# Collaborative Sketching (C-Sketch) – An Idea Generation Technique for Engineering Design

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## Abstract

This paper presents the development and evaluation of a technique (C-Sketch) for concept generation in a collaborative engineering design setting. The evaluation is based on cognitive models for creativity, problem solving, roles of images, sketches, and "blocks and tackles" in idea generation methods. The paper reviews both the intrinsic merit of C-Sketch, as well as relative merit compared to other techniques in the same class. This analysis is based on results from experiments on progressive idea generation methods conducted over five years. Both the process and outcome were evaluated, with greater emphasis on the latter. This study found that C-Sketch not only has intrinsic merit, but also measures higher in all outcomes when compared to Method 6-3-5. Also C-Sketch was at least as good as the Gallery Method in the quality of ideas produced and better in variety and novelty of ideas. This paper is a consolidation of all empirical studies related to C-Sketch.

# 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. A taxonomy of idea generation methods is presented in Shah (1998). The research presented here is concerned 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), Storyboarding (VanGundy, 1988), and possibly Synetics (Gordon, 1961).

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). At the end of each cycle, 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 contribution to 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 flow sequence for the sketches originating at Designer A and B. Flows for the other three sketches are omitted to avoid clutter, yet the flow is similar for sketches originating with Designers C, D, and E.

The sketch from the first designer is passed to the second, and so on until all designers have worked on the same sketch. As an example of the types of sketches that 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 match the complexity of the problem. 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 provocative stimuli from other idea sketches may prove to be catalysts in developing creative new constructs. 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, which designers use during the search 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 serpent 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.

In order to understand the intrinsic values of C-Sketch, it is first necessary to understand the rationale for C-Sketch. This paper will not only present the rationale, but also the results of empirical studies to test these assertions. 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 decomposition of these methods into their key ingredients or cognitive components, and the roles of images in design with a discussion on sketches are presented.

## 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* (Shah, et al., 2000). 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.

*Intuitive methods* have been placed 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 with which to start. 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*, 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* develop ideas by systematically exploring variations of an initial solution. *SIT*, *Forward Steps*, and *Inversion* are three methods belonging to this class.

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The various idea generation methods have some ingredients that are common with other methods. These components are embedded in these methods because they are believed to aid the idea generation process. For this study, "Blocks" are defined as conditions that work against the idea generation process. "Tackles" are defined as components that are used to counter specific blocks. "Promoters" are defined as components designed to aid in the idea generation process, but are not directly related to specific blocks. Tackles and promoters are identifiable components of idea generation methods. Some tackles and promoters are included indirectly, while others are inherent in the method.

Design fixation has been identified as a common block; it is the tendency of a designer to favor a design from previous experience, a design seen or developed by the designer (Jansson and Smith, 1989). A symptom of fixation is that new designs share more common features with previous designs. Purcell and Gero (1996) conducted a series of experiments using industrial designers and mechanical engineers to analyze design fixation. They found that industrial designers did not seem to become fixated and generated many solutions, while mechanical 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 how a change of frame of reference or breaking out of a fixated response is essential to get a sudden mental insight leading to the solution of a problem. Problems used in the experiment were a puzzle and an architectural design problem. Tackles proposed for fixation are provocative stimuli, random connections/inputs, and incubation. Provocative stimuli are any external stimuli to the designers that provide for a change of reference (DeBono, 1984; Osborn, 1979). Random connections and inputs are used to break designers out of the fixated response by stimulating divergent thinking (Grossman and Wiseman, 1993; Parnes, 1987). Incubation allows designers to set aside the immediate design problem for a later time, allowing the subconscious to cognate on the problem (Lawson, 1994; Cross and Cross, 1996).

Textual or mathematical problem representation is considered a block because it is rigid; transformation to new ideas is difficult. The tackle for this type of block is to use more flexible representations, such as pictorial or graphical representation (Cross and Cross, 1996; Lawson, 1994; Roy, 1993; Tovey, 1986). Another block that has been identified from the literature is premature judgment while developing designs and ideas (Grossman and Wiseman, 1993; Candy and Edmonds, 1996; Osborn, 1979; Kumar, et al., 1991; Cross and Cross, 1996). This block may force designers to discard early design ideas that do not evaluate well. A tackle to this block is to suspend judgment until later in the design process. This aids in both expanding and exploring the design space more fully (Kulkarni, 2000). Some tackles found in generation methods include emphasis on the quantity of designs (Basadur and Thompson, 1986; Purcell and Gero, 1996; Donovan, 1985) or the variety of the designs (Roy, 1993; Tovey, 1986). The emphasis on quantity both expands and explores the design space, while the emphasis on variety works in exploring the design space.

Engineering designers have been observed to be heavily goal orientated. A tight grip on problem specifications may cause a block. A change in the frame of reference of the designer (Akin and Akin, 1996; Barron, 1988; Candy and Edmonds, 1996) and use of analogies and metaphors (Candy, 1996; Candy and Edmonds, 1996; Cross, 1996; Ekvall and Parnes, 1984) help in overcoming this block.

Another related problem is the tendency to impose fictitious constraints on the design. Designers can overcome fictitious constraints by working on higher level problem, this implies shifting the abstraction level of the problem (Candy and Edmonds, 1996, Kolodner and Wills, 1996; Ward, 1994; Ward et al, 1995), and by breaking the rules to allow the expansion of the search space (Cross and Cross, 1996, Candy and Edmonds, 1996, Kolodner and Wills, 1996).

Some promoters that have been identified for idea generation include imagery and visual thinking and feedback from designers. Imagery and visual thinking encourages designers to operate at a more abstract level (Cross and Cross, 1996; Gross, 1996; Verstijnen, et al., 1998). Receiving feedback from fellow designers or external evaluation appears to facilitate both the exploration and expansion of the design space (Carson and Carson, 1993; Kolodner and Wills, 1996; Hist, 1992). Some promoters make use of previous knowledge for the generation of new ideas, this bridging process is important for innovative design. The use of combinatorial play (Cross, 1996; Kumar et al, 1991; Verstijnen et al, 1998) and analogies (Candy, 1996; Candy and Edmonds, 1996; Ekvall and Parnes, 1984) help the designer access earlier periods and trigger new ideas. When the designer is overwhelmed by the number of ideas, or no ideas at all, imposing constraints promotes creativity by focusing on the crux of the problem (Finke, 1990, Finke et al, 1992, Savage and Miles, 1998).

Table 1 gives a breakdown of the primary components found in some popular idea generation methods. The primary components identified in C-Sketch are the visual thinking/imagery, provocative stimuli, and flexible problem representation. 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 is discussed further in the following section. Provocative stimuli may be derived from the exchange of ideas between designers. This component of C-Sketch is intended as a creative stimulant and it is discussed later.

## Visual Cognition and Expression

The primary promoters and tackles on which C-Sketch was based are visual thinking/imagery, provocative stimuli, and flexible representation. The relationship of these components with creative design has been established in various studies in creative cognition, visual imagery, and design protocol studies (DeBono, 1984; Osborn, 1979; Cross and Cross, 1996; Lawson, 1994; Roy, 1993; Tovey, 1986; Gross, 1996; Verstijnen, et al., 1998). 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, such as 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.

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; 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.

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 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. 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. Larkin and Simon (1987) have shown that sketches are useful in problem solving because of their conciseness of representing data compared to sentential descriptions.

In sketches, relevant information is grouped spatially. It is claimed that the relative spatial positions between the different groups of data help the designer *see* new relationships between them, thus leading to insights about the design problem. In sentential data representation, information is more or less serially linked. 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.

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.

Probably the most important use of sketches is that they act as gestalts. 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. Sketches in the early design process are dense and ambiguous, thus affording reinterpretation of the sketches in many different ways (Goel, 1995). 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.

The question arises as to whether it is always better to use sketching as a representation in problem solving. Clearly, it depends on the problem type and the representation type that are more appropriate. Mechanical, architectural, and industrial design problems have predominant geometric aspects that make use of free hand sketches that are more appropriate for the representation of geometry than other forms. Other aspects of a design problem (fluid, thermal, electrical, etc.) may be better addressed using other visualization methods (symbolic or schematic). 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.

Although sketches may have 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 effective use of sketches comes with practice and experience. Experienced designers use sketching to help *generate* an image in the mind as if the sketch *talked back* to the designer (Goldschmidt, 1991). With increase in experience, the designer learns to cultivate the dialog 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).

Figure 3 illustrates the *talk-back* concept in the context of 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, *talk-back* begins and the designer enters a dialog with the sketch. As the dialog proceeds, sketching continues until the drawing cycle is over. Another designer who is the recipient of the sketch interprets it based on his/her domain and context knowledge to create a Mental Image and the process continues.

## Empirical Studies of C-Sketch: Intrinsic Merit

We have developed a comprehensive set of measures to evaluate effectiveness of idea generation techniques for engineering design problems. There are four measures: quantity, quality, novelty and variety (Shah et al, 2000). Quantity measures fluency as the total number of ideas. Quality measures the technical feasibility of an idea and its potential for fulfilling the described specifications. Novelty measures how unusual or unexpected ideas are. Variety measures the extent that the solution space is explored. Quantity and quality are absolute measures since they can be assigned independently to each idea. Novelty and variety are relative and can only be judged with respect to a set of ideas. In progressive idea generation methods, the quantity of ideas is fixed by the methods, which leaves quality, variety, and novelty as the only ones applicable for experiments on progressive methods conducted over the past five years. A summary of these and some other non-DAL experiments and findings are presented in the following sections.

Evidence of Generative and Exploratory Processes (Geneplore Model)

The objective of the first experiment was to find evidence of 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 focused 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).

Evidence of Tackling Design Fixation

An experiment was conducted 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 (Shah, 1998). 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 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 4. Sketches were photocopied before they were exchanged to facilitate the tracking of 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 units (RDU). Three quantities were measured: retention, modification, and fixation. Retention was measured as the ratio of the RDUs from the original idea that survived after changes were made by the second designer, to the RDUs in the original design. Modification was measured as the ratio of the RDUs added or deleted by the second designer, to the RDUs in the original idea. Fixation was measured as the ratio of the RDUs added by the second designer to the sketch received from the first designer, to the RDUs in the original design generated by the second designer. It was found that on the average 69% of the original concept was retained and the second designer modified only 31% of the concept. This indicates that designers did not show a tendency to force someone else's idea towards their own first ideas, while using 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 making more drastic changes, such as changes in physical principles, embodiment, geometry, layout, etc.

Evidence of Provocative Stimuli

There is evidence in the literature that provocative stimuli aid idea generation (DeBono, 1984; Osborn, 1979). A provocative stimulus is defined as an external input, which may act as a catalyst in idea generation. A protocol study on the components of C-Sketch was conducted at the DAL (Shah, 1998). This study demonstrated 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 by the previous designer provide provocative stimuli to the current designer. Passing the sketches provides these provocative stimuli by presenting the designers with new solution directions and new frames of reference from the previous designers. However, Finske, et al., (1992) found evidence to the contrary. They 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.

Evidence of Random Connections

Shah (1998) asserts that provocative stimuli components in an idea generation method may lead to creative misinterpretations. In the fixation experiment conducted by researchers at the DAL, misleading interpretations were found to relate primarily to concepts rather than configurations of design solutions (Shah, 1998). In the experiment, 14 instances of misinterpretations were found between designers' sketches. Of these 14 instances, 10 related to conceptual representations and 4 to configuration. Further, several incidents of misinterpretation of sketches were observed, many of them being conceptual misinterpretations. This happens because C-Sketch does not permit designers to communicate directly with each other. Misinterpretations lead designers along unexpected paths, increasing the chance for novel ideas.

Effect of Design Representation

McKoy (2000) evaluated the differences between textual and graphical representations of design concepts. In this experiment, 89 engineering students at Arizona State University were presented with: problem statements and partial solutions to the design problems either graphically or textually represented. They were asked to complete the designs, much as designers would mid-cycle in C-Sketch or the 6-3-5 Method. Additionally, the students were asked to interpret their own designs, converting the design from one representation to the other. From these experimental results, it was found that designers developed more novel, higher quality ideas with greater variation when asked to employ graphical representations. Statistical analysis on the results using ANOVA and Fischer pairwise comparisons illustrated that the quality and novelty of designs generated from sketching was greater than those from using textual representations. Additionally, the scores generated from analyzing the interpretations of the concepts demonstrate that textual interpretations of sketched solutions faired better than sketched interpretations of textual solutions (Figure 5). A more extensive analysis may be found in McKoy, et al., (2001).

Effect of Method Variables on C-Sketch

The C-Sketch method has three method variables that are adjustable: number of cycles, group size, and cycle time. A detailed description of experiments investigating the influence of these variables may be found in Kulkarni, et al. (1999) and Vargas-Hernandez (2000). First, a discussion of the influence of time and group size on creativity as represented in the work found in the literature is provided. This is followed by a discussion of the results of studies specific to C-Sketch.

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.

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 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 appeared 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).

An empirical study of the method variables was conducted to investigate the influence of the cycle time and number of cycles (passes), on the effectiveness of the C-Sketch method (Kulkarni, et al., 1999). 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. In addition to the quantity of features developed, the final designs were evaluated with respect to the three metrics of quality, novelty, and variety.

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: 6, 9, and 12 minutes for cycle time and 1, 2, and 3 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 add a new dimension to the design space. An example of a conceptual feature is the use of a wheeled military vehicle (Figure 6a). 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 (Figure 6b). Finally, detail features are those that secondary information to the design, without changing the artifact type. An example of detailed features would be to modify the canopy shape (Figure 6d). These three feature types were further decomposed into added, deleted, and modified, indicating the type of change to the design. Examples are illustrated in Figure 6 for the design generated by Designer A 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 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 2 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 were developed around a single design problem. From this analysis, it is believed that a cycle time of nine minutes in C-Sketch works best for simple design problems.

The conceptual results of the experiment have also been analyzed using measures derived for comparing idea generation methods (quality, novelty, and variety). Based upon the analysis, it was found that the number of cycles and the duration of cycle time seem to have little effect upon these measures. These results are illustrated in Figures 7, 8, and 9. 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.

## Empirical Studies on Relative Merit of C-Sketch

Comparative studies were also conducted at the DAL to evaluate the differences between three progressive idea generation methods, Method 6-3-5, Gallery Method, and C-Sketch, based upon the presence or absence of components (Shah, 1998; Vargas-Hernandez, 2000; McKoy, 2000). This section describes the experiments and summarizes the results of the experiments.

The objective of the first experiment was to compare Method 6-3-5, C-Sketch, and the Gallery method with respect to their rules for communication, concept representation method, and critique. 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 and critique. Method 6-3-5 allows only textual representation of ideas, while C-Sketch and the Gallery method permit the use of sketches. Table 3 illustrates how the methods compare with respect to type of representation and critique.

This comparison experiment 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. 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, 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 snap shots of all ideas with which they had been associated to answer specific questions in the survey forms. Results have been computed separately from the surveys and from direct analysis of data collected.

Results Based on Survey

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 4. The survey results record the impressions of the users and include possible misinterpretations by the designers when completing the survey.

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.

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. 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. Figure 10 illustrates the saturation levels of the three different methods after each iteration.

Results based on Data Analysis

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 analysis supports the results obtained using the surveys indicating that the designers did not think highly about Method 6-3-5. 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.

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 11. The results for novelty, quality, and variety for the three progressive methods are illustrated in Table 5, (Vargas-Hernandez, 2000) where 10 is the highest score, given to ideas with the highest novelty, quality or variety, and zero is the minimum.

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.

## Conclusions

There are several structured design idea generation methods available today but they are neither based on theory nor is there much empirical evidence as to their effectiveness. Scientific studies are needed to evaluate these methods and to distinguish between their necessary and superfluous components. Additionally, development of new theoretically based design idea generation methods will replace *ad-hoc* methods. An understanding of the interaction of human variables, method variables and design problem attributes, and the relationship of ideation processes to design outcome, will help companies determine which method to use under given conditions and how to constitute design teams. Such work will also help educators in finding better ways of teaching design synthesis.

The development and rationale of C-Sketch has been presented along with experimental data collected from five years of research. There is much evidence to suggest that sketches are useful as forms of concise data representation when compared with verbal and textual communication. Sketches allow users to read more information from the design than was originally included, acting as gestalts. These observations led to the development of C-Sketch by modifying Method 6-3-5 to use sketches rather than textual description of design concepts generated. C-Sketch has been shown to have components useful in idea generation, including provocative stimuli and flexible problem representation. These have supporting evidence found in both the relevant research literature and in the experiments described in this paper. Provocative stimuli allow designers to combine multiple concepts in unexpected ways. Also, it was found that while many design modifications were misinterpreted from the original intent, the misinterpretations served as launching pads for new design solutions.

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. It has been shown that C-Sketch prevents design fixation but why or how this happens is not yet known. 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 measures of quality, novelty, and variety of ideas generated using C-Sketch seem to reach a saturation point. Additional studies are needed to refine the guidelines of the variable value settings to match problem complexity and designer skill. 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 outperformed Method 6-3-5 in the three measured areas of quality, novelty, and variety of designs generated and was better than Gallery Method in novelty and variety. Further, the Gallery Method scored higher in the three 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 effectiveness of C-Sketch. C-Sketch is now being used in teaching conceptual design at several universities. It is hoped that researchers outside of ASU will conduct their own experiments to independently validate these findings. Finally, the engineering design research community is looking to psychologists interested in creative behavior to join in advancing this research field.

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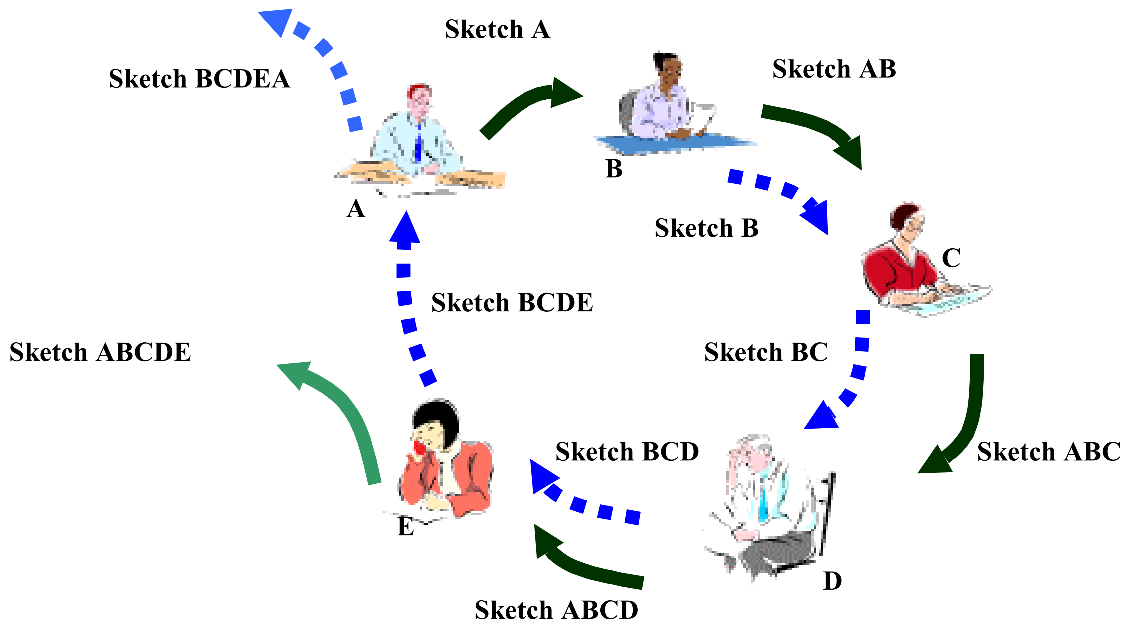



Figure 1 - C-Sketch Process

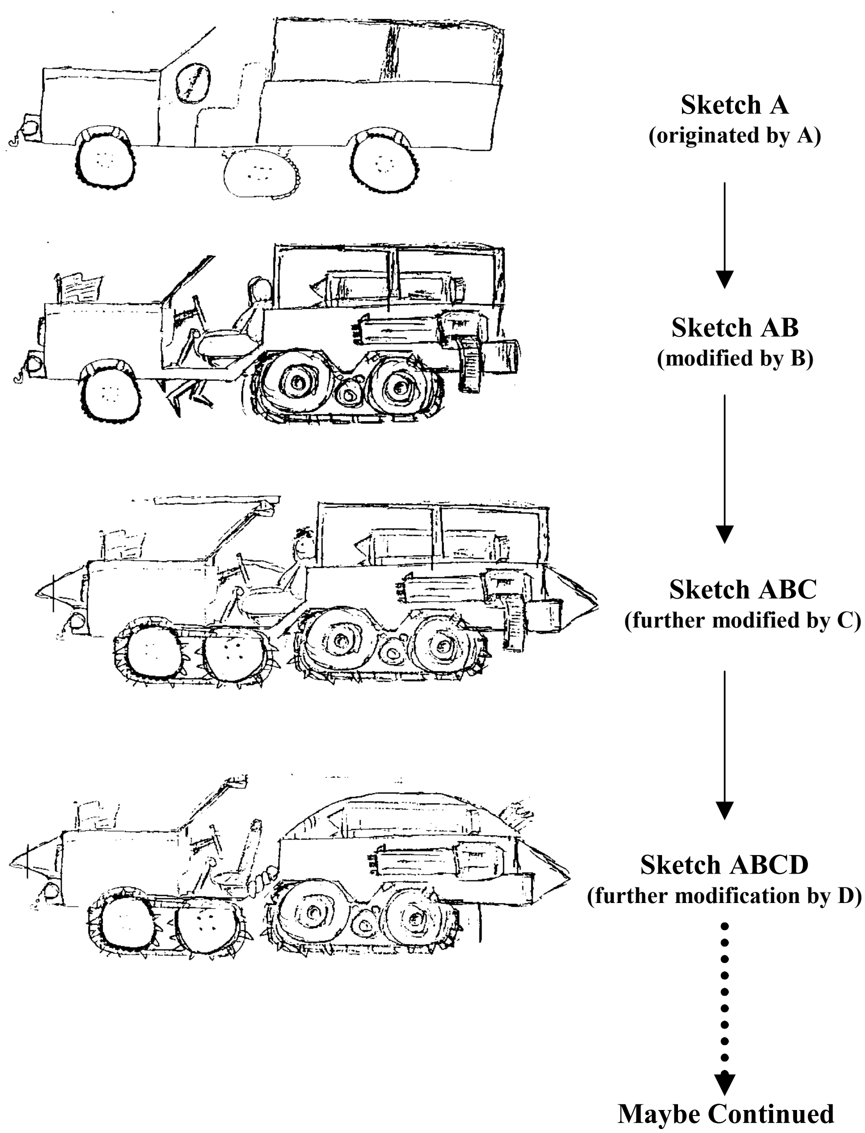



Figure 2 - Progressive-Generative Development of an Idea in a C-Sketch Sequence (Partial)

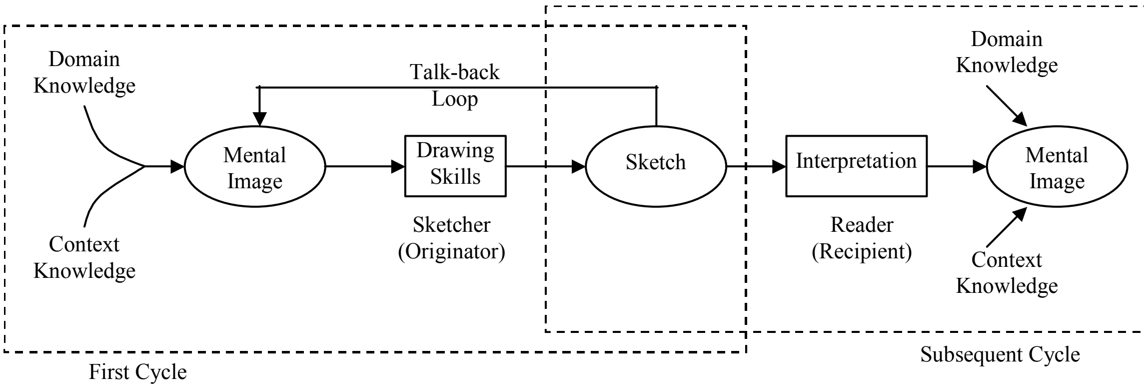



Figure 3 - Talk-Back in C-Sketch

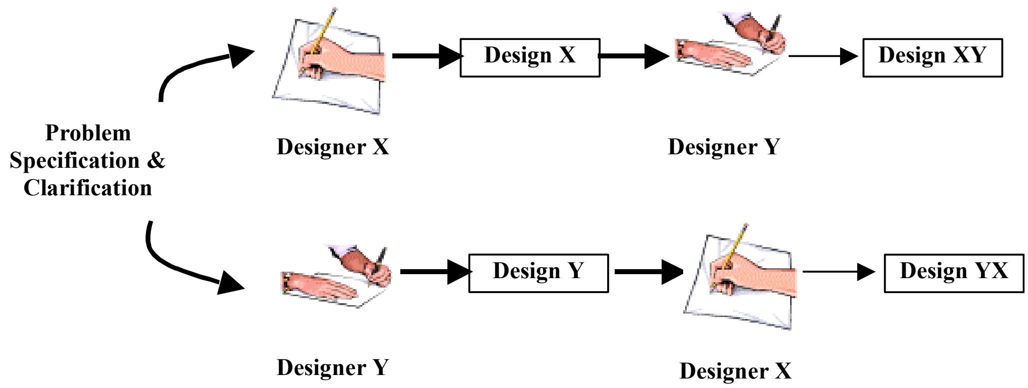
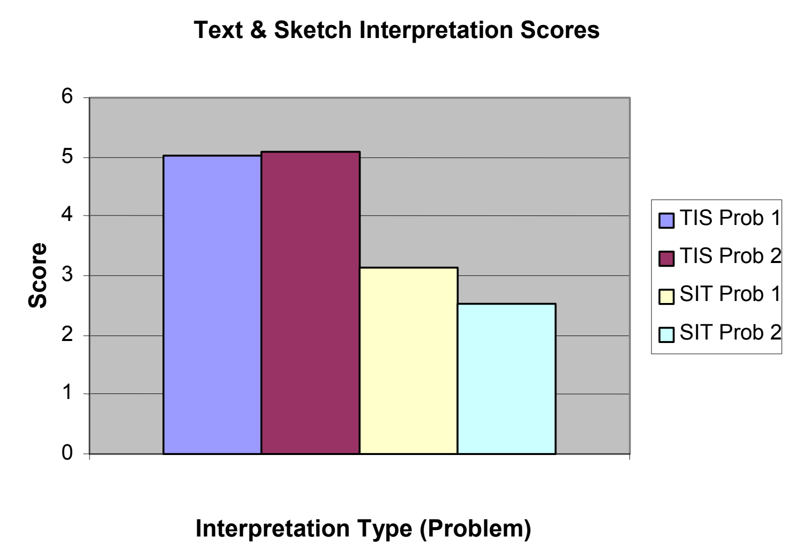



Figure 4 - Experiment Fixation Experiment Procedure




TIS: Textual Interpretation of Sketch
SIT: Sketch Interpretation of Text

Figure 5 - Interpretation Scores (McKoy, 2000)

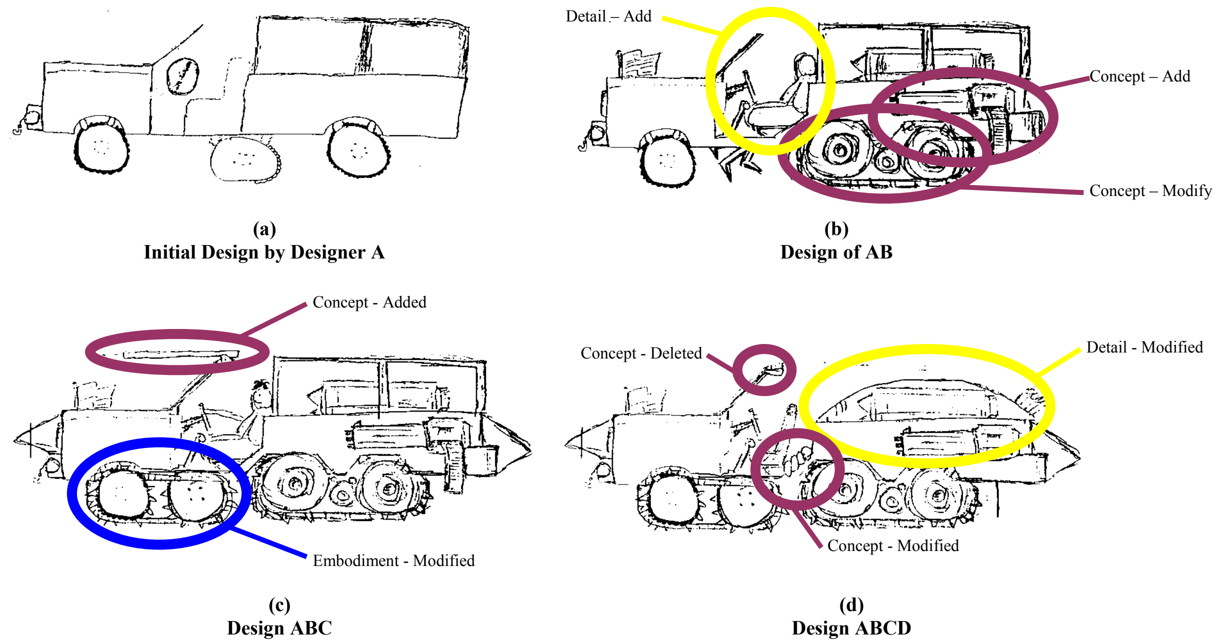



Figure 6 - Analysis of Progressive Sketches

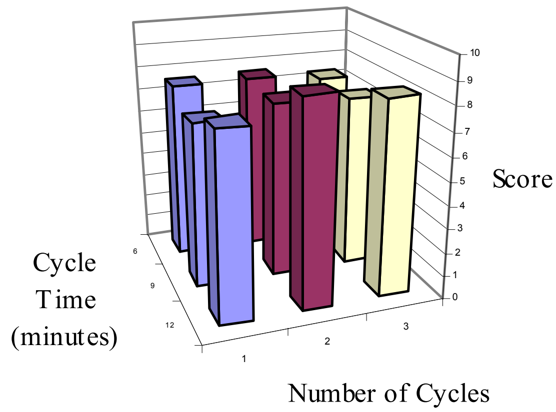



Figure 7 - Quality

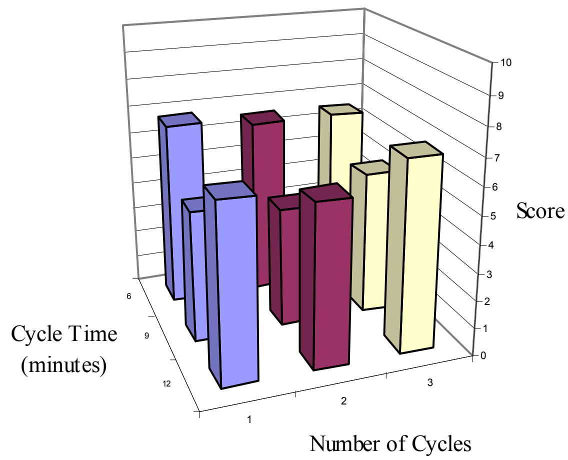



Figure 8 - Novelty

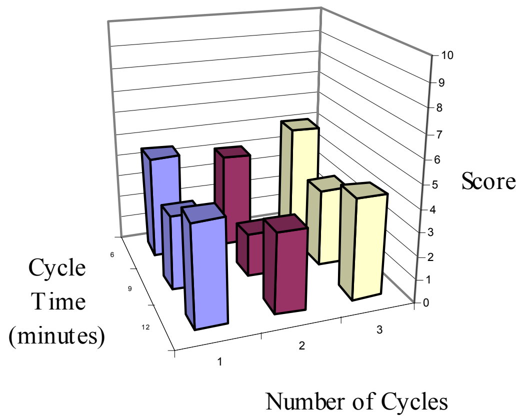



Figure 9 - Variety

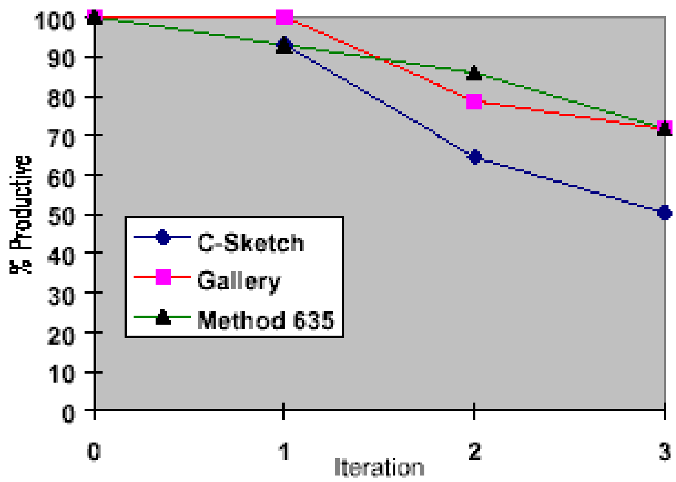



Figure 10 - Productivity Saturation (Shah, 1998)

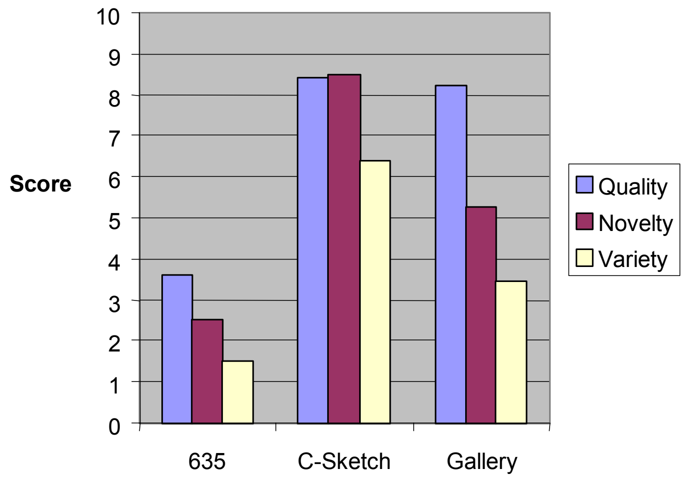



Figure 11 - Comparison of Idea Generation Methods (Vargas-Hernandez, 2000)

Table 1 - Decomposition of Idea Generation Methods into Components (Kulkarni, 2000)

| IG METHOD | TACKLES | PROMOTERS |
|---|---|---|
| Morphological Analysis | Random connections | Combinatorial play |
| Brainstorming | Provocative stimuli, Suspended judgment | Emphasis on quantity, Use of analogies |
| K-J Method | Random connections | Combinatorial play |
| Method 6-3-5 | Provocative stimuli | Delayed judgment |
| *C-Sketch* | *Provocative stimuli, Flexible problem representation* | *Imagery, visual thinking (graphical)* |
| Gallery Method | Provocative stimuli, Random connections | Imagery/Visual thinking, Feedback |
| Storyboarding | Provocative stimuli, Suspend judgment, Random connections | Emphasis on quantity, Sketching |
| Fishbone Diagrams | Random connections, Flexible problem representation | Emphasis on quantity |
| Synectics | Provocative stimuli, Suspend judgment, Change frame of reference | Use of analogies and metaphors, Imagery |

Table 2 - Probability of Variable Affects

| | Cycle Time | Number of Cycles | Interaction |
|---|---|---|---|
| Added Concept | 0.203 | 0.595 | 0.857 |
| Added Embodiment | 0.540 | 0.507 | 0.665 |
| Added Detail | 0.199 | 0.288 | 0.977 |
| Deleted Concept | 0.654 | 0.029 | 0.911 |
| Deleted Embodiment | 0.812 | 0.459 | 0.311 |
| Deleted Detail | 0.473 | 0.329 | 0.051 |
| Modified Concept | 0.852 | 0.031 | 0.221 |
| Modified Embodiment | 0.185 | 0.764 | 0.381 |
| Modified Detail | 0.048 | 0.898 | 0.838 |

Table 3 - Component Comparison of Methods

| Method | Representation Type | Judgment |
|---|---|---|
| 6-3-5 Method | Textual | None |
| Gallery Method | Graphical | Direct |
| C-Sketch | Graphical | Indirect |

Table 4 - Survey Results for Comparison Experiment (Shah, 1998)

| Question | Factor | Method | | |
|---|---|---|---|---|
| | | 6-3-5 | C-Sketch | Gallery Method |
| Do these methods provide provocative action/stimulus to other members? | Provocative Stimuli | 48% | 80% | 64% |
| How do these methods compare with each other with respect to creative outcome? | Creative Outcome | 60% | 67% | 72% |
| How do these methods compare with each other with respect to promotion of creative processes? | Creative Cognitive Processes | 50% | 63% | 75% |

Table 5 - Mean Scores for Progressive IG Methods – Set 97.

| Method (Problem) | Mean Variety Score | Mean Quality Score | Mean Novelty Score |
|---|---|---|---|
| C-Sketch (Cuckoo's Nest) | 4.50 | 8.30 | 7.1667 |
| Gallery Method (Surveillance Vehicle) | 2.32 | 6.88 | 6.4667 |
| Method 635 (Robo Tug) | 2.00 | 4.23 | 6.0152 |