Comput. & Graphics Vol. 14, No. 2, pp. 263-274, 1990
Printed in Great Britain.

0097-8493/90 $3.00 + .00

THE IMPORTANCE OF DRAWING IN THE MECHANICAL DESIGN PROCESS

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Abstract—This paper is a study on the importance of drawing (both formal drafting and informal sketching) during the process of mechanical design. Five hypotheses, focused on the types of drawings, their necessity in mechanical problem solving, and their relation to the external representation medium, are presented and supported. Support is through referenced studies in other domains and the results of protocol studies performed on five mechanical designers. Videotapes of all the marks-on-paper made by designers in representative sections of the design process were studied in detail for their type and purpose. The resulting data is supportive of the hypotheses. These results also give requirements for future computer aided design tools and graphics education, and goals for further studies.

1. INTRODUCTION

The goal of this paper is to study the importance of drawing (both formal drafting and informal sketching) during the process of mechanical design. This goal can be extended to state that we intend to show the *necessity* of drawing during all the developmental stages of a mechanical design. Through the information presented here, the requirements for future computer aided design tools, graphics education, and further studies will be developed.

All mechanical engineers are taught drafting. Thus, most engineers are skilled at making and interpreting these formal mechanical drawings. These drawings are representations of a final design (the end product of the design process) and they are intended to archive the completed design and communicate it to other designers and manufacturing personnel. Additionally, engineers are notorious for not being able to think without making "back-of-the-envelope" sketches of rough ideas. Sometimes these informal sketches serve to communicate a concept to a colleague, but more often they just help the idea take shape on paper. It is in considering how these sketches help an idea take form that gives a hint that drawing's role in engineering is more than just to archive a concept or to communicate with others.

Understanding the use of both drafting and sketching in design is important to help formulate the future development of Computer Aided Design or Drafting (CAD) systems. As CAD evolves and becomes more "intelligent," the question of what attributes these systems must have becomes more important. In the past, CAD system attributes have primarily been driven from developments in the computer industry. It is only through understanding drawing's importance in the design process that these systems can be based on design needs. Additionally, the pressures of CAD tool development, faculty time demands, and course expenses cause academic institutions to reevaluate the content of their "graphics" courses. Understanding drawing's importance in the design process helps establish what skills need to be taught to engineers during their training.

This paper is organized by first, in Section 2, clarifying the types of drawings used in mechanical design. The hypotheses to be addressed in this paper are given in Section 3. A discussion of research on the understanding of visual imagery to be used as a basis for arguments in support of the hypotheses is in Section 4. In Section 5 is a discussion of the results of data taken on how mechanical engineers use drawings during design. Lastly, in Section 6, is a discussion of how well the hypotheses have been supported and the implications of our findings on CAD development, educational requirements, and future research directions.

2. TYPES OF DRAWINGS USED IN DESIGN

Engineers make many types of marks-on-paper. In research, to be described in Section 5, we have broken down these marks into two main groupings: support notation and graphic representations. Support notation includes textual notes, lists, dimensions (including leaders and arrows), and calculations. Graphic representations include drawings of objects and their functions, and plots and charts.

Mechanical design graphic representations are often scale drawings made with mechanical instruments or CAD computer systems. These drawings, made in accordance with a set of widely accepted rules, are defined as having been drafted. Sketches, on the other hand, are defined as "free-hand" drawings. They are usually not to scale and may use shorthand notations to represent both objects and their function.

A differentiation must be made between the act of graphic representation and the medium on which it occurs. The medium, whether it be paper and pencil, a computer stylus on a tablet, chalk on a blackboard, or other medium may put interface restrictions on the representation. The following discussions are concerned with what is being represented, not with how the representation is made. However, the discussions point to the medium's restriction on representation and the need for improved interfaces.

Another aspect of drawings to be considered is the level of abstraction of the information to be represented. During the design process, the design is refined from an abstract concept to a final, detailed, drafted design. This can be clearly seen in an example taken from one of our studies described in Section 5. In this study the designer was developing an assembly to hold three batteries for a clock/calendar in a computer. Fig. 1 is a compilation of all the sketches and drawings one subject made during the development of a battery contact in this design. The number beside each graphic image is the percentage of the way through the design when the representation was made. The component is refined from a sketch that contains primarily functional information, to a refined, scale drawing of the final form. The first sketch in Fig. 1 shows two contacts (represented as circles) and a connection between them for current flow (represented as a line). The symbology here is clearly functional.

Even though a good percentage of an engineer's graphic representation is informal sketching, drafting is the focus of most engineering training and the strength of CAD systems. On the other hand, most engineers receive no formal training in sketching. It is often assumed to be some natural ability. Three typical texts used in teaching undergraduate "mechanical" drawing were reviewed[1-3]. Each of these presented only a few pages of information on sketching. Additionally, CAD systems do not support sketching in any meaningful way.

For the purposes of this paper, the term *CAD* is defined as the use of interactive computer graphics to help solve a mechanical design problem. Current CAD tools aid the mechanical design process in four ways: as an advanced drafting tool; through assisting in the visualization of hardware and data; by improving data organization and communication; and through being used as a pre- and postprocessor for computer-based analytical techniques such as finite element analysis, weight and mass properties, kinematic analysis, etc. For all these uses, the "design" must be refined to the point that a scale drawing of it can be made. Thus, for current systems, the "D" in CAD means drafting.

3. THE RELATION OF DRAWING TO PROBLEM SOLVING

The initial reduction of videotaped data taken of design engineers led to the publication of six uses of the act of drawing[4, 5]:

1. To archive the geometric form of the design.
2. To communicate ideas between designers and between the designers and manufacturing personnel.
3. To act as an analysis tool. Often, missing dimensions

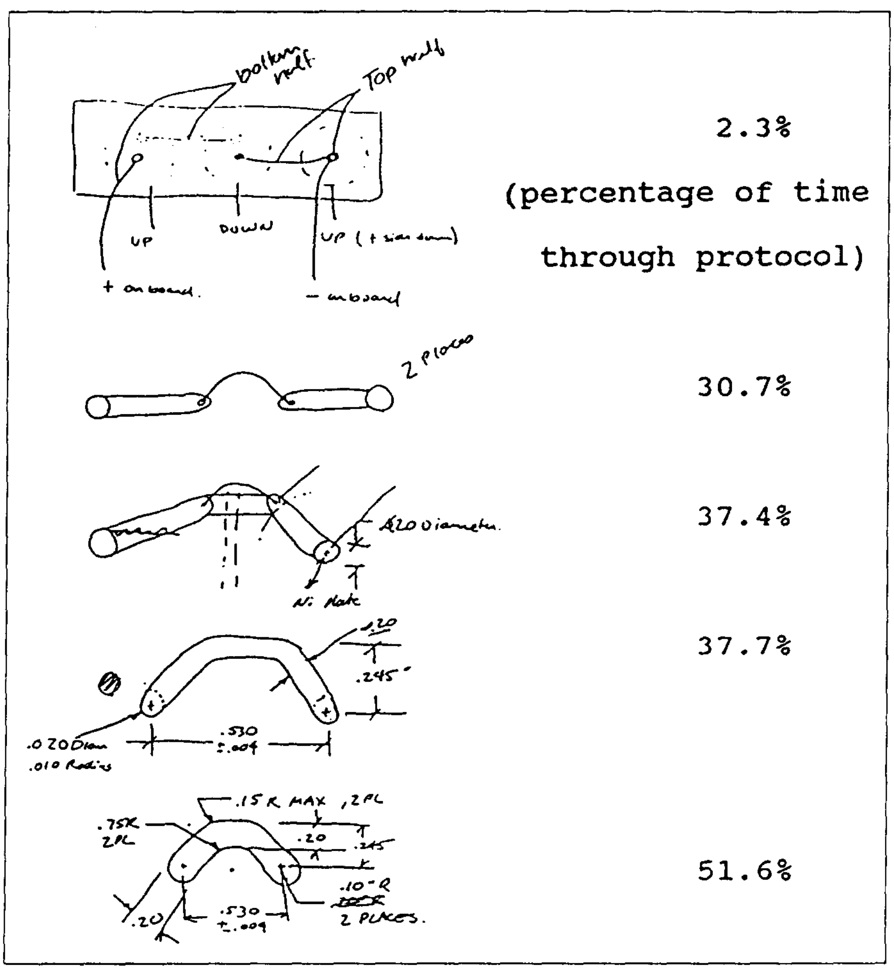

Fig. 1. The evolution of a battery contact—total protocol time of 8 hours and 34 minutes.

and tolerances are calculated on the drawing as it is developed.

4. To simulate the design.
5. To serve as a completeness checker. As sketches or other drawings are being made, the details left to be designed become apparent to the designer. This, in effect, helps establish an agenda of design tasks left to accomplish.
6. To act as an extension of the designer's short-term memory. Designers often unconsciously make sketches to help them remember ideas that they might otherwise forget.

It was realized that these observations were both overlapping and incomplete. In particular, based on the data and readings in the cognitive psychology literature, we felt that the last item was potentially much richer than stated. Thus, these observations have fostered five hypotheses. Each hypothesis is presented below followed by support from the literature. The mechanical design data in support of these hypotheses is in Section 5.

Hypothesis 1. *Drawing is the preferred method of external data representation by mechanical engineering designers.*

Designers represent data both internally, in their minds, and externally on paper, a computer screen, or other media. It is fairly obvious that designers like to draw in these mediums and prefer a picture to a written description of an object. It is important to understand why drawing representations are preferred over other forms such as text or propositions (if-then rules).

In *Why a Diagram is (Sometimes) Worth Ten Thousand Words*, by Larkin and Simon[6], the authors explore the use of diagrams in problem solving. Here a diagram is a drafted, schematic drawing representing the objects in a physics problem. In this paper, sentential (textual, indexed by position in a list—a sentence) and diagrammatic (graphical) representations and their effect on problem solving are compared. In comparing these, the authors conclude that:

1. Diagrams can group all information that is used together thus avoiding large amounts of search for needed elements. Text only indexes to the next element in the sentence list (the adjacent piece of information) while diagrams have many adjacent elements.
2. Diagrams explicitly preserve information about geometry and topology, whereas text is only serial in nature. This feature of diagrams allows for easy indexing of information to support computation processes. However, text preserves the temporal or logical sequence of information. This is lost in diagrams.
3. Diagrams use location to group information about a single element, avoiding the need to match symbolic labels. Diagrams automatically support a large number of perceptual inferences; the information can be indexed in a variety of manners.

It seems reasonable that these conclusions about diagrammatic representations can be extended to all graphical representations. Based on Larkin and Simon's conclusions, it is easy to see why, in the complexity of mechanical design, drawings are preferred over text.

Hypothesis 2. *Sketching is an important form of graphical representation serving needs not supported by drafting.*

Later in this paper we will analyze all the marks-on-paper made by a small group of engineering designers. Their drawing marks will be classified as either free-hand (sketching) or drafting marks. The hypothesis above states that the sketches have a role that more formal drafting cannot fill. Dan Herbert, in *Study Drawings in Architectural Design: Applications for CAD Systems*[7], considers the use of sketches (study drawings) in the solution of architectural design problems. He defines "study drawings" as "informal, private drawings that architectural designers use as a medium for graphic thinking in the exploratory stages of their work." Architects often make these study drawings in the borders of or adjacent to their formal drawings. In his paper, Herbert conjectures about the properties of sketches that affect the design process. These properties form the basis for his theory of the use of sketches in design.

In Herbert's theory, sketches are used because they provide an extended memory for the visual images in the mind of the designer. Since sketches can be made more rapidly than formal drawings, they allow for more facile manipulation of ideas. Furthermore, sketches allow the information to be represented in various forms, such as differing views or levels of abstraction. Thus, he calls sketches "graphic metaphors" for both the real object and the formally drafted object under development. In fact, Herbert claims that sketches are a principal medium of external thinking. Herbert's thoughts lead to the third hypothesis.

Hypothesis 3. *Drawing is a necessary extension of visual imagery used in mechanical design. It is a necessary extension of a designer's cognitive capability for all but the most trivial data representation, constraint propagation, and mental simulation.*

This hypothesis states that without data representation on media external to the designer, there can be no design of substantive problems. Anecdotal support for this hypothesis is evident in asking a designer to design something and observing him/her reach for a pencil or chalk. In the next section of this paper, we will discuss a model of information processing in human problem solving that gives some scientific support to these anecdotal observations and to the hypothesis. In this model, drawings are an extension of humans' limited ability to visualize objects in their mind.

The limitation of cognitive ability leads to the fourth hypothesis.

Hypothesis 4. Drawings require transformation from the designer's memory to the extended memory medium. The nature of the transformation is dependent on the characteristics of the medium.

The manner in which humans represent information in their memory is still a subject of much debate and research. Whatever the form of this internal representation, it is potentially different from the representation made externally on paper, in a CAD system, or through some other media. The transformation between these two media is one of both correspondence and implementation. Correspondence is the transformation between the internal and the external vocabularies. If the designer has a visualized 3-D object in his/her mind and wants to represent the object externally, it can be transformed into an isometric, orthographic, or other 2-D representation and drawn on paper or with a 2-D CAD tool, or it can be transformed to boolean primitives and represented on a solid modeling tool.

Further, depending on the medium chosen, there is the additional necessity to transform the image to meet the requirements of the implementation. The cognitive process for drawing a line with a pencil is different from that for specifying the end points for a CAD representation of the line. Both the research of Larkin and Simon and of Herbert focus on correspondence. There is no literature known to the authors concerning the effect of implementation on the cognitive load of the designer.

Even though the exact form of human memory is still unknown, it is generally discussed by psychologists in terms of cognitive units or chunks of data. The nature of these cognitive units, which will be discussed in the next section, leads to the fifth and final hypothesis.

Hypothesis 5. Drawings both utilize and determine the cognitive units (design features) used in mental image formulation. Thus, the designer's cognitive information organization is interdependent with the drawing's characteristics.

This hypothesis is double edged. It seems obvious that the content and structure of drawings is dependent on the mental image and how it is formed (its cognitive chunks). It is debatable whether or not the mental images are influenced by the drawings. This issue will be addressed again later.

4. A COGNITIVE MODEL OF MECHANICAL DESIGN

In an earlier description of designers as information processors[8], we presented Fig. 2 as the environment in which the design takes place.

This figure is based on the model developed by Newell and Simon[9] and called the Information Processing System (IPS). The figure can be viewed as a

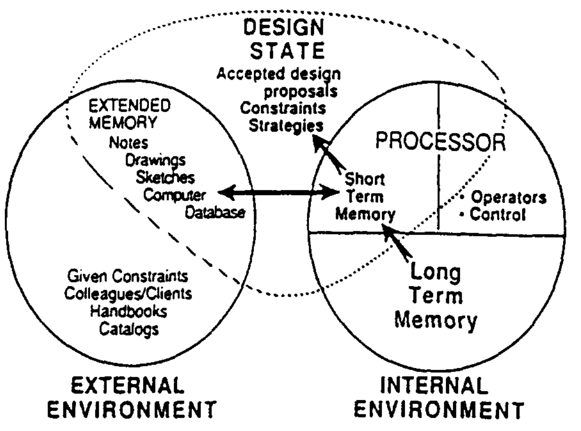

Fig. 2. The design environment.

"map" of the locations in which information about the design may be stored. It is divided into an internal work space (inside the mind of the designer) and an external workspace (outside the mind of the designer). Within the designer, there are two locations corresponding to the two different kinds of memory: short-term memory (STM) and long-term memory (LTM). There is also a "processor" that is responsible for applying operators and controlling the design process. In Ullman, Dietterich, and Stauffer[8], 10 operators were identified that characterize the problem solving in mechanical design. External to the designer there are many "design state storage locations" including graphical representation media such as pieces of paper and CAD tools, as well as other sources such as textual notes, handbooks, and colleagues.

Thus, the design or some feature of the design can only be represented in three locations: STM, LTM, and the so-called, external memory. Each "location" has certain properties that affect how it can be used in design. In order to support the hypotheses about the importance of drawing in the mechanical design process, this model needs to be discussed in more detail.

To discuss drawing's role in the mechanical design process, the characteristics of the STM, the LTM, and the information flow between them and the external environment will be developed. This detail is based on Newell and Simon's model, the extensions of it to visual imagery by Kosslyn[10–12], and the effort to codify it by Anderson[13]. It must be realized that the contents of the model given here are not fully agreed to in the cognitive psychology community, but they are certainly secure enough to provide a basis for discussing the role of drawing in mechanical design.

4.1. *Short-term memory*

Short-term memory is very fast and powerful. The contents of the STM comprise the information we are aware of, our conscious mind. All design operations (*e.g.*, visual perception and drawing creation) are made on information that is brought into short-term memory. Unfortunately, STM has limited capacity. Studies have shown that it is limited to approximately seven cognitive units or "chunks" of information[9]. Although limited in capacity, the STM is a fast processor with processing times on the order of 100 msec[17].

In the view of Kosslyn, one function of the short-term memory is as a visual buffer[12]. In this capacity, it is considered a hard-wired, special purpose, short-term buffer that evolved from the need to process information from the eyes. Thus, this buffer is viewed as a coordinate space with limited spatial extent, more clarity toward the center, and the image fading without regeneration effort. The visual buffer supports images derived from the eyes during perception, and from both the eyes and the long-term memory during idea generation and manipulation.

4.2. *Long-term memory*

The long-term memory, on the other hand, has essentially infinite capacity, but access is slow (from 2 to 10 seconds per chunk). Access to long-term memory is also not direct. Instead, memories must be triggered by some cue or retrieval strategy based on information in short-term memory. During design, parts of the design state are stored in long-term memory. These are relatively easy to cue because, at any time, currently important parts of the design state are in short-term memory and can act as pointers for the knowledge in the long-term memory.

In terms of visual imagery, according to Kosslyn there are two different types of information stored in the long-term memory: facts about objects (including size of objects, how they are put together, names of superordinate categories, their function, etc.) and encodings of the literal appearance of the object (list of coordinates where points should be placed in the visual buffer). Shepard[14] argues that there may not be a concrete or "first order" isomorphism between an external object and the corresponding representation. He proposes a "second order" isomorphism in which functional relations among objects are modeled and stored. It is clear that the information about images contains more than the literal appearance and that a propositional memory must be included as part of the visual image.

4.3. *Cognitive units*

The contents of the cognitive units processed in the LTM and STM are not exactly clear. Anderson[13], in his effort to build a computer simulation of human information processing, utilizes three types of data representations for these units: spatial images, textual data, and propositions. It will be shown that the spatial representation view of memory is especially important in considering the form-oriented field of mechanical engineering design.

There is virtually no evidence in the literature about the way in which designers encode information about mechanical objects in their memory. There has been much conjecture about this, however, as the chunks of data, more commonly referred to in engineering design as the design features, are the basic building blocks of human design organization. Thus, if a design is to be represented in a manner that is most easily communicated to/from a human designer, then the information should be encoded in features that are familiar to him or her. Current CAD systems use features that are made of geometric primitives such as lines, arcs, solids, and icons. There are the features designers are taught to use, but it is not clear that these are the way the information is best organized in their memory and most easily indexed. This gives rise to the following questions: Where do these features come from? Is it that designers have a natural set of features in their heads, or is the patterning developed through their education?

The only windows that exist to study the chunking of objects in a designer's head are through his/her representation of these features as written text, words, drawings, or gestures. Features used by humans to represent geometry and topology are often not easily represented textually or verbally, but can be graphically represented quite easily. For example, novice chess players, when asked to recall the position of chess men on a board, did so on a man-by-man basis. However, experts recalled patterns of men, larger, more complex features than the novice[15]. These chunks had no formal "names" that could be represented as a simple written or spoken term, but they could be graphically represented by the positions on the board quite easily. Similar experiments in the domain of architecture[16] resulted in chunks that, although easily represented graphically, could only be awkwardly represented textually as, for example, "A string of exterior walls" or "Two wall segments with windows forming an exterior corner of a square space."

The only experiment of this nature performed on mechanical engineers was performed by Waldron and Waldron[18]. In this experiment, novices (undergraduate students), intermediates (graduate students), and experts (practicing engineers) were shown an assembly drawing for a short period of time. The drawing was then covered and the subjects asked to reproduce it. By observing the videotaped protocols of the subjects performing this task, it was evident that the novices remembered line segments, the intermediate subjects remembered objects such as gears, and the experts remembered functional components embodying a large number of physical objects.

4.4. *How the IPS model supports the hypotheses*

The above description is important to the understanding of the use of graphical representations in mechanical design, as it gives insight into the correctness of the hypotheses put forward in Section 3.

First, it must be noted that all the tasks performed on a design require either recall of information from the long-term memory or manipulation in the short-term memory. Since the number of chunks of information the STM can work with is limited and mechanical designs get complicated very rapidly, the short-term memory forms a critical bottleneck for human designers. Additionally, as the STM transforms information so rapidly and the long-term memory so slowly, only external representations made through transforming the image to graphic or textual representation can serve as added memory. Since textual information is so limited in characterizing form, graphic representation is the only reasonable memory extender for mechanical designers. This supports the first hypothesis.

The second hypothesis, that sketches serve purposes not supported by drafting, has much to do with the speed of the representation. One purpose in making a graphic image in the external environment is so that it can be viewed, encoded in the STM, and parsed in a new way. In other words, rapid external image generation allows designers to "see" information differently than the way it was generated. Thus, the method of generating the external image must be rapid and flexible or it will slow down the cognitive processing.

Since the STM is so limited in capacity and mechanical design is so complex, drawings are needed in design as an extension of the visual imagery capability. Thus, the IPS model supports hypothesis 3. Considering both hypotheses 2 and 3, drawing both extends the capacity of the STM and gives the capability of reparsing the information for continued processing.

The fourth hypothesis stated that graphical representation is a metaphor for visual imagery and it requires transformation dependent on the medium. It would be ideal if the medium image representation requirements exactly matched the image representation in the short-term memory. In one sense, this match always occurs in that, to some degree, the medium used formulates the image chunks that are stored in the long-term memory and later form a basis for generating and inspecting the image in short-term memory.

The fifth hypothesis states that graphical representation both utilizes and determines design features. We have historically been constrained to two-dimensional media (*e.g.*, pencil and paper) and these have, to some degree, formed our representations. It is not clear how we encode and store three-dimensional objects. There is one argument that memory is object-centered and that the object can thus be manipulated as a solid model. This is countered by the argument that memory is viewer-centered and thus only the specific view stored in LTM can be used for generation or inspection [12]. Thus, the current state of cognitive research is not yet refined enough to support this hypothesis.

5. SUPPORTING EVIDENCE FROM STUDIES OF MECHANICAL DESIGNERS

In previous research, we and our colleagues have taken videotaped protocols of mechanical design engineers solving realistic design problems. To support the hypotheses in this paper, sections of the videotaped data were reevaluated to identify data germane to the hypotheses. The following section briefly reviews the source of the data. This is followed by an evaluation of marks-on-paper made by the subjects in their solution of the problems.

5.1. *The protocol experiments*

Five mechanical design engineers of varying background and experience were given the initial specifications for one of two fairly simple, yet realistic, industrial design problems. The engineers were requested to think aloud as they solved the problems. Their verbal reports, drawings, and gestures were video- and audiotaped for a period of 6–10 hours. The taped data were then transcribed to obtain a "protocol" of the design session. Each designer made numerous drawings during his/her solution of the problem. All of these were on paper, and the subjects were required to work in ink so that a complete history of their marks-on-paper would be obtained. Some subjects found this restriction frustrating, and, in retrospect, erasing could have been allowed as the veodeotape clearly shows their efforts on the paper. It should be noted that CAD systems were not used in the study because none of the designers used CAD in their daily practice, and its use would have added another variable to an already complex experiment design.

During the protocols, the subjects were asked to talk continually, not to explain what they were doing but just to talk along with their effort. Experiments have shown that verbalizing during problem solving does not alter the content of the solution [19]. If the subject was silent for more than about 10 seconds, the examiner would remind him/her to keep talking.

The two problems used in the study were the "battery contacts" problem and the "flipper-dipper" problem. The battery contacts problem statement, in abbreviated form, is the following:

> Design a plastic envelope (dimensions provided) and the electrical contacts to accept three batteries to power the time clock in a new computer. The batteries (detailed dimensions provided) must be connected in series and to an adjacent printed circuit board. The external dimensions of the envelope are provided as are needed contact pressures. The volume is 50,000 units/month for three years and the assembly will use a robot.

Two subjects, S1 and S2, solved this problem.

The flipper-dipper problem statement, in abbreviated form, is the following:

> Design a mechanism that will accept a 10″ × 10″ × .063″ aluminum plate from a worker, lower one side so that it just touches the surface of a chemical bath (to receive a chemical coating), lift the plate off the bath surface, flip it over, lower and coat the other side, and present it to the worker for removal. There were only to be 3 of these built.

Three subjects, S4, S5, and S6, solved this problem. More details of these problems and the solutions can be found in [5, 8, 20].

Approximately 46 hours of data were taken. All of the data was transcribed and analyzed to determine the general problem flow. In these early stages of working with the data, it was realized that the act of drawing fulfilled needs beyond that of documenting the design. These observations prompted this investigation.

Several detailed analysis techniques were tried on selected parts of this data in an attempt to develop an analysis method that provided insight into the goal structure of the design. It was found that an analysis based on tasks, episodes, and operators was most revealing and was reasonably repeatable by different researchers. Results of this research are reported in [8, 20]. Additionally, this data has been used as a basis for developing representations[21, 22] and a computer model of mechanical design[23]. There has also been an effort to automate the reduction of the data using a technique called pause analysis.

Fifteen sections of the protocol data were analyzed for the content and purpose of the marks made on the paper. Three sections were taken from the protocol of each of the five subjects, S1, S2, S4, S5, and S6. For each subject, a section was chosen when: 1) the primary task was conceptualization, 2) the primary task was refining the design, and 3) the primary task was documenting the design. These three areas were representative of the significant phases of the design process (conceptualization, layout, and detail design). The 15 sections of protocol data consisted of 174 minutes of data. Within this 3+ hours of data, all the marks made on the paper by the designers were investigated.

It must be pointed out that the protocol data was not taken specifically for this study. Thus, the data analysis performed and the statistics given are considered as preliminary pointers to studies specifically aimed at now identifiable issues. Protocol data is always subjective and time consuming in reduction, but usually gives insight into where more detailed studies need to be performed.

5.2. *The types of marks-on-paper in the protocols*

The selected sections of protocol data were reviewed and each marking action was noted. A marking action was defined to be a series of marks made between significant marking pauses, where a significant pause was taken to be greater than one second. This value was chosen for three reasons. First, it appeared that for pauses longer than one second, the subject's focus of attention changed. In other words, the marks before a one-second pause served a different goal than those after. Second, pauses less than a second could be interpreted as just a change in gripping the pencil, moving the hand out of the line of sight, or other manifestation of the media. Third, Chase and Simon, in their study of chess players, used two seconds, with the caveats that this time was a bit arbitrary and that the results of the study would not change significantly if the value were changed by a small amount. In our study, less than 10% of our data would be eliminated if the significant interval were changed from one second to two.

It is assumed that each marking action is the external representation of a chunk of information. This assumption is commonly used[15, 16] and seems reasonable. During the pause, the subject either recalls information from long-term memory or processes information in the STM to form a new chunk. Then, during the drawing action, the piece of information is represented externally.

A total of 363 actions were identified. Each action and its preceding pause took an average of 29 seconds. In Ullman, Dietterich, and Stauffer[8] it was shown that the average problem-solving episode was about 59 seconds; thus there are approximately two marking actions per problem-solving episode.

Within the 29-second average length of pause plus action, the average length of time to make a mark on paper is 7.3 seconds with a standard deviation of 7.8 seconds. This value can be further refined by considering the marks made in the differing design phases where for conceptual design the average is 6.8 seconds, for layout design the average is 8.4 seconds, and for detail design the average is 7 seconds. The standard deviation on this data is 5.7, 8.37, and 8.7 respectively. The standard deviation on this data is high, as there are many different activities performed during these drawing actions. Many actions that were longer than one minute were used for recalling information used previously or in copying a previously designed part over for detailing. These sections may actually have more than one cognitive chunk being represented, but the action seemed focused on one goal and thus these were regarded as one chunk of data.

To facilitate analysis, the 363 marks-on-paper are divided into "draw" marks and "support" marks. These are further refined into "sketch" and "draft" marks, and "text," "dimension," and "calculate" marks respectively. Thus there are five types of marks-on-paper. They are defined as:

- *Sketch:* Drawings of features made free-hand. Typical sketches are shown in Fig. 1.
- *Draft:* Drawings made with mechanical devices. An example of this is when subject S5 uses a straight edge and a ruler to lay out the "chair" mechanism, part of his device to hold the plate in the flipper-dipper problem. As shown in Fig. 3, the subject used orthographic projections.
- *Text:* Letters, words, or numbers that are not part of a dimension on a drawing and not part of a calculation. An example of this is when subject S1 writes down some manufacturing notes next to the drawing of the spring contact in the battery contact problem as shown in Fig. 4.
- *Dimension:* Dimensions or dimension lines on a drawing (either a sketch or a draft). An example of this is when subject S6 dimensions the location of some blocks and wire hoops that were part of his plate handling mechanism in the flipper-dipper problem solution. This is shown in Fig. 5.
- *Calculate:* Equations and answers to calculations. Combines constraints or design proposals to derive

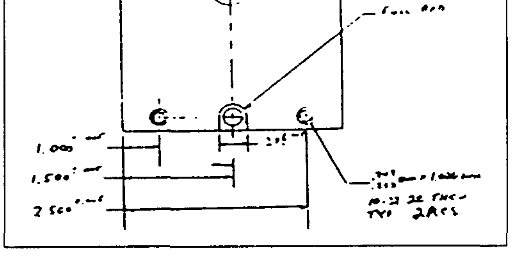

Fig. 3. Drafting example from subject S5.

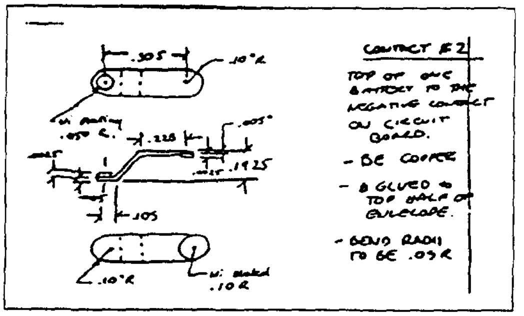

Fig. 4. Text example from subject S1.

new information. An example of this is when subject S2 is trying to determine the stress and deflection in the spring due to the given contact force; see Fig. 6.

There was some debate as to how to differentiate between sketch and draft. There are two measures to consider: (a) the use of instruments and (b) whether or not the drawing was to scale. Consistency with traditional college graphics texts[1, 2, 3] suggests that the criteria should only be the use of instruments which is as defined above. All the subjects had instruments at hand. However, some subjects chose to make their scale drawing free-hand. It would seem that they felt that it was easiest not to use the instruments. The differentiation between sketch and draft is made even more clear by considering the point in the design when the drawing was made. When the subjects were trying to conceptualize the design, 100% of the drawings were sketches. Later in the design, during the layout and detail phases, this drops to 52% as some of the subjects used instruments to draw their refined design while others continued to sketch.

Orthogonal to the types of marks-on-paper is the purpose of the marks. Each of the 363 marks was reviewed to find the purpose for making it. The purposes for making marks-on-paper are "add," "patch," "refine," and "recall information." Each of these is defined below:

- *Add:* The subject makes a specific mark for the first time that is not a given constraint (an initial specification). If the topic of the mark is a given constraint, the subject is recalling information (see below). An example of an Add is when subject S6 draws the grippers to hold the plate for the first time, thereby adding them to his design as shown in Fig. 7.
- *Patch:* The subject detects a constraint violation and alters the design without changing the level of abstraction. An example of this is when subject S1 sketches the third sketch in Fig. 1. Here she realizes that the contact, as originally drawn in the second sketch and being recalled here, will interfere with a wall (dashed lines) that has been added to the design since the second sketch was made. She scribbles out part of what she has recalled from the second sketch and patches the design by angling the contact upwards.
- *Refine:* The subject makes a drawing or writes supporting information for the object at a less abstract level than previously. An example of Refine is when subject S1 changes the design of the contact from a wire connecting two oval pieces of sheet material to one continuous piece as shown in Fig. 1.
- *Recall Information:* The subject recollects something that has been drawn or noted previously, or that is a given constraint. No new information is specified. An example of this is when subject S6 is drawing the water level, table area, and plate, which are given constraints in the problem. This is shown in Fig. 8.

Based on the types of marks-on-paper and the purpose of the marks, the 363 actions have been classified as shown in Table 1.

It is interesting to note the subject-to-subject variation in our data. With such a small database, there is concern that the results are not generalizable. This concern is realistic and warranted, and thus we have only based our conclusions on the aggregated data. In reviewing all the drawings used by the five subjects (including those not included in the data reduction in this paper), it was observed that subject S1 only sketched and never used isometric drawings. Subject S2, solving the same problem, also sketched and almost exclusively used isometrics. Subjects S4, S5, and S6 used a mix of isometrics, orthographics, and 2-D drawings. However, S4 and S5 did nearly all of their work with instruments (drafted), and S6 did no drafting. One area that was influenced by the problem is in the use of calculations. The two subjects who solved the battery contacts problem used calculations in the

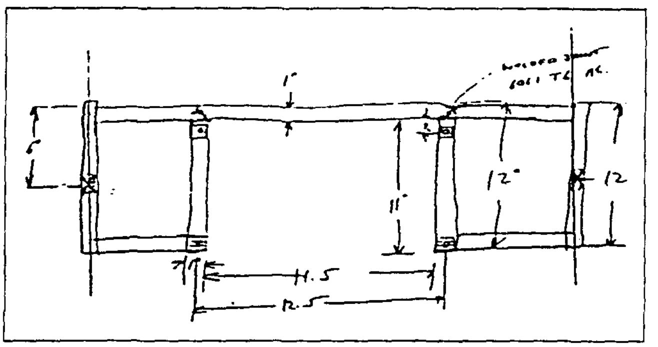

Fig. 5. Dimension example from subject S6.

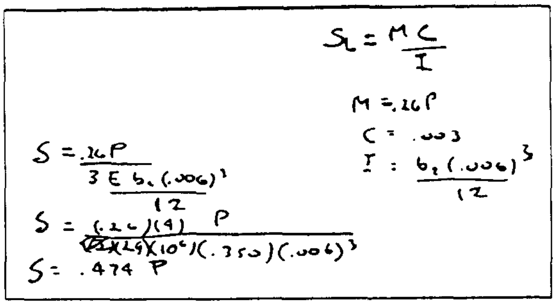

Fig. 6. Calculate example from subject S2.

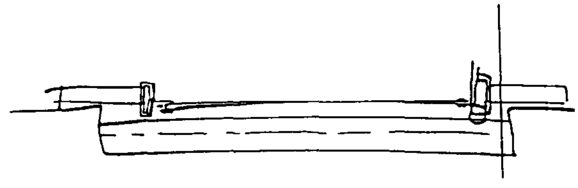

Fig. 8. Recall information example from subject S1.

sections of their protocols studied, whereas the other three subjects, solving the flipper-dipper problem, did not. To add some numbers to these observations, consider the drawing actions (we lump sketch and draft together to account for S5's use of drafting). For the 111 add actions the subject variation is S1 = 10, S2 = 7, S4 = 48, S5 = 32, and S6 = 14. The mean and standard deviation are 4.9 actions and 4.7 actions respectively. For the 14 patching actions, the statistics are 10.3 actions and 8.4 actions. For the 53 refining actions they are 7 actions and 6.4 actions. Finally, for recalling information they are 7.2 actions and 9.5 actions.

5.3. *Support of hypotheses*

Support for the first hypothesis, that drawing is the preferred method of external representation, comes as no surprise. Of the 363 marks-on-paper, only 9% were for text and 5% for calculations. The remainder were either sketching or drafting (72%) or dimensioning in support of the drawing (14%). These percentages are fairly consistent across all the subjects, as shown in Table 2.

The second hypothesis states that sketching is an important form of representation in mechanical design. In our data, 67% of the drawings were sketches. An argument could be made that many of these sketches could have been made using drafting equipment or on a CAD system. A counterargument is that with the average length of these sketching actions at eight seconds, the use of instruments could have slowed the drawing action to the point that the cognitive problem solving would be impaired.

The third hypothesis, that drawing is a necessary extension of visual imagery, becomes most evident in the simulation sections of the protocols. It is certainly clear that many drawing actions were not to document the results of the design activity but were part of the design process itself. It is further logical that if the subjects could have performed these simulations in their heads, they would have done so without making the sketches. It was noted in [8] that the subjects never compared their design proposals to more than two or three constraints. It was hypothesized that this was due to short-term memory limitations. Here it is clear that the drawings not only provide the subjects with a memory extension, but they also force the proposed design and constraints to the same level of abstraction and the same representation for comparison. Thus it can be concluded that these simulations on paper are necessary to the design effort.

An attempt was made to develop statistics from the data in support of this hypothesis. However, the data is not consistent nor complete enough to support the premise. Future studies will need to be developed to specifically test for its validity.

The fourth hypothesis, that drawings require transformations dependent on the medium, is difficult to support. First, this data only utilized a single external medium, pen and paper, thus eliminating any discussion of the effect of implementation. Secondly, understanding how humans store and manipulate visual information is still not very well known. It seems clear that humans can perform visual image processing in either two or three dimensions [10]. However, studies are not yet conclusive in answering such questions as: Are all stored chunks of 3-D information stored as 3-D images, or are they stored as projections of images; if the images are 3-D, are they viewer-centered (objects described from the viewer's vantage point) or object-centered (description independent of viewpoint) [24]; and if images can be either 2-D or 3-D depending on the need, how is information transformed from one representation to the other?

One piece of evidence in determining the amount of transformation occurring is in the use of 2-D drawings versus 3-D drawings. In the protocol data it is clear that often the problem solving is satisfactory in two dimensions. At other times the subjects made 3-D sketches or orthographic draftings of the objects they were designing. The data was reviewed to find the use of these different representation styles. The results of this review are shown in Table 3 with the percentage of each representation in each phase in parentheses.

It is evident that in conceptual design most of the graphics are 2-D (59%), in the layout stage it is a mix of methods, and in the detail phase the representation has mostly been transformed to orthographic (78%). It seems evident that designers can readily transform between these representation methods. This suggests that one of the representations in memory is 3-D.

The fifth hypothesis, that drawings both utilize and determine cognitive units, will be addressed one part at a time. First, there is strong evidence to support the

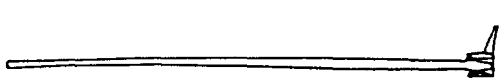

Fig. 7. Add example from subject S6.

Table 1. Classification of actions.

	Draw		Support			
	Sketch	Draft	Text	Dimension	Calculate	Total
Add	50	61	29	0	6	146 (40%)
Patch	14	0	0	0	1	15 (4%)
Refine	43	10	0	3	4	60 (17%)
Recall info	68	17	5	47	5	142 (39%)
Total	175 (48%)	88 (24%)	34 (9%)	50 (14%)	16 (5%)	363 (100%)

notion that drawings utilize cognitive chunks. Chase and Simon[15] assumed that the information between significant pauses was a representation of a single cognitive unit. Akin[16] followed this assumption, and it seems reasonable here because the subjects clearly performed an action as one continuous effort. It could be that processing is occurring parallel to representation and thus the external marks-on-paper are a sequence of chunks with the pauses occurring when there is nothing to represent. However, the literature does not support this view, and neither does our data. In a typical example, subject S6 is trying to mount a wire. He is about one hour into his design when he spends a one-minute period making the sketch shown in Fig. 9.

This is a study drawing, where the circled numbers are our notation for the separate actions. As he has previously drawn the isometric bar labeled "9" along with the block on top of it, these are recalled/sketched rapidly (10 seconds); there is then a short, one-second pause, and then the hole is added. The hole is a new feature and thus could not have been stored as part of the block. This sketch takes only one additional second and is labeled "10." Then the wire that has been sketched before with various bends is recalled after a three-second pause. This wire has been patched so many times in the design effort that precedes this example section that it is unclear whether he recalls or patches the wire here. Now, with the wire in the hole, he has accomplished the goal of mounting the wire except that there is a constraint on how close the wire must be to the end of the block. After a 38-second pause during which he simulates the position of the wire relative to the constraint, he adds line 12, patching the design to meet the constraint. It is evident that each drawing action represents a separate feature of the design, and it is reasonable to assume that these are also at least some of the cognitive chunks the designer is dealing with.

How the drawings determine these cognitive units is unknown. This issue is similar to the debate as to whether language patterns thought[25]. Do the tools with which the designer represents objects affect how they are stored? Our data gives no answers to this question.

6. CONCLUSIONS AND IMPLICATIONS FOR CAD DEVELOPMENT, EDUCATION, AND FUTURE RESEARCH

The evidence both from research in cognitive psychology and from the protocol studies of designers points to the importance of drawing in the design process beyond the documentation of final designs. Not only are drawings the preferred form of data representations for the designer, but they are a necessary part of the design process. Sketching as a form of drawing has been shown to have properties that make its use important in design. Additionally, the medium for external representation plays an active role in the amount of transformation needed to draw images from the STM and in the content of the cognitive chunks used. Finally, although with weak support, it has been shown that drawings are a window to the cognitive process used in problem solving by design engineers.

This study has also raised many questions and leaves much room for further research in this area. The very methodology used to determine the effectiveness of drawings in support of the cognitive process is in need of additional work. At a minimum, the recording of the drawings, both sketches and draftings, should be automated. Obviously, the more facile the representation medium the more it will be used and the more data recorded. Thus it is of interest to develop a method to allow rapid sketching and drawing to complement the cognitive process.

The observations concerning the use of drawings in the design process indicate areas for CAD tool devel-

Table 2. Types of marks made by each subject.

	S1	S2	S4	S5	S6	Total
Sketch, draft, or dimension	57 (78%)	61 (78%)	75 (90%)	52 (87%)	68 (97%)	313 (86%)
Text	13 (18%)	5 (7%)	7 (9%)	7 (13%)	2 (3%)	34 (9%)
Calculate	3 (4%)	12 (15%)	1 (1%)	0	0	16 (5%)
Total	73	78	83	59	70	363

Table 3. Design phase versus graphic representation style.

		2-D	Orthographic	Isometric	Total
Conceptual (All Sketch)		47 (59%)	29 (37%)	3 (4%)	79
Layout	Sketch	6	18	17	
		(49%)	(26%)	(25%)	69
	Draft	28	0	0	
Detail	Sketch	0	34	21	
		(3%)	(78%)	(19%)	115
	Draft	4	56	0	
Total		85	137	41	263

opment. Since drawings play such an active role in the design process, CAD tools need to be more than tools to record well thought-out and structured concepts. Specifically:

1. CAD systems must allow for sketching input. This is necessary for a number of reasons. First, it is a rapid representation method. Rubber banding and select methods traditional to CAD systems are simply not fast enough. Second, the additional cognitive load to implement current systems is detrimental to the design process. Icon and menu selecting add an unneeded step to creating an image. Third, in conceptual design in particular, it is not necessary that all graphical representations be as refined as that demanded by current CAD systems.
2. CAD systems must allow for a variety of interfaces for the designer. This does not mean more ways to define a circle, but an effort to match the interface to and the image on the CAD system to that needed by the designer. In other words, future CAD development needs to be driven from the "D" and not from the "C" in "CAD" where the "D" is for design. This will require focused cognitive studies of the use of new CAD systems. There are no studies in the literature known to the authors that indicate that CAD developers have studied the needs of the designers in any meaningful way.
3. CAD systems must recognize domain-dependent features and treat them as entities. On one level this has been done through grouping and macros. However, there is need for features at diverse levels of refinement and for the recognition of functional features. Only novice designers utilize simple primitives such as line and arc: experts remember and index features functionally. If CAD systems are to be truly design tools usable by expert designers, then the ability to operate at varying levels of refinement and functionality are a must. In fact, some of the variational systems introduced on the market since 1987 have some of the needed capability.
4. CAD tools need to be able to manage constraints (even abstract and functional constraints) and insure their satisfaction, as it is evident that human designers are cognitively limited in this ability. Constraints are both given at the beginning of a design (design requirements) and are derived as design decisions are made. Both types need to be recorded and used to insure that the design meets the given constraints and is complete in light of the design decisions.

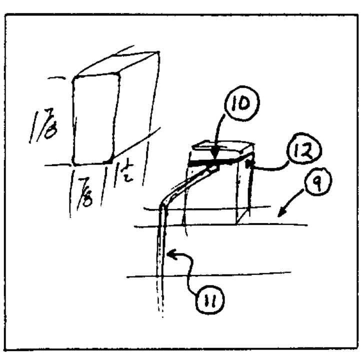

Fig. 9. Subject S6 trying to mount a wire.

In engineering education, these results point to the importance of being able to represent design concepts graphically. It appears that the very design process itself is limited by the ability to use graphics as a cognitive extension. This implies the need for training not only in the standard drafting skills, but additionally in the ability to represent concepts that are more abstract and best represented as sketches. Thus, the training of good designers is somewhat dependent on training in graphic skills including both formal drawing and informal sketching.

Acknowledgments—Support for the original protocol study that served as a basis for this study is from the National Science Foundation grant number DMC 85-14949, 1985–1987. Support for the pause analysis of the data is from a Schlumberger gift. The detail analysis of the data is supported by a Tektronix grant.

REFERENCES

1. T. E. French and C. J. Vierck, *Graphic Science*, McGraw-Hill, New York (1958).
2. W. J. Luzadder, *Fundamentals of Engineering Drawing for Design Product Development, and Numerical Control*, 7th edition, Prentice Hall, Englewood Cliffs, NJ (1977).
3. G. G. S. Voland, *Modern Engineering Graphics & Design*, West Publishing Co., St. Paul, MN (1987).
4. R. C. Fang, *2D Free Hand Recognition System*. Master's Report, Oregon State University, Corvallis, OR (April 1988).
5. D. G. Ullman and T. G. Dietterich, Toward expert CAD. *Computers in Mechanical Engineering* **6**(3), 56–70 (1987).
6. J. Larkin and H. Simon, Why a diagram is (sometimes) worth a thousand words. *Cognitive Science* **11**, 65–99 (1987).

7. D. Herbert, Study Drawings in Architectural Design: Applications for CAD Systems. *Proceedings of the* 1987 *Workshop of the Association for Computer-Aided Design in Architecture (ACADIA)* (1987).
8. D. G. Ullman, T. G. Dietterich, and L. A. Stauffer, A model of the mechanical design process based on empirical data. In *AIEDAM*, Clive Dym (Ed.), Academic Press, New York, 33-52, (1989).
9. A. Newell and H. A. Simon, *Human Problem Solving*, Prentice Hall, Englewood Cliffs, NJ (1972).
10. S. M. Kosslyn, *Ghosts in the Minds Machine*, W. W. Norton, New York (1983).
11. S. M. Kosslyn, J. Brunn, K. R. Cave, and R. W. Wallach, Individual differences in mental imagery ability: A computational analysis. In *Visual Cognition*, S. Pinker (Ed.), Bradford Book, MIT Press, 195-243 (1985).
12. S. M. Kosslyn, *Image and Mind*, Harvard University Press, Cambridge, MA (1980).
13. J. R. Anderson, *The Architecture of Cognition*, Harvard University Press, Cambridge, MA (1983).
14. R. N. Shepard, The mental image. *American Psychologist*, 125-137 (February 1978).
15. W. G. Chase and H. A. Simon, The mind's eye in chess. In *Visual Information Processing*, W. Chase (Ed.), Proceedings of the 8th Annual Carnegie Symposium on Cognition, Pittsburgh, 215-281 (1972).
16. O. Akin, *Psychology of Architectural Design*, Pion Ltd., London (1986).
17. S. K. Card, T. P. Moran, and A. Newell, *The Psychology of Human-Computer Interaction*, Lawrence Erlbaum Assoc., Hillsdale, NJ (1983).
18. M. B. Waldron and K. J. Waldron, Conceptual CAD tools for mechanical designers. *Proceedings of Computers in Engineering Conference*, Vol. II, V. A. Tipnis and E. M. Patton (Eds.), San Francisco, 203-209 (1988).
19. K. A. Ericsson and H. A. Simon, *Protocol Analysis; Verbal Reports as Data*, MIT Press, Cambridge, MA (1984).
20. L. A. Stauffer, *An Empirical Study on the Process of Mechanical Design*. Oregon State University Thesis, Corvallis, OR (September 1987).
21. J. Tikerpuu and D. G. Ullman, Data representations for mechanical design based on empirical data. *Proceedings of the* 1988 *International Computers in Engineering Conference*, V. A. Tipnis and E. M. Patton (Eds.), San Francisco, 245-254 (August 1988).
22. B. D. McGinnis and D. G. Ullman, *The Evolution of Commitments in the Design of a Component*. Submitted to the 1989 Harrogate ICED Conference (November 1988).
23. U. Warrier, *A SOAR-based Computational Model of Mechanical Design*. Master's Thesis, Oregon State University, Corvallis, OR (1988).
24. P. Jolicoeur and S. M. Kosslyn, Coordinate Systems in the Long-Term Memory Representation of Three-Dimensional Shapes. *Cognitive Psychology* **15**, 301-345 (1983).
25. R. E. Mayer, *Thinking, Problem Solving, Cognition*. W. H. Freeman and Company, New York (1983).