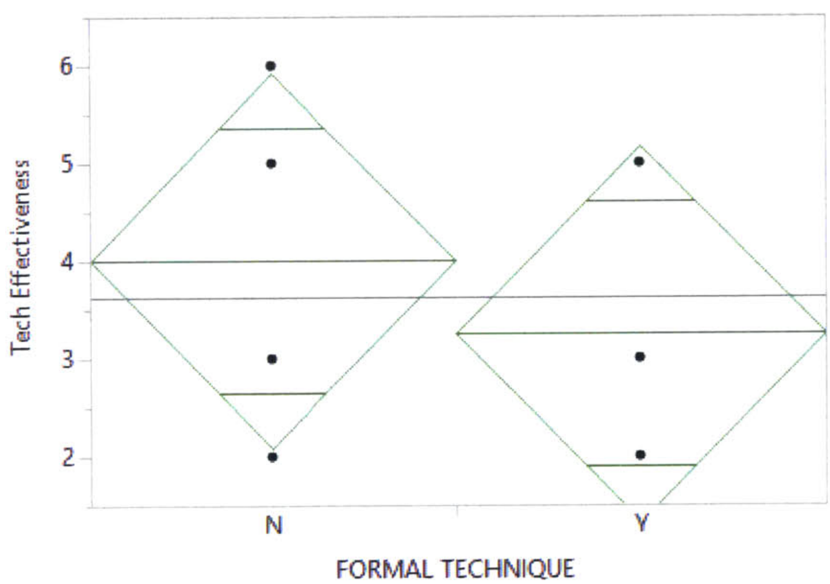

Figure 23: One-Way ANOVA Level of Technique Effectiveness vs. Formal Technique

5.7 Influence of White Board Use

In Figure 12, Figure 14, and Figure 16 there is a consistent outlier amongst the de-facto technique groups, Group #2. This group was the only one of the four de-facto technique groups to decide to capture their ideas on paper instead of the white board. If the overall results are regrouped by whether the group used the white board or paper to capture ideas and a one way ANOVA is performed on the variety score, for example, the results show a statistically significant difference, (F=57.1, p=.0003), see Figure 24. Similarly statistically significant results are obtained when quantity, novelty, or variety metrics are reviewed.

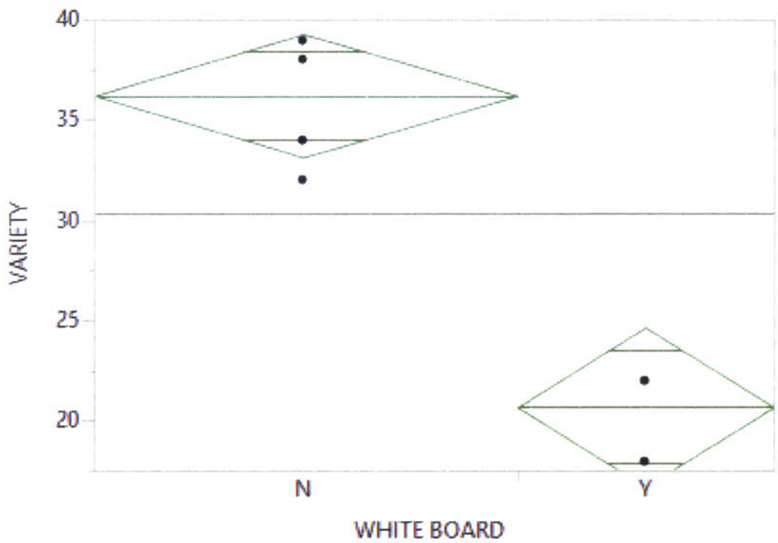

Figure 24: One-Way ANOVA Variety vs. White Board Use

5.8 Correlation of Metric Scores

Also of interest is the correlation results between the metric scores themselves, as given in Table 8.

Table 8: Correlation between Functional Idea Scores

Functional Idea	QUANTITY	VARIETY	NOVELTY	QUALITY
QUANTITY	1	0.999	0.991	0.896
VARIETY	0.999	1	0.989	0.887
NOVELTY	0.991	0.989	1	0.905
QUALITY	0.896	0.887	0.905	1

The results show a very strong relationship between all the metrics used. Quantity and Variety scores are nominally 1 to 1, that is because only non-redundant ideas were counted for the quantity score, meaning that every idea fell into its own variety bin by default, since the bins were defined as unique ideas. If the definition of what constituted a bin was much broader than what was used for this analysis, for example: “a mechanical device to relocate snow”, then what was scored as unique ideas, snow plow, snow sweeper, and snow blower, could instead of having a Quantity and Variety score of 3, it would have had a Quantity score of 3, and a Variety score of 1. Also, Variety, Novelty, and Quality are all strongly correlated.

6 Phase II Discussion of Results

6.1 Research Question 2: Efficacy of Idea Generation Technique

The experimental results clearly show that under the conditions of this experiment the formal technique, modified c-sketch, out performs the de-facto technique on all performance metrics. From observing all the experimental groups some trends emerged that at least qualitatively suggest some of the potential reasons behind these results.

Productivity. Observing the groups it quickly became apparent that the modified c-sketch groups were more productive. The de-facto groups struggled initially to organize themselves, deciding who was going to draw, should they go around the room suggesting ideas in turn, or free of all, should they talk about the issues, or jump right into potential solutions, some worried about giving ideas that didn’t seem feasible, most apologized for their inability to sketch well. In contrast the modified c-sketch groups all started individually sketching, there was little, to no conversation. Procedural mechanisms of waiting for one person to sketch or give an idea, even though there was no experimental constraint on the number of people capturing ideas, other than they had to work as a group, for the de-facto groups seemed to put them at a disadvantage as compared to the modified c-sketch groups.

Performance Pressure/Social Loafing. Amongst the modified c-sketch groups, there was likely a certain amount positive performance pressure that reduced the amount of social loafing by group members. This can be attributed to the fact that after the first drawing session a participant had to give their ideas to another participant, and it is likely that participants felt the need to perform for their group mates, they just couldn't hand them a blank sheet of paper. Also, when a participant received ideas from another, it is likely they felt more obligated to improve on those ideas, compared to ideas that have been shared on a white board. On the contrary the de-facto groups, particularly the three that used the white board, suffered from at least one member of the five person groups not contributing in a significant way. They were content to allow others to "run the show."

Group Evaluation. All de-facto groups seemed to spend some significant amount of time evaluating the feasibility of their ideas. This group evaluation not only took time away from idea generation, but it seemed to narrow the potential solution space that would be acceptable to have an idea count. In the modified c-sketch groups, while there were a few instances of idea evaluation on the sketches, generally most efforts were focused on expanding the potential solution space. It should be noted however that in their evaluations of the modified c-sketch technique often participants complained about the inability to talk to their group members about the ideas, assuming it was a hindrance not to do so. Paradoxically, it seems likely though that if they were able to talk amongst themselves more evaluation of ideas would have occurred, leading to poorer results. Interestingly, prior research into online distributed design teams were found to perform better on some measures, likely also due to the focusing effect of working individually and in effective isolation [43] as is the case in this experiment.

Need for Consensus. This seemed to play a role in reducing the number of ideas in the de-facto groups. From experimental observation, ideas that were scored on modified c-sketch groups were often discussed and pocket vetoed by the de-facto groups because of a lack of a strong positive reaction to the proposed idea. Often the backer of the idea would propose the idea once again, sometimes with positive results, sometimes not. For the modified c-sketch groups, the only person that needed to be convinced to log an idea was the author himself, which is emotionally a much easier hurdle to cross, especially since the modified c-sketch technique affords the participant two forms of protection from outside judgment: anonymity and lack of need for group consensus.

6.2 Research Question 3: Impact of Design Fixation on Idea Generation

The presence of a fixating example had only a slight effect on the outcome of the idea generation sessions, and nothing was statistically significant. Also, there was no significant interaction between the fixating example and the technique used. The effect of the fixating example was much weaker, or even non-existent, than expected prior to the experiment. From observations of the two de-facto groups that were given the fixating example, there was little discussion of the example during idea generation. Actually, it seemed as if these groups were doing all they could to come up with ideas that were *different* from the example, instead of being focused on it. It was not expected that the groups would use the fixating example in that manner, even though avoiding the example might have also attributed to a potentially smaller solution space. This use of the example might stem from the fact that it was tagged as "The Current Solution" which after the poor performance of the public transportation system during the winter of 2015 was clearly shown to be lacking and other potential ideas were needed, and is therefore an inferior solution that needs to be improved in some way. The modified c-sketch groups did not have any discussions during the idea generation experiment, so understanding the reasoning behind the impact of the example on their approach isn't known.

6.3 Discussion of Other Notable Results

From observation of the four groups using the de-facto approach, it was clear that while most would say they were performing brainstorming, it would not meet the criteria Osborn set out for this technique. This is also in contrast to the fact that on the survey 95% of participants said they have used Brainstorming at Draper Laboratory. The differences between what was done with the de-facto approach and what would be a purely Brainstorming activity are interesting to evaluate. First, it seems as if people believe they are performing Brainstorming, but in reality they are using some unregulated technique that has some similarities with Brainstorming. The results of this experiment should not be construed to show that Brainstorming is less effective than a modified c-sketch approach. Instead these results should point to the fact that these practitioners rarely perform pure Brainstorming as often as they might think, and that this modified approach has statistically significant deficiencies with respect to a more formalized approach.

Interestingly, participants were also less comfortable with the modified c-sketch approach, although it out performed the de-facto approach. One possible reason for this expression of discomfort was linked to the fact that modified c-sketch made them think harder, stretch more than the de-facto approach. Also of interest is that not a single participant believed that the fixating example hurt their output, while the impact of the example wasn't statistically significant, the results are contrary to the perception of the participants. In both of these cases it seems plausible to believe that the participant's perception did not match reality.

Reviewing the group results, it seems that ideas were more refined amongst the modified c-sketch groups with much more additional detail than what was done in de-facto groups. This is likely due to the nature of how the ideas were presented. In the modified c-sketch technique since ideas are sitting in front of each participant, the ability to easily add refining details is easier than standing up from a conference room table and doing modifications on a white board to another participants' sketch. It could also be that towards the end of the idea generation period, people ran out of wholly new ideas and started to just improve or modify what they have seen, in modified c-sketch groups, whereas de-facto groups continued to try and develop standalone product solutions.

7 Conclusions and Future Work

7.1 Summary

The use of a formal technique improved the idea generation outcomes based on the four the performance metrics measured. The presence of a fixating example was not shown to have a significant detrimental impact on the results of the experiment. It is likely that those that received the example were actually trying to avoid its use, creating a reverse fixation state that potentially could have been the cause of the results. The de-facto method used suffered from all the well-known problems of working in groups when divergent thinking is desired: procedural inefficiencies, constant desire to build consensus, desire to converge on solutions, evaluate ideas, during the process, and social loafing. The modified C-sketch approach provided a mostly evaluation free environment, reduced the social loafing aspect by the positive effects of peer evaluation, that spurred participants to work hard to develop more ideas, and lastly there was no need to have group consensus for the ideas.

The difference in outcomes between the three de-facto groups that used the white board and the one group that used paper on the conference room table seems to merit further study. Observing these groups, the group that did not use the white board seemed to have all members more engaged in the process, which seemed to reduce the social loafing aspect as well as giving group members the ability to record multiple ideas at the same time. While they were working as a group, the individual sketchers seemed to feel that they have the freedom to put ideas down on paper without having group consensus like those that were using the white board.

Reviewing the results of the multivariable correlations provided in Table 7, it is unlikely that the results of this experiment were impacted by these uncontrolled variables. This lends credibility to the overall results obtained.

7.2 Limitations

One limitation of this experiment is the broader applicability of the results. The de-facto technique might only represent reality at Draper Laboratory and de-facto at other organizations could be widely different. The example given might have been too real for the groups to become fixated on, especially since it was called "The Current Solution". It seemed that groups thought they had to come up with other solutions than the fixating example.

The quality scoring could have been done at the product solution level instead of at the functional idea level, it is not clear if that would have resulted in a different outcome. Potentially, the modified c-sketch groups would have outperformed the de-facto groups the same, since generally their designs had more detail, realism.

7.3 Possible Future Work

The work presented in this thesis could be extended in various ways. While two replications of this experiment were done, further replication of this work using the de-facto techniques in use at other engineering organizations would lend credibility to the conclusions of this work. It would also be noteworthy to compare the results of a de-facto technique with a formal Brainstorming technique. The discussed "white board effect", should be studied under a controlled experiment. This would be a very interesting experiment, since many organizations are moving more towards white board use, rather than hand sketching.

Future work could also include a more detailed experiment with students versus practitioners. Characterizing how organizational power structures influence the results of group idea generation techniques amongst practitioners which might be largely absent or substantially different than within studies that involve solely engineering students.

8 Appendix

8.1 Participant Initial Survey

Participant Survey, please provide some information about yourself:

1. Draper Engineering Staff Level:

MTS-I MTS-II SMTS PMTS DMTS LTS

2. What is your primary engineering domain experience:

Mechanical Electrical Software Test Systems Quality Other__________

3. How often do you perform conceptual design tasks at Draper:

Weekly Monthly Every 3 months Once a Year Almost Never

4. Do you usually commute to work using public transportation in the winter months?

Yes No

5. Do you usually do the snow removal at your residence?

Yes, manually Yes, snow blower No, it's done by someone else (family member, prof. service)

6. Check any idea generation techniques you have used at Draper, excluding today's exercise:

Brainstorming
Brainsketching: doing individual sketching and reviewing others work before continuing
Functional Analysis: Decomposing a problem into it functional parts to identify solutions
TRIZ (Theory of Inventive Problem Solving): Using a database of pre-ordained design solutions
C-Sketch, (6-3-5): These are progressive sketching techniques
Other______________________

7. If you saw an example solution today do you think it helped or hurt your overall idea generation process?

I didn't receive an example solution today   It helped   It hurt   It had no impact either way

8. How comfortable were you with the idea generation technique you used today?

Comfortable   It was OK   It was awkward

9. How effective was the idea generation technique you use today?

Very effective   Effective   It was OK   It was detrimental

10. Many organizations have different cultures for idea generation, how would you characterize how Draper, in your experience, does idea generation?

11. Any other comments or observations you would like to share?

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