Evaluation of Collaborative Sketching (C-Sketch) as an Idea Generation Technique for Engineering Design

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Abstract

This paper presents the first evaluation of a technique for concept generation in a collaborative engineering design setting (C-Sketch). A survey of relevant literature provides the foundation for this evaluation. This review includes the underlying sciences of idea generation and the issues directly related, such as cognitive models for creativity problem solving, roles of images, sketches, and a survey of “blocks and tackles” in idea generation methods. The paper reviews both the intrinsic properties of C-Sketch and the results of comparative studies. This analysis is based on results from experiments on progressive idea generation methods conducted over five years at the Design Automation Lab at Arizona State University and other experiments found in the literature. The intrinsic properties examined are provocative stimuli, feedback, design fixation, and the method variables of C-Sketch. The comparative studies analyze C-Sketch and other methods of the same class and type, namely Method 6-3-5 and Gallery method. This paper concludes that C-Sketch has intrinsic properties useful in idea generation. Finally, experimental results show the advantage of C-Sketch over Method 6-3-5 and Gallery Method for selected design problems, indicating that C-Sketch is an effective, idea generation tool for the graphically dependent domain of mechanical engineering.

1 Introduction

Studies estimate that nearly seventy percent of the life cycle cost of a product is determined during conceptual design (National Research Council, 1991). Therefore, there is a need to use methods that would help designers develop better and more innovative solution concepts during design. Several idea generation (IG) methods have been developed over the past four decades and have been described in the design literature. These methods may be broadly classified into two categories: intuitive and logical. Intuitive methods are aimed at increasing the flow of ideas, removing mental blocks and increasing the chances of occurrence of perceived creativity promoters. Logical, or systematic, methods use engineering principles and/or catalogued solutions from past experience to generate design solutions. A taxonomy of idea generation methods is presented in Shah (1998) and Kulkarni (1998). The research presented here is interested primarily with C-Sketch, which is an intuitive method. Other methods in the same category are brainstorming (Osborn, 1979), the Gallery Method (Pahl and Beitz, 1996), the K-J method (Hogarth, 1980), Storyboarding (VanGundy, 1988), and Synetics (Gordon, 1961), among others.

Choosing when to use sketching for idea generation depends on the problem type and the representation type that is more appropriate. Mechanical, architectural and industrial design problems have predominant geometric aspects that make the use of free hand sketches more appropriate for the representation of geometry. Other aspects of a design problem (kinematics, thermal, electrical, etc.) may be better addressed using other visualization methods (symbolic, kinematic or schematic) for its representation, this may impose some rigor in the format of sketching. Added to the problem type and representation type, a design problem also has different levels of abstraction for which some representations are more appropriate. In an example from Shah and Wilson (1989), a gear train is represented at different levels of abstraction: kinematic representation, systematic force analysis, tooth form...
In the past, cognitive psychologists and design researchers have studied the role of sketches and images in the generation of creative ideas for solving design problems. There is much anecdotal evidence supporting the belief that when designers are given a design problem they reach for their pencils to draw what are commonly known as “back of the envelope” sketches. These are rough drawings, or doodlings, which designers use during the search process for a design solution. In fact, Ullman, et al., (1990) state that engineers are notorious for not being able to think without these sketches to shape ideas and concepts. There is also considerable anecdotal evidence from introspective reports from the literature that suggests the important role that mental imagery plays in the creative process. Some famous examples are Kekule’s dream about a snake seizing its own tail, leading to the discovery of the Benzene structure (Findlay, 1948) and Watson and Crick’s use of imagery to establish the helical structure of DNA (Miller, 1984). While this sampling of anecdotal reports does not establish that images actually play the crucial functional role attributed to them, one could be missing something of potential importance if one assumes that visual imagery is of no consequence in discovery.

Collaborative sketching (C-Sketch) is an idea generation method that was proposed originally in 1993 in the Design Automation Lab (DAL) at Arizona State University under the name of 5-1-4 G (Shah, 1993). It originated as an extension of Method 6-3-5 (Rohrbach, 1969) in which 6 designers generate 3 ideas at each of 5 passes. The method, 5-1-4 G, was so named for the number of designers (5), the number of ideas upon which the designers worked at a time (1), and the number of passes (4). The “G” indicated that the method was a graphically oriented method. The method was renamed to C-Sketch in an attempt to provide a more descriptive name.

In the C-Sketch method, designers work on developing graphical representations of solutions to a design problem. The method is suitable for use after the problem definition and clarification stage in the engineering design process. Designers work independently, developing a sketch of their proposed solution to the problem for a predetermined length of time (cycle-time). When the time has expired, the sketch is passed to the next designer. This designer may then add, modify, or delete aspects of the design solution. The fundamental limitation to changes in the sketches is that the entire design may not be erased. In this manner, the sketches are passed sequentially through the design team. Designers add their own imprint on the design sketches. At the conclusion of the exercise, a set of solutions will be available, the number of which equals the number of designers participating in the method. A secondary constraint is that sketching is the only allowed mode of communication among design team members. Figure 1 illustrates the pattern for passing the sketches in a group of designers. The sketch from the first designer is passed to the second, and so on until all designers have worked upon the same sketch. As an example of the types of sketches which may be generated using C-Sketch for design, Figure 2 illustrates some sketches generated in experiments on C-Sketch as a progressive idea generation method.
There are two basic method variables in C-Sketch: the time allocated for each designer to work upon a sketch and the number of designers in a loop. These two variables may be adjusted to obtain different outcomes. Other variables that are involved in employing C-Sketch that are independent of C-Sketch include the type of designer, the problem type, the goals of the designer, and the environmental variables at the time of use. These variables influence the operation of C-Sketch as they would influence other idea generation methods.

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. In order to understand the intrinsic values of C-Sketch, it is first necessary to understand the rationale for these three pillars of C-Sketch. Kulkarni (1999a) provides a discussion on blocks and tackles in innovative thinking. These will be discussed later in the paper. This paper will present the first coherent view of C-Sketch, including benefits and limitations of its use. Intrinsic merit found in the development of the method will be discussed. Further, results of comparative studies of C-Sketch will be presented and discussed. This is the first paper detailing the application and the merits of the new idea generation method, C-Sketch.

2 Literature Review

In the study of the applicability of C-Sketch as an idea generation method, it is first necessary to study the underlying sciences of idea generation and issues directly related. A survey of idea generation methods, a brief overview of cognitive models for creativity and problem solving, a survey of “blocks and tackles” in idea generation methods, the roles of images in design, and a discussion on sketches.

2.1 Idea Generation Techniques

Several methods exist today that are believed to aid the process of idea generation in engineering design and to enhance innovative thinking. These methods have two features in common – they formalize the idea generation procedure through certain rules and they externalize design thinking through sketches and other means. Some methods have been developed for the use of individuals, while other are designed for the use of groups.

Structured idea generation methods may be broadly classified into two categories: intuitive methods and logical methods. Intuitive methods work by stimulating the unconscious thought. The outcome is unpredictable, yet there is an increased chance of achieving a novel solution. Logical or rational methods involve systematic decomposition...
and analysis of the problem. These methods make use of conscious, deliberate processes that force the generation of solutions in a predictable manner. Idea generation methods have been classified as shown in Figure 3.

**Figure 3 - Classification of Idea Generation Methods (Shah, et al, 2000b)**

*Intuitive methods*, as found in the top of Figure 3, have been classified into five categories: *germinal, transformational, progressive, organizational*, and *hybrid methods*. *Germinal* are methods that are meant to be used when a designer is making a fresh start on generating ideas; such as when the designer does not have any existing solutions to start with. Some examples of Germinal methods are Morphological Analysis (Zwicky, 1969), Brainstorming (Osborn, 1979), and the K-J Method (Hogarth, 1980). *Transformational methods* are used to generate ideas by modifying existing ideas. There are three transformational methods: Checklists (Osborn, 1979), Random Stimuli (DeBono, 1970), and PMI Method (DeBono, 1970). *Progressive methods* are methods in which ideas are generated by repeating the same set of steps a number of times, thus generating ideas in discrete progressive steps. Three progressive methods have been identified, including Method 6-3-5 (Rohrbach, 1969), C-Sketch (Shah, 1993), and the Gallery Method (VanGundy, 1988). *Organizational methods* are those that help designers group together the ideas that have been generated in some meaningful way. The Affinity Method (Mizuno, 1988), Storyboarding (VanGundy, 1988), and Fishbone Diagrams (Fogler and LeBlanc, 1995) belong to this class of methods. *Hybrid Methods* such as Synectics (Gordon, 1961) combine many different techniques to address varying needs at different phases.

*Logical methods*, as found in the bottom of Figure 3, have been classified into two categories: *History Based Methods and Analytical Methods*. *History Based Methods* involve the use of past solutions that have been catalogued or archived in some form of database. Two methods belong to this category namely Design Catalogs (Pahl and Beitz, 1996) and TRIZ (Altshuller, 1984). *Analytical Methods* developed ideas by systematically exploring variations of an initial solution. SIT, Forward Steps and Inversion are three methods belonging to this class of methods.

### 2.2 Blocks and Tackles

The various idea generation methods discussed earlier are composed of sub-components, either explicitly or implicitly. These components provide hindrance or aid in the problem solving or idea generation process. Some types of components include sketching, analogies, and provocative stimuli. Mechanisms that promote innovative thinking or overcome blocks to innovative thinking do exist and these have been identified through research studies (Kulkarni, 1999b). There appear to be conflicting views about the usefulness of some of these components. Blocks are defined as components that work against the idea generation process. Tackles are components that are used to counter the blocking components. Promoters are components designed to aid in the idea generation process without countering a block. Some of the components in the idea generation methods are included directly, while others are inherent in the method. Evidence for and against various blocks and tackles is abbreviated in Table 1. A complete set of evidence may be found in Kulkarni (2000). The references with an asterisk constitute evidence against a particular tackle. Also presented in the table is whether each tackle is thought to lead to the expansion and/or
exploration of design space. Similarly, a list of promoters and evidence for and against each of them is presented in Table 2.

**Table 1 - Evidence Related to Blocks and Tackles (Kulkarni, 2000)**

<table>
<thead>
<tr>
<th>BLOCKS</th>
<th>TACKLES</th>
<th>EVIDENCE</th>
<th>EFFECT ON DESIGN SPACE</th>
</tr>
</thead>
<tbody>
<tr>
<td>rigid problem representation</td>
<td>flexible problem representation</td>
<td>(Cross and Cross, 1996), (Lawson, 1994), (Roy, 1993), (Tovey, 1986)</td>
<td>Expand</td>
</tr>
<tr>
<td>(textual, math.)</td>
<td>(abstract, pictorial)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>design fixation</td>
<td>provocative stimuli</td>
<td>(DeBono, 1984), (Osborn, 1979)</td>
<td>Expand, explore</td>
</tr>
<tr>
<td>random connections</td>
<td>(Grossman and Wiseman, 1993),</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Parnes, 1987), (Zwicky, 1969)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Incubation</td>
<td>(Cross and Cross, 1996),</td>
<td></td>
<td>Expand, explore</td>
</tr>
<tr>
<td></td>
<td>(Kumar et al, 1991),</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Lawson, 1994), (Parnes, 1987)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>imposing fictitious constraints</td>
<td>Break rules</td>
<td>(Candy and Edmonds, 1996), (Kolodner and Wills, 1996)</td>
<td>Expand</td>
</tr>
<tr>
<td>work on higher problem</td>
<td>(Candy and Edmonds, 1996),</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Kolodner and Wills, 1996)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

(*) Opposing Evidence

**Table 2 - Evidence Related to Promoters (Kulkarni, 2000)**

<table>
<thead>
<tr>
<th>PROMOTER</th>
<th>EVIDENCE</th>
<th>EFFECT ON DESIGN SPACE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Combinatorial play or synthesis</td>
<td>(Cross, 1996), (Kumar et al, 1991), (Verstijnen et al, 1998)</td>
<td>Explore</td>
</tr>
<tr>
<td>Imagery / Sketching</td>
<td>(Akin and Lin, 1995), (Cross and Cross, 1996), (Gross, 1996),</td>
<td>Explore</td>
</tr>
<tr>
<td></td>
<td>(Lawson, 1994), (Lawson and Loke, 1996)*, (Roy, 1993), (Tovey, 1986),</td>
<td></td>
</tr>
<tr>
<td></td>
<td>(Verstijnen et al, 1998)</td>
<td></td>
</tr>
<tr>
<td>Feedback from designers</td>
<td>(Carson and Carson, 1993), (Hist, 1992), (Kolodner and Wills, 1996)</td>
<td>Explore, expand</td>
</tr>
<tr>
<td>Imposing constraints</td>
<td>(Finke, 1990), (Finke et al, 1992), (Finke et al, 1992)*, (Savage and Miles, 1998)</td>
<td>Explore</td>
</tr>
</tbody>
</table>

(*)* Opposing Evidence

Table 3 provides a breakdown of the primary components found in a selection of idea generation methods. The two primary components identified in C-Sketch are the use of sketching and imagery and provocative stimuli. Sketches, as the only form of communication and solution representation in C-Sketch, have been shown useful for several reasons, both in the literature and through experiments. Sketching shall be discussed further in the following section. Provocative stimuli are derived in C-Sketch from the possible misinterpretation of the sketches as passed between designers. This component of C-Sketch is intended as a creative stimulant and is discussed further.

**Table 3 - Decomposition of Idea Generation Methods into Components (Kulkarni, 2000)**

<table>
<thead>
<tr>
<th>IG METHOD</th>
<th>COMPONENTS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Morphological Analysis</td>
<td>Random connections, combinatorial play and synthesis</td>
</tr>
<tr>
<td>Brainstorming</td>
<td>Suspend judgment, emphasis on quantity, provocative stimuli, use of analogies</td>
</tr>
<tr>
<td>K-J Method</td>
<td>Random connections, synthesis and combinatorial play</td>
</tr>
<tr>
<td>Method 6-3-5</td>
<td>Provocative stimuli</td>
</tr>
<tr>
<td>C-Sketch</td>
<td>Provocative stimuli, imagery and sketching</td>
</tr>
<tr>
<td>Gallery Method</td>
<td>Provocative stimuli, random connections, sketching, feedback from designers</td>
</tr>
<tr>
<td>Storyboarding</td>
<td>Suspend judgment, emphasis on quantity, sketching, provocative stimuli, random connections</td>
</tr>
<tr>
<td>Fishbone Diagrams</td>
<td>Emphasis on quantity, pictorial problem representation, random connections, synthesis</td>
</tr>
<tr>
<td>Synectics</td>
<td>Use of analogies and metaphors, suspend judgment, change frame of reference, provocative stimuli, imagery</td>
</tr>
</tbody>
</table>

2.2.1 Role of Images

Traditionally, research in visual thinking and sketching has been of interest to experts in two fields – cognitive psychologists and researchers studying architectural and engineering design. Cognitive psychologists have tended to focus more on visual imagery, i.e. the use of mental images in visual thinking and creativity. Since sketching is often viewed as an extension of, or complementary to mental imagery, a survey of the work of cognitive psychologists in this area seems relevant. For a complete comparison of the sketching and textual representation for idea generation see McKoy (2000).

3 Visual Cognition and Expression

Most cognitive psychologists agree that mental images exist. However, they are divided in their opinion regarding the mental representation of these images. One group supports a propositional representation of mental images, i.e. they propose that mental images are not really stored as images with spatial properties, but are stored descriptively in words (Miller, 1984; Pylyshyn, 1981). The other group contends that mental images are quasi-pictorial representations i.e. the literal appearance of the image of an object is stored spatially in polar coordinates and facts about the objects are encoded in lists of propositions (Miller, 1984). Kosslyn (1977) and Shepard (1978) conducted experiments to demonstrate that mental images are represented spatially by studying the time it took for subjects to scan transformed objects. Despite much experimentation, the debate on the mental representation of images has not been resolved yet. However, what is important is that cognitive psychologists acknowledge the existence of mental imagery, of which sketching is an extension.

3.1 Role of Visual Cognition and Expression in Design

Design researchers also have looked at the role of sketching in creativity and design. Ullman et al (1990) studied the role of sketches in the design process. In their protocol studies, they found out that during the design process 72% of the marks made on paper by designers were sketches or draftings. Two thirds of these drawings were freehand sketches. Goldschmidt (1992) studied the use of “serial sketching” in architectural design. It has been observed that during the design process, designers draw not one but a series of sketches. As sketching progresses, new shapes and relationships among shapes are created on paper, far beyond what was intended at the outset. Thus, sketches provide feedback to the sketcher in a way that other representations cannot provide.

Larkin and Simon (1987) have shown that sketches are very useful in problem solving because of their conciseness of representing data, compared to sentential descriptions. They show the inefficiency of working out a simple pulley problem in physics in terms of sentences exclusively, compared to a visual solution of the problem. Through an example of solving a problem in geometry, they also make an important point that sketches offer insights to a problem, which would simply not be likely to be made through sentential reasoning. This contests the claim made by some cognitive psychologists that linguistic modes of reasoning are superior to visual reasoning in scientific problem solving.

3.2 Sketching

The primary promoter on which C-Sketch was developed is the use of sketching and imagery. In a protocol study, Akin and Lin (1995) found that drawings are used for different purposes throughout the design process. The details and sub-concepts are incorporated into the initial conceptual rendering, evolving the design from concept to detail. Some sketches foster novel ideas while others are routine representations of established concepts. Early drawings represent a different composition of three principal activities: examining, drawing, and thinking.

3.2.1 Concise Data Representation

Sketches offer a concise method of representing design constraints and knowledge about the design problem or artifact. The use of sketches is encouraged to solve analytical problems. In sketches, relevant information is grouped spatially. The relative spatial positions between the different groups of data help the designer to see new relationships between groups of data, thus leading to insights about the design problem. The relationships between groups of information are typically of a one-to-many kind when sketches or diagrams are used. Thus, one group of information can be quickly related to several other groups of information, thus facilitating quick processing of all the information. In sentential data representation, information is more or less serially linked, i.e. information in one sentence can usually be related to that in a few of its neighboring sentences. Finding relationships between information stored in widely separated sentences is tedious, and the human mind will miss these relationships more often than not. Larkin and Simon (1987) show the usefulness of sketches by comparing the number of computations and searches that have to be made when the same problem is represented in terms of sentences and in terms of sketches. Sketches require fewer computations and searches. Thus, spatial grouping of relevant data plays an
important role in the problem solving process. It aids the process of making unexpected connections between different groups of data, which has been described as a promoter of creativity.

Creative ideas usually occur as fleeting thoughts in the mind and need to be captured quickly on paper before they are lost (Hanks and Belliston, 1980). Sketches do not require that the figure be drawn to exact scale or that exact dimensions be specified. Since they can be created quickly, sketches allow for facile manipulation of ideas. Sketches are thus “graphic metaphors” for the real object. Since most sketches are not used for communication, a designer can use personal shorthand notations to represent symbolically pertinent information.

3.2.2 Sketches as Gestals

Probably the most important use of sketches is that they act as gestalts, i.e. the designers are able to read off from the sketch far more information than was invested in initially creating the sketch. As designers inspect their own sketches, they see unanticipated relations and features far beyond what was intended at the outset. These new relations and features suggest ways to refine and revise their previous ideas (Suwa and Tversky, 1997). Designers are also known to come up with new enhancements to their ideas while they sketch out their original mental images. Goldschmidt (1991) suggests that sketches give access to various mental images – figural or conceptual, that may potentially trigger ideas that might be useful in solving the design problem at hand. According to Goel (1995), sketches in the early design process are dense and ambiguous, thus affording reinterpretation of the sketches in many different ways. It is believed that sketching in the early phases of design helps designers pick up potentially meaningful hints that could help define a specific problem space in which a search for a solution is likely to be productive (Goldschmidt, 1994). Seeing groups of things in the sketch in a different yet meaningful context is the essence of imagery.

Although sketches have all the advantages described in the preceding sections, it has been observed that designers benefit to different degrees from the use of sketches. A possible answer lies in the way people use sketches. Larkin and Simon (1987) state that sketches are of help only to those who know how to make full use of them, i.e. only if information is represented effectively by designers in their sketches are they really helpful. Effective use of sketches comes with practice and experience. Lay persons use sketches to just represent an image held in the mind. Experienced designers, in addition, use sketching to help generate an image in the mind (Goldschmidt, 1991) as if the sketch talked back to the designer. Figure 4 shows how this talk-back occurs in C-Sketch. The Sketcher (originator) creates a Mental Image of an idea based on his/her domain and context knowledge. The drawing skills of the sketcher transform the mental image into a sketch, which is a physical representation. The expressability of the sketcher is a measure of how close the sketch is to the mental image. During the elaboration of the sketch, the talk-back loop is completed and the designer enters a dialogue with his/her material. As the dialogue proceeds, sketching continues until a concept is deemed sufficiently coherent. With increase in experience, the designer learns to cultivate the dialogue to fully exploit its potential (Beittel, 1972). It has been found from protocol studies that experienced architects are better than students at reading abstract features and relationships from sketches (Suwa and Tversky, 1997). Thus, experience plays a major role in the effectiveness of the use of sketches. As more and more sketches are used, designers get better at drawing insights into a problem from their sketches. This process is repeated in subsequent cycles of C-Sketch in which the reader interprets the sketch based on his/her domain and context knowledge to create a Mental Image, from which to create a sketch.

![Figure 4 - Talk-Back in C-Sketch](image)

4 Intrinsic Properties of C-Sketch

Incorporated into C-Sketch are many of the blocks/tackles and promoters discussed in the previous section. These issues are discussed below, demonstrating how the components are influential in design and further how they
are found in C-Sketch. It should be noted that not all blocks/tackles and promoters are found in every idea generation method. Thus, only those that are directly related to C-Sketch are discussed. The intrinsic properties of C-Sketch discussed include Provocative Stimuli and Design Fixation. Also discussed are the method variables and their apparent impact on the utility of C-Sketch as an idea generation method.

Over the past five years, four sets of experiments, component protocol study, fixation experiment, comparison experiment, and influence of method variables experiment, have been conducted on progressive idea generation methods at the DAL. In these experiments, groups of designers used specific idea generation methods for different open-ended mechanical design problems. No other experimental studies where designers used a specific idea generation method for engineering design, except for studies on brainstorming or “free-form thinking” (Shah, 1998), have been found in the literature. These experiments provide evidence of the utility of C-Sketch in terms of blocks and tackles and in terms of promoters. This section will discuss both literary support for inclusion of the components and the experimental evidence collected in the DAL of the effect of the components of C-Sketch.

4.1 Design Fixation

Design fixation may be simply defined as: the tendency of a designer in a progressive idea generation method to exert the designer’s own design preferences through out the idea generation process. While it is important to allow designers to stamp their own influence on the design, it is equally important not to have a single designer dictating the course of the design. Thus, design fixation is generally considered a block in the idea generation process, although it may improve quality and add detail to the design.

Purcell and Gero (1996) conducted a series of experiments using industrial designers and mechanical engineers to analyze design fixation. They found that aesthetic designers did not seem to become fixated and generated many solutions, while designers became fixated quite often. The authors hypothesize that the production of a large number of designs might perhaps prevent the occurrence of fixation effects. Akin and Akin (1996) showed through experiments how a change of frame of reference or breaking out of a fixated response is essential to get a sudden mental insight (SMI) leading to the solution of a problem. Problems used in the experiment were a puzzle (called the nine dot problem) and an architectural design problem.

An experiment was conducted at the DAL (Shah, 1998). The objective was to verify if C-Sketch helped designers explore new paths based on concepts they received from others or whether they remained fixated on their original ideas. Sixteen designers were paired up, half of them from industry. Two design problems were used in the experiment. Each subject generated a solution sketch on their own (unlike the component protocol studies mentioned in section 4.1.1) and then exchanged it with their partner. Subjects then were asked to improve the solution they had received from their respective partners. The procedure for the experiment is shown in Figure 5.

![Figure 5 - Experiment Fixation Experiment Procedure](image)

Sketches were photocopied before they were exchanged to trace the development of each idea. Designers were asked to label the copies of the sketches they had generated and copies of the sketches they had received from their partners before they made any modifications. This was done in order to determine whether designers misinterpreted the sketched concepts they received from their partners.

The changes made to the sketches were measured by dividing each sketch into “units” that consisted of related drawing entities. Three quantities were measured: retention, modification, and fixation. Retention was measured as the ratio of the units from the original idea that survived after changes were made by the second designer, to the units in the original design. Modification was measured as the ratio of the units added or deleted by the second designer, to the units in the original idea. Fixation was measured as the ratio of the units added by the second designer to the sketch received from the first designer, to the units in the original design generated by the second designer. It was found that on the average sixty-nine percent of the original concept was retained and only thirty-one percent of the concept was modified by the second designer. This indicates that designers did not show a tendency to force someone else’s idea towards their own first ideas, when they used C-Sketch. Designers also
showed a greater tendency to enhance existing features in the sketch they had received from their partners (such as adding more detail), rather than make more drastic changes, such as changes in physical principles, embodiment, geometry, layout, etc. Further, several incidents of misinterpretation were observed, many of them being conceptual misinterpretations.

The experiment did result in some interesting findings about the C-Sketch method. It was found that C-Sketch, which does not permit designers to communicate directly with each other, seems to promote opportunities for conceptual misinterpretations. Misinterpretations are believed to help trigger novel and unexpected ideas that a designer would not have developed if the designer correctly understood the design that was passed to the designer. It was also observed that designers used the ideas they generated to enhance the ideas they received. Thus, the fixation experiment seems to further strengthen the observations of the component protocol studies that C-Sketch seems to promote the combination of different ideas to get new ones.

4.2 Provocative Stimuli

*Provocative stimuli* is a concept that has evolved from observations of the performance of C-Sketch and other progressive idea generation methods at the DAL. While there is some evidence for provocative stimuli in the literature, such as the use of luck (DeBono, 1984) and provocation (Osborn, 1979), the concept used here is derived from the DAL research. A provocative stimulus is defined as external inputs, which may prove to be catalysts in idea generation. These external inputs are generally derived from misinterpretation of design concepts, where one designer feeds off the misconstrued design of another designer.

Provocative stimuli may be generated from several sources in C-Sketch, the primary source being the misinterpretation of sketches. Finke et al. (1992) conducted an experiment in which subjects were asked to use pre-inventive forms that someone else had generated, instead of constructing their own pre-inventive forms. It was found that subjects were able to generate far fewer creative inventions compared to those who had generated their own pre-inventive forms. Thus, the pre-inventive form created by one person may not be so useful to other people, and in fact may lead to misleading and irrelevant interpretations. This concept of misleading and irrelevant interpretations may be viewed as positive in an idea generation method, as the misinterpretations may lead to provocative stimuli. Shah (1998) asserts that provocative stimuli components in an idea generation method may lead to creative misinterpretations.

A protocol study on the components of C-Sketch (Shah, 1998) was conducted at the DAL. This study demonstrates that C-Sketch helps designers combine two or more concepts in unexpected ways, since subjects were observed to develop new concepts by combining the second concept with the concept they were provided in the first cycle. In this manner, the sketches provided by the previous designer provide random stimuli to the current designer.

The objective of this experiment was to find evidence for creative cognitive processes described in the *Geneplore* model (Finke et al., 1992) when designers used the C-Sketch method to solve a design problem. Eight subjects were used in the experiment, all graduate students in Mechanical Engineering. Two design problems were used in the experiment. The experiment is focussed on studying how using someone else’s ideas influenced one’s own idea generation process. Therefore, two solutions were generated in the form of sketches in advance for each problem. Only the exploratory cycles of C-Sketch were simulated in this experiment by providing all the subjects the same two solutions one after the other. Each subject was given fifteen minutes to interpret the sketches and further improve these solutions. The subjects were asked to think aloud while being videotaped. Transcripts of the videotapes and photocopies of the original and modified sketches were used as the data for identifying generative and exploratory cognitive processes.

Since only exploratory cycles of C-Sketch were simulated, more exploratory processes were expected to occur than generative processes. On an average, exploratory processes accounted for 53.5% of the total time, while generative processes accounted for only 37.5% of the total time. It was observed that most of the subjects spent more than half their time in understanding, interpreting, and evaluating the idea that was given to them. Generative processes were more difficult to identify compared to exploratory processes. Several processes described in the *Geneplore* model were nearly absent, most of these being generative processes. Two additional mental processes namely meta process and problem assimilation were identified. Meta process, also known as meta-cognition, is the process where a designer monitors the designer’s own actions to decide on the strategy of how best to proceed further with solving the design problem. Problem assimilation is the process of understanding the assigned design problem.

The study was successful in demonstrating that cognitive mental processes could be identified when designers used an idea generation method to solve an engineering design problem. Psychologists use very simple problems or tasks in controlled experiments while studying cognitive processes. The usefulness of observing the occurrence of
cognitive processes and using them as a measure for evaluating the effectiveness of idea generation methods is questionable though, since it is not possible to relate this to the level of creativity involved (Smith and Ward, 1999).

Further, in the fixation experiment conducted by researchers at the DAL (Shah, 1998), misleading interpretations were found to relate primarily to concepts rather than configurations of design solutions. In the experiment, fourteen instances of misinterpretations were found between designers’ sketches. Of these fourteen instances, ten related to conceptual representations and four related to configuration sketches. The focus of the fixation experiment was not to investigate provocative stimuli, but rather to analyze design fixation on progressive idea generation methods.

4.3 Method Variable Properties of C-Sketch

The C-Sketch method has only two method variables that are adjustable. The number of cycles and group size have a direct impact on the method. Further, there is evidence in the literature and from experiments at the DAL which indicate how time and group size affect idea generation. A detailed description of the experiments may be found in Kulkarni, et al. (1999b) and Vargas-Hernandez and Shah (2000).

4.3.1 Time

According to Finke et al. (1992), when subjects are given extended time to explore their pre-inventive forms, they nearly always discovered a potentially useful invention or idea. Finke (1990) reports several examples of invention concepts that were generated in this way and purports the idea that constraints on time might undermine the idea generation process.

4.3.2 Group Size

Thornburg (1991) conducted a research study to identify the effect of group size and diversity on creative performance. Previous experiments had found that individuals working alone outperformed members participating in “real” groups (Thornburg, 1991). Real groups are groups where people interact overtly as opposed to nominal groups where people work together without any direct interaction. It was found in previous experiments that with decreasing group size, Creative Production Percent (CPP) increased until a group size of two was reached. CPP is defined as the percent performance of a group compared to the performance of an individual. For groups of two, also known as dyads, the output of group members equals or exceeds that of individuals.

Dyad groups outperform real groups, but nominal groups outperform both in terms of the number of ideas generated. This suggests that C-Sketch, in which nominal groups participate, should produce more ideas than groups with overt group activity. Group diversity has a significant positive effect on the performance of nominal groups. It may be concluded that it is better to employ nominal groups when group members are diversely oriented and a large number of ideas are needed.

Goldschmidt (1995) compares how individual designers and design teams function differently. The study is based on the common protocol sent to different design researchers by Delft University to compare the individual interpretations of the protocol. After a detailed analysis, it appears that individuals function much the same way as teams in bringing their work to fruition. An individual plays different roles such as raising questions, generating ideas, and finding answers, whereas in a team individual members play these roles. Additionally, there does not seem to be much difference in the level of productivity. However, the study does not address the situation when an individual is inclined toward specific roles. If an individual is adept at raising questions, but finds it difficult to answer them, then that individual working alone may not be as effective as when working in a group. Another study on the effectiveness of brainstorming in engineering problem solving shows that group problem-solving processes are not necessarily superior to individual efforts (Lewis et al., 1975).

4.3.3 Method Variable Experiment

The objective of the method variable experiment conducted in the DAL was to investigate the influence of the method variables, cycle time and number of cycles (passes), on the effectiveness of the C-Sketch method (Kulkarni, et al., 1999b). The effectiveness of the method was evaluated directly in terms of the outcome, by examining the number of features and types of features generated at each cycle. The researchers sought to identify general trends in the design activity in terms of additions, deletions, and modifications made to the sketches during successive cycles and for different cycle times. One hypothesis was that designers would modify existing solutions in progressive steps during each cycle. A second hypothesis was that groups with less cycle time would make conceptual changes while those with higher cycle times would change details.

The two independent variables in this experiment were identified as the cycle time and the number of cycles. Each of these factors consisted of three levels: six, nine, and twelve minutes for cycle time and first, second, and third for the number of cycles. The data was analyzed by considering cycle time to be the independent variable. Each cycle was viewed as a block since all the three groups carried out each cycle simultaneously. Thus there were
three blocks corresponding to the three cycles and each block contained three runs corresponding to the three cycle times.

The sketches were analyzed by comparing the modifications made by each designer. Features, defined here as interpretable geometry, were classified as concept, embodiment, or detail. Concept features are those feature that add a new dimension to the design space. An example of a conceptual feature is the weaponry added to the vehicle. Embodiment features are those features that are used to explore the design space. Changing from an open wheeled vehicle to a treaded vehicle is a type of embodiment change. Finally, detail features are those which add little new information to the design, but are used to “finish” it. An example of detailed features would be to modify the seat cushion into components. These three feature types were further decomposed into added, deleted, and modified, indicating the type of change to the design. Examples of a selection of the features are illustrated in Figures 7-10 for the design generated by Designer F in the nine-minute group. The features are circled and identified as the design progresses from the initial design to the final design. It is clear that the fundamental concept of an armed, wheeled, ground vehicle is maintained throughout the design. Minor concepts, embodiment changes, and details are added, modified, and deleted in most iterations.

From analyzing the results, it was found that lengthening the time increases the number of added and modified detail features. It was found that there is a drop-off in the number of concept features after a two to three cycles. For the most part, the number of cycles and the time of cycle statistically do not interact, except for deleted detail. Table 5 contains the probability of variable affect as determined by ANOVA tests. The highlighted values indicate that the variable (column) has a significant effect determining the number of features (row). For example, the intersection of Cycle Time and Modified Detail is highlighted with a value of 0.048. This indicates that the cycle time has significant effect upon the modification of detail features throughout the method. Values below 0.050 are deemed to have high influence.

It should be noted that the results from the experiment are limited by the number of participants and further trials are needed for complete verification. In addition, increasing the complexity of the design problem may yield different results. The current sets of experiments are developed around a single design problem. From this analysis of the experimental results of the C-Sketch method variable experiment, it is believed that a cycle time of nine
minutes allows proper time for designers to interpret the passed design and to make conceptual changes to the design for simple design problems.

The conceptual results of the experiment have also been analyzed using metrics derived for comparing idea generation methods. These metrics of quality, novelty, and variety are discussed at length in (Shah, et al., 2000a). Based upon the analysis, it was found that the number of cycles and the duration of cycle time seem to have little affect upon the metrics. These results are illustrated in Figures 11, 12, and 13. From the graphs, it is clear that there is little difference with respect to the metrics when evaluating the conceptual aspects of the designs, regardless of the time or the iteration. Thus, it may be concluded that C-Sketch provides constant support in terms of quality, novelty, and variety in the generation of basic concepts. In developing the designs into embodied and detailed designs, the two variables, cycle time and number of cycles, still have an influence.

Figure 10 - Quality
Figure 11 - Novelty
Figure 12 - Variety

5 Comparative Studies on C-Sketch

The DAL conducted a comparative study in 1997 (Shah, 1998; Vargas-Hernandez and Shah, 2000) evaluating the differences between three progressive idea generation methods; Method 6-3-5, Gallery Method, and C-Sketch. This section describes the experiment and the results of the experiment.

5.1 Comparison Experiment

The objective of this experiment was to compare Method 6-3-5, C-Sketch, and the Gallery method with respect to their rules for communication and representing ideas. Method 6-3-5 and C-Sketch do not permit direct discussion between group members, while the Gallery method has specific times for group discussion. Method 6-3-5 allows only textual representation of ideas, while C-Sketch and the Gallery method permit the use of sketches. In the component protocol studies and the fixation experiment, no specific variables were explicitly studied in the experiments. This comparison experiment, however, involved three variables: the type of idea generation method, the type of design group, and the type of design problem. Design group and design problem were used as control variables, since the researchers were interested in comparing only the effectiveness of the three idea generation methods. Three sets of designers were used. Set 1 consisted of Mechanical Engineering undergraduate students, Set 2 had Mechanical Engineering graduate students, and Set 3 had practicing designers from the industry. Having five members in each set blocked the effect of group size. Three different “equivalent” design problems were chosen for the experiment. Each group solved all three-design problems using a different idea generation method for each problem. The experiment involved nine runs corresponding to the different combinations of idea generation methods, design problems, and design groups.

When using Method 6-3-5 and C-Sketch, each group was allowed ten minutes per cycle, and three cycles were conducted: one generative and two exploratory. When the groups used the Gallery method in the comparison experiment, two ten-minute design sessions were carried out with a ten-minute discussion session in between. Carbon copies of sketches and written ideas were collected at the end of each cycle for C-Sketch and Method 6-3-5. For the Gallery Method, carbon copies of the design sketches were collected at the end of each design session, and the discussion period was videotaped. Designers were asked to fill out survey forms at the end of each experiment. There was one general survey form, and one form specific to each method. The designers could refer to copies of any idea they had touched to answer specific questions in the survey forms.

5.1.1 Provocative Stimuli

After completing three design problems using the three idea generation methods, the group members were given a survey to determine their preferences between methods. The results of these surveys may be found in Shah (1998) and partially in Table 5. The survey results record the impressions of the users and includes possible misinterpretations by the designers when completing the survey.
Table 5 - Survey Results for Comparison Experiment

<table>
<thead>
<tr>
<th>Question</th>
<th>Factor</th>
<th>Method</th>
</tr>
</thead>
<tbody>
<tr>
<td>Do these methods provide provocative action/stimulus to other members?</td>
<td>Provocative Stimuli</td>
<td>6-3-5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>48%</td>
</tr>
<tr>
<td>How do these methods compare with each other with respect to creative outcome?</td>
<td>Creative Outcome</td>
<td>60%</td>
</tr>
<tr>
<td>How do these methods compare with each other with respect to promotion of creative processes?</td>
<td>Creative Cognitive Processes</td>
<td>50%</td>
</tr>
</tbody>
</table>

It is clear that the factor of provocative stimuli is greater in perception for C-Sketch than for 6-3-5 or the Gallery Method. However, to date, no formal investigations indicate that provocative stimuli from C-Sketch actually promote creativity. The experiment also examined the number of cycles it took for participants to feel that they could no longer contribute to the idea generation process. Designers seemed to reach saturation faster when they used C-Sketch, compared to the other two methods. However, the designers indicated that C-Sketch provided the most provocative stimuli during idea generation.

5.1.2  Text, Graphical and Verbal Communication

According to the surveys, most designers (83%) preferred sketches to textual descriptions. They were divided in their opinion on the benefits of silence vs. direct discussion. Thirty percent of the designers preferred the absence of direct communication, as is the case with Method 6-3-5 and C-Sketch, while thirty-eight percent preferred direct discussions. The remaining designers were neutral on the issue. Most designers preferred C-Sketch and the Gallery method to Method 6-3-5. A set of experiments is being conducted in parallel with this work for the explicit analysis of Idea Generation using sentential or graphical representations.

5.1.3  Comparative Effectiveness of C-Sketch

Important observations regarding each method were made from an ANOVA analysis of the data with respect to identified metrics of quality, novelty, and variety. Method 6-3-5 had the lowest scores for quality, novelty, and variety of ideas generated, while C-Sketch got the highest scores for these three measures. The data collected and illustrated in Figure 13 is based upon analysis of the completed designs for the comparison experiment. This supports the results obtained using the surveys indicating that the designers did not think highly about Method 6-3-5 (Table 5). The ideas generated using Method 6-3-5 were found to have only conceptual information with no configuration information at all. Further, the three ideas generated by a designer in each cycle of Method 6-3-5 seemed to be slight variations of the same basic idea. In some cases, for the second and third ideas designers just described some additional modifications to the first idea. Thus, Method 6-3-5 does not seem to help generate three separate parallel ideas in each cycle as is claimed.

Figure 13 - Comparison of Idea Generation Methods

When the Gallery method was used, the first design session (before the discussion session) produced ideas that had high scores for variety but low to medium scores for quality. However, at the end of the second design session (after the discussion session), the scores for variety went down but the quality of the ideas improved, as shown in Figure 14. This seems to indicate that during the discussion session, designers picked up the best elements from the ideas generated by others to improve their own ideas in the second design session. However, all the designers seemed to have used the same idea to modify their own idea, which resulted in ideas that were better but not very different from each other and hence resulted in low scores for variety. Method 6-3-5 seems to be the least effective of the three methods, while C-Sketch and the Gallery method seem to be more useful.
6 CONCLUSIONS

C-Sketch has been presented here for the first time in the literature with a detailed description of the method and justifications for the method collected from five years of research at the DAL. C-Sketch has been presented in this paper as a useful tool in progressive idea generation. This method has been developed based upon the understanding of the importance of sketching in the domain of engineering design generally and mechanical engineering design specifically. Sketches are useful as forms of concise data representation as compared with verbal and textual communication. Sketches allow users to read more information from the design that was originally included, acting as gestalts. Applying the realization that sketches are important in mechanical engineering design, the progressive idea generation method 6-3-5 was modified to include sketches rather than textual description of problem solutions. In this manner, C-Sketch was born, nearly seven years ago.

C-Sketch has been shown to have components useful in idea generation, including provocative stimuli and designer feedback through silent criticism. These have supporting evidence found in both the relevant research literature and in the experiments conducted at the DAL. Provocative stimuli, as with the use of analogies and misinterpretations, were first found in C-Sketch in the component protocol studies. It was found that while many design modifications were misinterpreted from the original intent, the misinterpretations served as launching pads for new design solutions. Provocative stimuli allow designers to combine multiple concepts in unexpected ways. The stimuli result from random misinterpretations of sketches and the use of visual analogies.

Designer feedback through learned assessment from silent criticism provides the designers with implied evaluation of their designs, reinforcing generation of quality ideas. Seeing how others interpret each other’s designs aids the designer in evaluating their own designs. Despite the potential for design fixation, or a designer imposing their own design solutions overwhelming upon the design group, little evidence was found that C-Sketch fostered this fixation.

In assigning the variable values in C-Sketch, experiments indicate that cycle time, number of cycles, and the interaction between the two do affect the number of features at each pass depending upon feature type. Further, the metrics of quality, novelty, and variety of ideas generated using C-Sketch seem to reach a maturation point after which little additional modification is found. In preliminary experimentation, results suggest that three cycles of nine minutes might be most effective for the problem given the designers. From these results, additional experiments need to be executed to further refine the guidelines of the variable value settings based upon the desired outcomes and problem classifications.

Given the experimental results of the comparison experiment, C-Sketch is shown to be more effective than two other progressive idea generation methods, the Gallery Method and Method 6-3-5. C-Sketch out performed both of the other methods in the three measured areas of quality of design, novelty of designs generated, and variety of designs. Further, the Gallery Method scored higher in the three metrics than Method 6-3-5, thus indicating that sketches are a useful means of communication in idea generation. Seven years of use and five years of experimentation have demonstrated the utility of C-Sketch in engineering design. More experimentation for fine-tuning the C-Sketch method variables with respect to type of designer and type of design problem is necessary for optimal use of the method. Additionally, experiments are required to analyze the difference between fixation derived from using others’ sketches and fixation derived from using one’s own sketches. This may provide insight about the need to pass sketches, rather than continue working on one’s own design solution.

![Figure 14 - Comparison of Gallery Method](image-url)
7 ACKNOWLEDGEMENTS

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