AN ANALYSIS OF A PEN-BASED TOOL FOR ACQUIRING ENGINEERING DESIGN INFORMATION

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ABSTRACT

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This thesis deals with the design and testing of a pen-based information acquisition tool called the *Electronic Engineering Notebook*. It is designed to help engineers capture, organize, structure, browse, and retrieve design information. It consists of pages which one can write and sketch on using a stylus. It contains a dynamic table of contents which automatically updates itself when pages are added, moved, or deleted. Information can be organized or structured through links within or across notebooks using *anchors and links* and *forms*. Information can also be browsed or searched using a variety of methods.

Three studies were conducted to evaluate and discover problems relating to the use of the EEN. The results of the studies indicate that paper was a better medium for writing, however, for reading and sketching, the EEN fared just as well. The results also indicate that people need a comparatively large surface for writing, reading, and sketching. The studies also indicate that EENs should have large colour display screens (approx. 9″x6″) with anti-glare etched writing surfaces, reasonable access rates, handwriting translation rates that are 97% or better [LaLomia 94], and availability of applications that support engineering activities.

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Chapter 1 Introduction

1.1 Problem Description

Complex engineering design projects, which involve hundreds of participants, are commonly faced with communication and coordination problems. In large design projects, the design task is often too complex for any individual or small group of individuals to effectively address all aspects of the design [Kitzmiller 89]. In situations such as these, the design would typically be decomposed into manageable components and then be divided amongst members of the engineering design team. Consequently, a problem arises in coordinating the activities of multiple participants, that is, how to manage each design task so that it integrates well with the results of others [Fox 92]. Coordinating design teams is difficult because design components are often highly integrated with each other. As a result, changes that are made to one part of the design will have trickle down effects on other parts. Unfortunately, changes occur frequently during the course of a project life and oftentimes, efforts are wasted and delays occur because design changes are not promptly communicated to those that are affected. The ability to effectively communicate design information can enhance coordination and design efficiency by reducing delays and improving decision making. For example, individuals who are responsible for designing a portion of an artifact will advance the state of their solution until they are hindered by the absence of information, at which point they will (1) wait for the desired information, (2) seek it out, or (3) make assumptions and continue on [Morse 90]. With effective communication, where information can be readily conveyed to design participants who need it, unnecessary delays can be avoided and quality decisions or assumptions can be reached. In general, the lack of coordination will typically lead to sub-optimal decisions and, in turn, will ultimately lead to high costs, low quality, and delays in completion [Fox 92].

In a recent study conducted by Crabtree et al. [Crabtree 93], project delays caused by poor coordination were examined. Twenty-five problem cases were studied and the results showed that over 50% of the cases were problems related to acquiring and accessing information. In the cases where there were problems in acquiring information (24% of the cases), the information was difficult to obtain because it was not available in any form except in the minds of individuals. In the cases where there were problems in accessing information (32% of the cases), the information was available in some form, either electronically (on a computer system) or physically (on paper), but was difficult to locate or access.

The second part of the study focused on what activities engineers spent their time on. The survey indicated that engineers spent about 13% of their time gathering information, 29% problem solving and thinking, 21.5% documenting work, 8% planning activities, 9% negotiating requirements, 18% supporting and consulting, and 2% doing other things such as downtime, administrative functions, travelling, and expediting. Consequently, activities involving coordination (all except problem solving, thinking and other things) accounted for approximately 69% of an engineer's time.

Acquiring and accessing information (comprising of information gathering and documentation activities 34.5%) were the biggest problems observed, occupying a significant portion of engineers' time. Two reasons why information was difficult to acquire and access from existing information systems was that (1) information lacked sufficient structure (therefore could not be easily browsed and retrieved) and (2) the information that engineers were most interested in was never captured in the system in the first place. Engineers were particularly interested in information that answered questions about the behaviour and purpose of design objects such as "What does this do?" and "Why is this here?", however this type of information was rarely recorded [Kuffner 90].

It has been speculated that redesign and design understanding would be significantly improved if the final design included more information about the history of the design process [Ullman 87] because designers are generally interested in information other than that which is contained in standard design documentation [Kuffner 90]. In current design practice, the main form of communication is through design drawings, plans, and specification sheets. These recording methods only capture the end results of the design process and therefore important design knowledge such as the rationale behind design decisions and assumptions never get recorded [Nagy 91]. This lack of documentation often leads to errors and delays in design projects because decisions are made based on inadequate information which may eventually affect decisions made downstream. Furthermore, because most new designs are not revolutionary but are designs built incrementally on past technologies [KAD][Meister 87], any information that is captured during the design process will not only provide valuable information to the current project, but will also provide valuable information to future related projects because engineers will draw on past design experiences and information when they design [Ballay 87][Balachandran 93][Meister 87].

A first step in improving information access is to make information more conveniently available to those who need it. For this to happen, (1) more information must be captured onto systems and (2) better methods for organizing, structuring, and retrieving this information must be provided so that others can gain access to it. Unfortunately, getting engineers to capture more information is not a simple task because they generally do not like generating documentation because it is time consuming and tedious. In a study conducted by Jakiela and Orlikowski [Jakiela 91], they found that designers generally disliked generating documentation and articulating design rationales. Designers quoted "I always hate documenting things after we have solved them. So at the stage that we were ready to detail or build, we had already solved the problem, and now we had to write it up... I think in pictures, not words. I hate words, so documenting the process was a pain..." [Jakiela 91].

Traditionally, most project design information was captured in individual engineering notebooks. Nowadays, engineers use computers to help them document information because they provide many benefits over pen and paper methods. For instance, moving, copying, and deleting texts and objects is considerably more efficient to do on a computer than on paper. Unfortunately, computers have also hindered the engineer's ability to capture information. Because it is not always easy to enter text and figures into computers, engineers tend not to use computers to document design information during the design process but will use them only when it is convenient to do so, which is usually after the design work has been completed. Quite often, what ends up being recorded is only information relating to the final design; information regarding intermediate steps that were taken to reach the final design or decision is not captured in the final documentation. Ironically, this is the information that engineers are most interested in. More intermediate information could be obtained if computers could be used to record information at the design stage. However, engineers do not always have computers with them when they design and make decisions because oftentimes they are in places where they do not have access to their computers such as in meeting rooms and on-site laboratories. Furthermore, even when engineers are working with computers they seldom use them to record design information. Many engineers find that writing on paper is more efficient than typing on computer, in which case, they will do initial design work on paper first and then enter it on a computer. Keyboard interfaces are particularly not well suited to engineers because when they design and generate documentation, they tend to generate a lot of figures, which is difficult to produce using a keyboard interface. According to a study performed by Ullman et al. (1990) on mechanical design engineers, approximately 85% of the material that they recorded was, in one form or another, graphics-related (drawings, sketches, dimensions), 5% were calculations, and 10% were text. Among the drawing-related activities, 67% were sketches [Ullman 90].

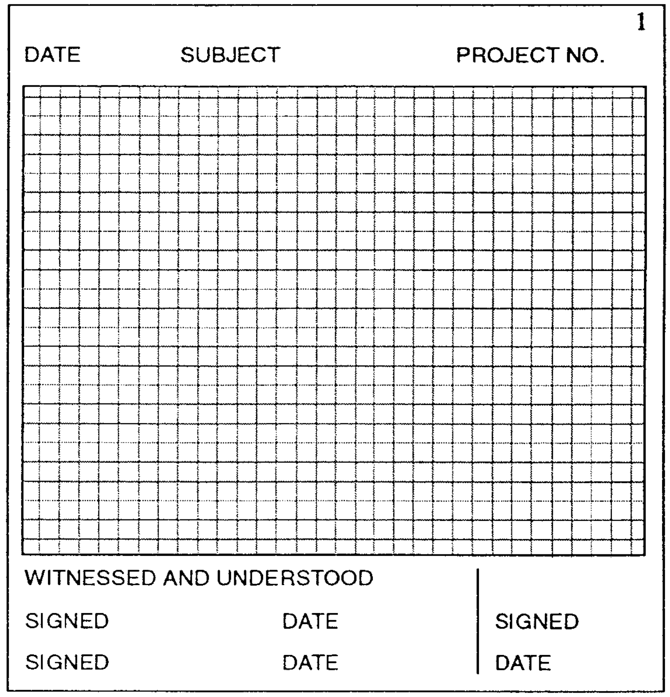
The role of sketching in the design process is often overlooked. "The term sketch or sketching is not a license to become sloppy or incomplete" [Edel 67]. In simple terms, sketching is merely a manual process of presenting spatial information and relationships for communicating ideas to others and provides designers with a means of exploring and analyzing situations, clearing up thoughts, and solidifying and refining ideas [Edel 67][Cross 85]. Designers normally do not know the exact details of what they are about to sketch until a part of the sketch is made [Ballay 87]. In addition, sketching facilitates visual thinking [Radcliffe 91], provides a visual simulation of ideas, serves as a completeness checker, and provides a kind of "external memory" [Ullman 87][Sinclair 94].

Paper is still the medium of choice when it comes to sketching even though it lacks any processing capability [Lakin 87]. Paper and pencil is still the quickest way to record ideas. During the conceptual stage, traditional computer tools (e.g. CAD) have actually hindered the creative design process [Uejio 91]. The average length of time it took to complete a sketch was approximately 8 seconds [Ullman 90], therefore tools such as CAD are not suitable because they do not provide designers with a quick and effective way to record their thoughts and ideas before they are forgotten. Also, comparisons of CAD tools for designing power supplies reveal that traditional paper methods are 3 to 10 times faster [Martin 90].

Sutherland states that it is only worthwhile to make a drawing on an electronic medium if you get something more than just the drawing [Lakin 87]. Many computer drawing tools allow users to visualize, analyze, and organize their drawings in ways that make the overall drawing experience easier and less tedious. These tools were expected to reduce the designer's manual work load and yield more time for creative activity. In many cases these tools did reduce the manual load but did not create more time for creative work [Tomiyama 91]. In fact, they actually hindered this activity because they did not provide the agility and quickness that was needed. For computer tools to be used effectively for drawing, Lakin suggests that the interface must be agile enough so that it does not interfere with one's thinking and quick enough to allow ideas to be written down [Lakin 89].

Traditionally, project design information was captured in individual engineering notebooks. Engineering notebooks provide a convenient medium for recording information during the design process. They are used for keeping notes of on-going activities, recording ideas and decisions, making calculations, drawing sketches, and establishing claims to ideas and concepts [Winfield 90]. The standard engineering notebook consists of a permanently bound notebook with numbered pages and space allocated for project numbers, titles, signatures, and dates of the originators and witnesses (see Figure 1). An ideal engineering notebook would contain a complete, comprehensible record of all the bits of information that was generated or processed by an engineer (e.g. assumptions, decisions, explanations, ideas, results, strategies, etc.). It would allow one to follow the progression of a design from start to end. However, notebooks are seldom maintained to this ideal level of completeness because designers can generate up to 1000 pages of conceptual design documents a year [Baya 91][Leifer 91] and managing this volume of information would be a difficult task. Maintaining documents of this magnitude would require considerable time and effort because it would involve such tedious tasks as indexing and cross-referencing.

Figure 1 A Standard Engineering Notebook Page



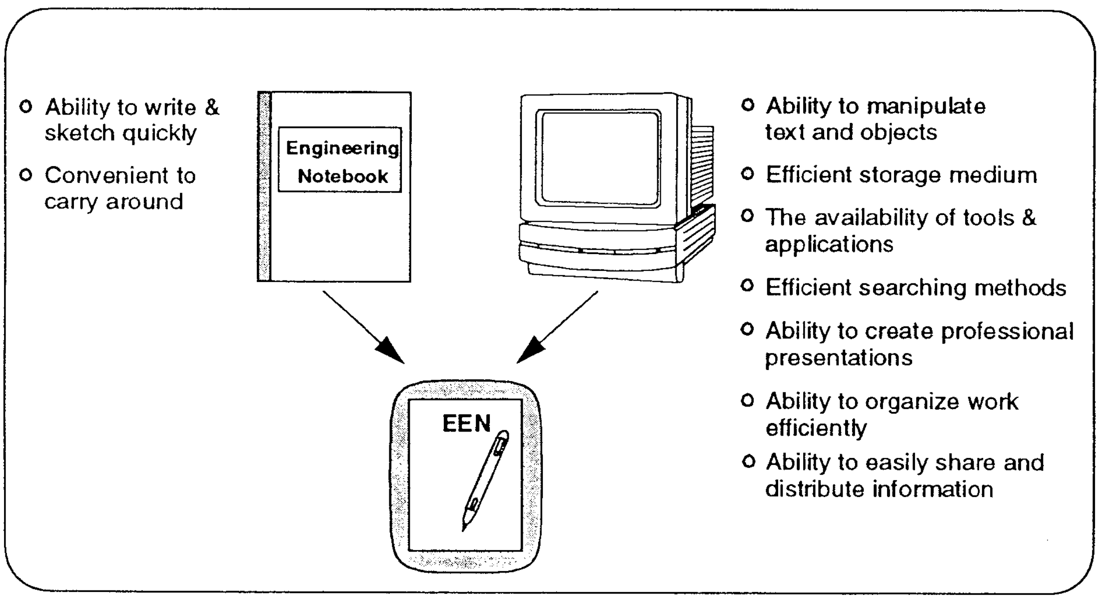
In an effort to improve the documentation process, computer-based notebooks (see section 2.2) have been explored[Fowler 94][Toye 93][Uejio 91][Lakin 89][Leifer 91]. These notebooks (which function like paper-based notebooks) are designed to help engineers record and share design information. They contribute valuable notions on how to organize, and retrieve information, but fail to address a more difficult problem, that is, how to get engineers to deposit design information into systems efficiently.

As part of the Design-in-the-Large (DITL) project at the University of Toronto, we have been constructing an information acquisition/design tool called, "The Electronic Engineering Notebook" (EEN). The EEN is designed to help engineers capture, organize, structure, browse, and retrieve design information (see Chapter 3). It permits engineers to enter information anywhere on a page and provides structuring capabilities that allows information to be retrieved and accessed. The EEN consists of pages which one can write and sketch on using a stylus. It contains a dynamic table of contents which automatically updates itself when pages are added, moved, or deleted. Unlike a bounded paper-based notebook, the EEN can display multiple pages at the same time. Multiple notebooks can also be created, if needed, and can be stored on a bookshelf. Information can be organized or structured through links within or across notebooks using *anchors* and *links* and *forms* (see section 3.2.2). Information can also be browsed or searched using the various methods provided (see section 3.2.3).

Our philosophy has been to first adapt technology to existing engineering practices, then motivate engineers to modify their practices to enhance quality and productivity [Fox 92]. One of the principal differences between our effort and the other notebook efforts mentioned above is that we address the importance of unintrusive acquisition of design information. The success of the EEN will depend not only on its functional capability, but also on its ability to help engineers acquire information unintrusively, because engineers will not use technology that hinders their ability to perform.

With the recent availability of mobile pen-based computing technology we have been able to explore the benefits of using this technology in designing a tool to help engineers capture design information. Pen-based systems that are portable are particularly well suited for capturing engineering design information. They eliminate some of the impediments that are imposed by existing systems, such as the inability to record information away from the desk (due to the lack of portability of most documentation systems) and the inability to write and draw quickly (due to keyboard constraints). Furthermore, pen-based devices provide a "pen and paper" interface that engineers prefer using and provide the processing capability that engineers need to organize and structure design information (see Figure 2).

Figure 2 An Integration of Notebook and Computer



Because pen-based computing technology is a relatively new technology that has not been used or tested in an engineering environment, much of our effort was spent testing the usability of this technology in an engineering environment.

1.2 Hypotheses

A first step in improving information access, and ultimately coordination, is to make information available to those who need it. For this to happen, more information must be captured onto systems and better methods for organizing and structuring this information must be provided to make it accessible to others. To achieve this, we need to provide tools that (1) can help engineers capture design information in ways that are as easy and convenient to use as pen and paper, and (2) can help engineers organize and structure information in useful ways. The EEN, as described in brief above (and in detail in Chapter 3), is designed to meet these objectives.

A major focus of this paper is to determine whether engineers can effectively use the EEN to capture design information. The basic skills involved in capturing information include writing, reading, and sketching, and these are the criteria we use to measure the EEN's effectiveness. We compare the engineer's ability in performing these tasks on an EEN to a sheet of paper (our benchmark). The following are our hypotheses:

Expectation: Engineers are able to capture information effectively on the EEN. To prove this we will attempt to falsify our null hypothesis

$H1_O$: Engineers can write on a sheet of paper more effectively (quickness and quality) than they can write on an EEN.

$H1_A$: Engineers can write on an EEN just as effectively (quickness and quality) as they can write on a sheet paper.

$H2_O$: Engineers can read from a sheet of paper just as effectively (quickness) as they read from an EEN.

$H2_A$: Engineers can read from an EEN just as effectively (quickness) as they read from a sheet of paper.

$H3_O$: Engineers can sketch on an EEN just as effectively (quickness and quality) as they can on a sheet of paper.

$H3_A$: Engineers can sketch on an EEN just as effectively (quickness and quality) as they can on a sheet of paper.

With a relatively wide selection of pen-based computing hardware available, EENs can be constructed in various sizes ranging from a screen dimension of 4x3 to 9x6 inches. Smaller EENs are desirable in that they are more convenient to carry around than larger ones, however, we expect that smaller EENs will not be practical for engineers to use and furthermore will hinder their ability to effectively capture and document information. The following are our expectations and hypotheses that we will test in our experiments.

Expectation: Screen size affects reading, writing, and sketching performance.

$H4_O$: Engineers are able to write quicker and more legibly on large screen EENs (9x6) than on small screen EENs (4x3).

$H4_A$: Engineers are able to write just as quick and legibly on large screen EENs (9x6) as on small screen EENs (4x3).

$H5_O$: Engineers are able to read quicker from large screen EENs (9x6) than from small screen EENs (4x3).

$H5_A$: Engineers are able to read just as quick from large screen EENs (9x6) as from small screen EENs (4x3).

$H6_O$: Engineers are able to sketch better quality drawings on large screen EENs (9x6) than on small screen EENs (4x3).

$H6_A$: Engineers are able to sketch just as well (with the same quality) on a large screen EENs (9x6) as on small screen EENs (4x3).

Chapter 2 Background and Related Work

2.1 Introduction

The Electronic Engineering Notebook is designed to help engineers capture, organize, structure, browse, and retrieve design information (see Chapter 3). It permits engineers to enter information anywhere on a page and provides structuring capabilities that allows information to be retrieved and accessed efficiently. There are other efforts such as those from the SHARE project at Stanford University, Baylor College of Medicine's Virtual Notebook System, General Electric's Electronic Design Notebook, and the Electronic Design Notebook developed, jointly, by the Center for Design Research at Stanford and NASA that overlap our effort. Our effort distinguishes itself from those mentioned above in a number of ways. Those notebooks primarily focus on providing users with functionality for organizing and retrieving information, while our effort focuses on helping engineers acquire design information unintrusively. Unlike the other notebooks, the EEN (1) is intended to provide engineers with the ability to capture design information quickly and efficiently and (2) provides capability for structuring this information which is not provided by the other notebooks except for the notebook from the SHARE project. These efforts as well as others are reviewed in the following sections.

2.2 Related Work

The SHARE Project

The SHARE project is a joint effort between the Center for Design Research at Stanford University and Enterprise Integration Technologies of Palo Alto, CA [Toye 93]. The goal of SHARE is to establish a "shared understanding" of a design by applying information technologies and promoting electronic information sharing in helping design teams gather, organize, and communicate design information. Macintosh PowerBooks equipped with commercial software such as FrameMaker (a document publishing application), Aldus Persuasion (a presentation tool), AEC Fastrack (a time-line management tool), Claris MacProject (a critical path management tool), Microsoft Excel (a spreadsheet tool), Ashlar Velum (a drafting tool), and Wolfram Research Mathematica (a modelling tool) are used to help capture and communicate design information. The PowerBook can be connected directly to a campus local-talk network or through a modem connection. A file server on the local area network provides backup and access to files. FrameMaker is used for generating notes and reports and building templates. Generic templates are provided to give documents a consistent format and structure. Templates are supplied with pre-defined tags and fields to help users organize their notes. The core tags and fields used are: title, requirement, decision, opportunity, priority, participant, question, idea, document reference, meeting date, rationale, issue, action item, contact, author, direction, assumption, and human contact reference. The layout of this template resembles that of a paper notebook; it has a left and right page. Information entered into the notebook can be organized chronologically or by category and is linked to a giant distributed web. Users can navigate through this web to search for specific information even though data may be stored in a different format [Toye 93].

PowerBooks were used instead of workstations in an attempt to give engineers more opportunity to use computers to capture design information in their daily activities. It was thought that engineers would be more willing to include computers in their daily activities if they were not tied to workstations. However, engineers remain restricted to using a keyboard/trackball interface, which is not an efficient interface for recording figures or mark-ups. This prototype notebook is in the process of being evaluated in a 9 month engineering design course at Stanford University and no results have yet been made available.

The Virtual Notebook System

The Virtual Notebook System was developed by the Baylor College of Medicine [Fowler 94][Burger 91]. The goal of the VNS was to enhance information sharing in the collaborative work of scientific groups. It supports group work and the dynamic collection of information. The VNS user interface was designed after a laboratory researcher's notebook. The screen layout resembles a page from a typical notebook. The VNS provides the direct manipulation of objects such as text, images, video, and audio. It operates from a workstation in the X-window environment. Object tagging, browsing, direct searching, and linking are some tools provided by the VNS to encourage information acquisition and organization. Two different links are available with the VNS (page links and action links). A page link is used to reference a page from the same notebook or from a different notebook. An action link provides a visual association between a page and an external program. The VNS also provides groupware features like permitting multiple users to simultaneously create and modify information on a shared page.

The VNS is a working system and is actively being deployed at the Baylor College of Medicine and also has been licensed by the Athena Project at MIT [Burger 91]. The VNS is now available commercially by The ForeFront Group, Inc. The VNS allows information to be organized through links, however it does not provide any capability for structuring information. With the EEN, information can be structured using forms or templates. Also, a version that will provide pen-based user interface support is being developed [Fowler 94].

GE's Electronic Design Notebook

The Electronic Design Notebook was developed by General Electric Corporate Research and Development as part of the DARPA Initiative in Concurrent Engineering (DICE) project [Uejio 91]. The goal of EDN was to allow team members to view the status and history of a project. The EDN acts as a project notebook where information such as decisions, alternatives, and results can be recorded. The EDN operates from a desktop computer and uses FrameMaker as its primary interface application. The organization of information in the EDN is based on a calendar approach (see Figure 4). A calendar is displayed and notes are attached to specific dates. Notes can also be linked to keywords, other documents, or applications. To allow users to find their notes easier and faster, indexes are provided for navigating through information in the EDN.

Similar to the VNS, it allows information to be organized through links, but does not provide any method for formally structuring information. Because it is operated from a workstation its use is limited, especially, to engineers who are always on-the-move [Uejio 91].

CDR's & NASA's Electronic Design Notebook

The Electronic Design Notebook (EDN) is a joint effort between the Center for Design Research at Stanford University and the NASA Ames Research Center [Lakin 89]. The goal of the EDN is to provide a tool to support conceptual design with the agility of a paper notebook and the process-

Figure 3 VNS Interface

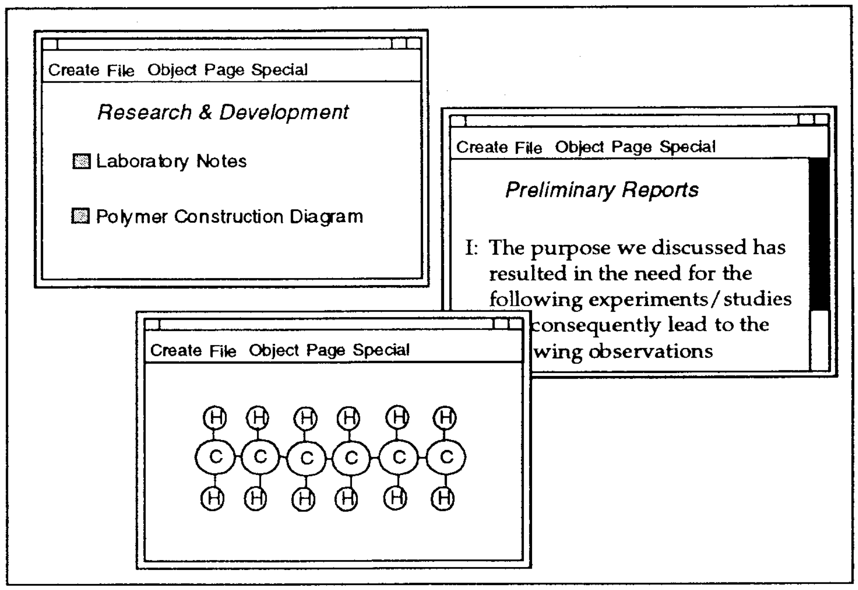
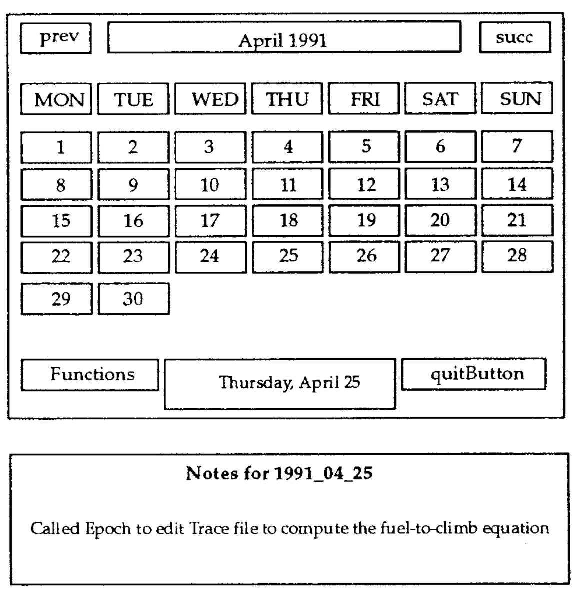


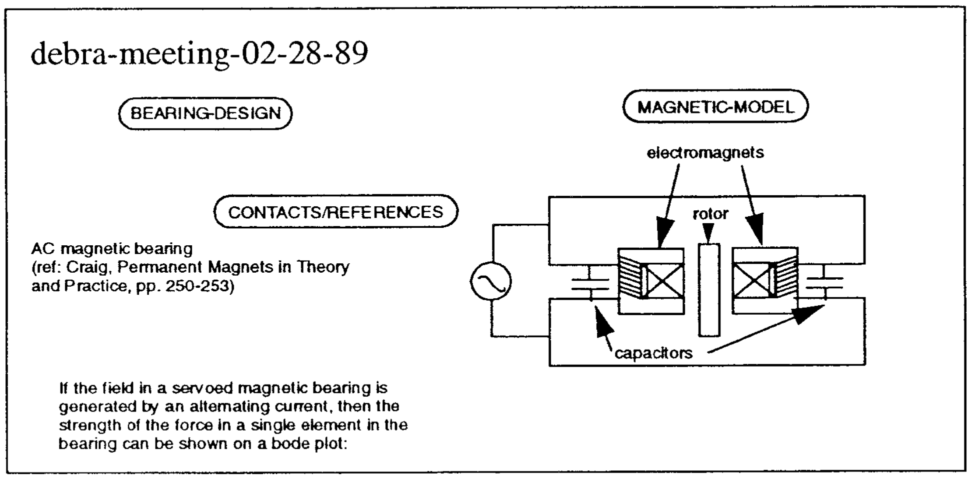
Figure 4 EDN Interface



ing power of a computer. The EDN uses the vmacs system which is an editor that allows text and schematic drawings to be intermixed. It uses a keyboard interface which provides the user with the freedom to input text and graphics much easier and quicker than a menu-based system. Tags displayed in ovoid boxes are used to link objects to design requirements (see Figure 5). A major feature of the EDN is its ability to allow a user to query the system for specific information and in return get an automatically generated map of notebook pages that correspond to the query [Baudin 91][Baya 91][Lakin 89][Leifer 91][Sivard 89].

A significant difference between our effort and EDN's is that we emphasize the importance of helping engineers capture information, unintrusively. EDN's approach has been to compromise ease-of-use for agility in hope that the system provides an overall benefit to the user. As quoted in [Lakin 89], "... (EDN) is not user friendly, it is agility friendly (i.e. easy to use once mastered but is difficult to learn initially)...".

Figure 5 A Typical EDN Page



2.3 Other Related Work

Lastly, there are a few other efforts related to our work such as the SuperBook, gIBIS, SIBYL, and the Design History Tool which are briefly described below. These are not considered design notebooks but have notebook or design knowledge capturing capabilities.

SuperBook is a hypertext-like system designed for accessing documents that already exist [Egan 89]. It takes existing text and automatically converts it into a multi-windowed browser. Once the text has been converted, a user can then use the browser's elaborate search and navigation capability which includes a dynamic table of contents and a history of search words. The SuperBook is a good example of a text browsing tool that can help a user locate information efficiently, however it does not provide capability for creating, modifying, and connecting new information. [Egan 89][Remde 87].

gIBIS [Nagy 91], SIBYL [Lee 90], and the Design History Tool [Chen 90] are considered in the class of design rationale tools. gIBIS (graphical Issue Based Information System) is a tool based on the IBIS model, developed by Horst Rittel, which consists of a relational database and hypertext system. It was designed to capture the design history of a project and to support computer mediated teamwork. It allows multiple users to post *issues*, *positions*, and *arguments* to specific problems. Issues are defined as identified problems, positions are proposed solutions, and arguments support or oppose a position [Nagy 91]. SIBYL is a tool for managing group decision rationale. It is used to describe the knowledge that is gathered in a decision making process. It focuses on capturing *goals*, *alternatives*, and *arguments* [Lee 90]. The Design History Tool is implemented in HyperClass, an object-oriented programming environment, and Vantage, a solid modelling package. It was designed to help capture the decision making process during the design process. It focuses on capturing *decisions*, *constraints*, and *alternatives* during the evolution of a design [Chen 90].

These tools are strictly designed to capture the decision making part of the design process and do not provide any design capability such as the ability to make calculations and draw sketches. They do, however, provide valuable concepts for preserving design knowledge.

2.4 Studies on Pen-based computing

> "Companies have delivered experiments to the market; they rushed to put something out. Now they are correcting their mistakes" - [Waurzyniak 94]

This statement, describing the pen-based computing industry, is a very accurate assessment of the problems faced in this industry. Over the past several years, numerous pen-based products have emerged onto the market. Many of these products have suffered dramatic setbacks because they were "rushed" out too soon. It is difficult to estimate how much testing was performed on these products before they were introduced onto the market, but, judging by the amount of literature that is readily available relating to studies involving pen-based computing, it seems very little testing was done.

The literature, that is available, primarily focuses on studies relating to handwriting recognizers and alternative inputting methods for pen-based computing. Handwritten input has not been a very dependable method for entering information because of poor recognition performance which is why efforts have been shifted towards finding alternative methods of inputting information into portable computers.

Studies have been performed to compare various handwriting recognizers [Chang 94] and to determine the acceptable level of recognition rate by users. A recognition rate of 97% or higher was found to be acceptable by users. Most participants rated the range of 90% to 95% accuracy as "very poor" [LaLomia 94]. There have also been studies evaluating the effect of delaying the display of recognition until needed [Nakagawa 91]. Because errors in recognition distract users, delaying the display improves the situation by eliminating interruptions to the train of thought.

Comparison studies have been performed to determine the effectiveness of handwritten input compared to alternative input methods. They have focused on such devices as soft keyboards, keypads, pie pads, etc. [Brown 88][McQueen 94][Mahach 89][Gelderen 93] and alternative methods of writing such as *Unistrokes* [Goldberg 93]. *Unistrokes* are specially designed alphabets that are aimed at speeding up writing, reducing recognition error, and allowing "eyes-free" entry of information similar to touch typing on keyboards. For example, letters "e", "a", "t", "i", "r" are all straight lines, and hence are fast to write. The obvious disadvantage is that these special alphabets must be learned. Several studies have compared hand printing to keyboard tapping on pen-based computers [MacKenzie 94][McQueen 94][Mahach 89][Brown 88]. These studies showed that using a soft QWERTY keyboards was faster (QWERTY: 22 wpm; printing: 16.3 wpm) and more accurate (QWERT: 98.9%; printing 91.9%) than hand printing, for character data entry [MacKenzie 94]. Another study, which was similar, found that the use of a "virtual keyboard" was 25% faster than handwriting for text correction [Gelderen 93]. There have also been studies that compare gestural commands (commands issued with a pen) versus keyboard commands [Wolf 88]. They found that users performed operations approximately 30% faster while using a gestural interface as oppose to a keyboard interface.

In other related literature, studies have been performed to compare the performance of reading and writing on computers (with keyboards) to paper [Gould 87][Hansen 88]. The results of these studies have determined that reading from paper was faster than reading from computer screens. It took approximately 25% longer to read from a screen than from paper [Muter 82]. Results for writing tasks (typing) were not as conclusive but studies have shown that for expert writers using computers required 50% more time than on paper [Gould 81]. Factors that were found to influence reading and writing performance included page size, legibility, responsiveness [Hansen 88], and CRT technology [Gould 87]. Since the time these studies were done, technology has changed significantly, therefore we could expect the performance difference, now, between reading and writing on paper versus computers will be much less.

2.5 Conclusion

The notebook efforts from Stanford University, Baylor College of Medicine, General Electric, and the Center for Design Research at Stanford and NASA in many ways are similar to and different from our effort.

Similarities

The concept of operation of these notebooks are similar. They permit users to (1) enter information freely and informally, (2) organize information using hypertext capability, and (3) access stored information through browsing and parametric searches.

The look and feel of these notebooks were also similar. "Notebook" metaphors have been adopted by many of these notebooks with exception to GE's EDN which adopted a calendar metaphor. Metaphors reflect familiar objects and structures in our environment and provide consistency, familiarity, and predictability [Parsaye 93a]. The notebook metaphor, which is composed of pages to which one can write on and turn to, provides an interface which engineers can easily relate to.

Differences

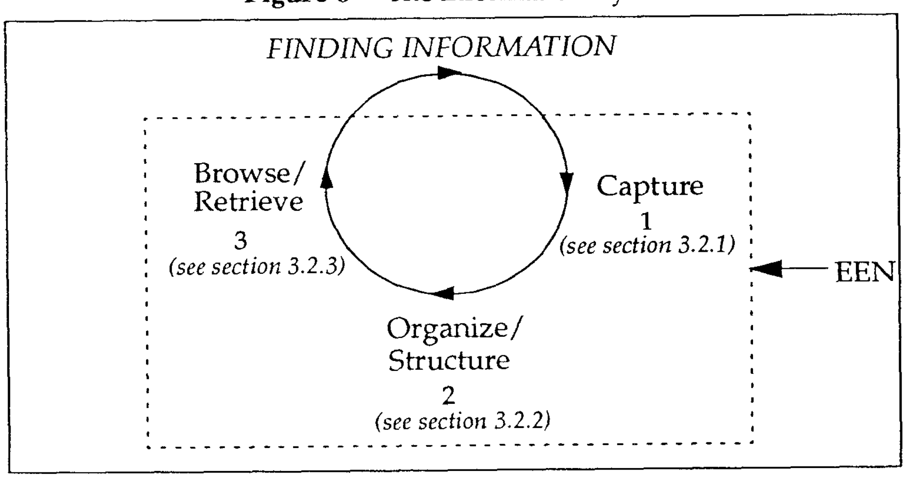
Our effort distinguishes itself from those mentioned above in a number of ways. Those notebooks primarily focus on providing users with functionality for organizing and retrieving information, while our effort focuses on helping engineers acquire design information unintrusively. Unlike the other notebooks, the EEN (1) provides engineers with the ability to capture design information quickly and efficiently (using a pen) and (2) provides capability for structuring this information which is not provided by the other notebooks except for the notebook from the SHARE project.

Chapter 3 Electronic Engineering Notebook Architecture & Functionality

3.1 Introduction

As part of the Design-in-the-Large (DITL) project at the University of Toronto, we have been constructing an Electronic Engineering Notebook designed at helping engineers capture, organize, structure, browse, and retrieve design information. As mentioned earlier, a major problem contributing to poor coordination was due to the inability to find information in existing systems. In many cases, the information was available but was too difficult to access and in other cases, the information was not available because it had never been recorded in the system in the first place. If we are to improve an engineer's ability to find information (see Figure 6) we need to (1) provide them with easy-to-use tools that will encourage them to capture more design information (see section 3.2.1), (2) provide them with the capability to organize and structure this information in ways that make it accessible (see section 3.2.2), and (3) provide them with the capability to browse and retrieve this information efficiently (see section 3.2.3).

Figure 6 The Information Cycle



3.2 Goals and General Requirements

3.2.1 Information Capturing

An important goal of the EEN is to provide engineers with a means for capturing design information efficiently. If more information is to be captured, incentive must be provided to engineers to include EENs in every part of their daily activities. The EEN provides several features, all packaged in a notebook-size computer, that will encourage engineers to use it in their work. It has an easy-to-use user-interface that is based on familiar pen and paper concepts that functions similarly to an engineering notebook, an input device that is a stylus which provides quickness in entering information, and applications such as spreadsheets, databases, and calendars which will allow them to perform various tasks on the EEN.

The infrastructure of the EEN is provided by the PenPoint™ operating system. PenPoint™ provides an easy-to-use interface that is based on familiar pen and paper concepts. The layout of the notebook includes a table of contents, tabs for marking sections, and a page flipper for turning pages. The table of contents automatically updates itself when pages are added or deleted. It functions as a starting point for navigating to different parts of the notebook. PenPoint™ also supports handwritten input as well as keyboard input. Handwritten input can be entered virtually anywhere on the screen using a stylus and can be translated to printed text, at anytime, if desired. The accuracy of translation from handwriting to text is roughly 96 - 98% with training [Forman 94]. Handwritten input can be emphasized by bolding, italicizing, underlining and highlighting. Words stored in both ink and text format can be searched and spell-checked. Shortcuts in the form of gestural commands can be used to move, copy, or delete text. For example, to cross out a word, a gestural command drawn in the form of an 'X' will erase it.

Sketches are also supported by the electronic notebook and can be drawn anywhere on the screen. Various styles of drawing "paper" can be selected, if desired, such as blank, line, and grid. Pen tips can be adjusted to suit the various sizes and colour (grey scale) necessary for drawing. Objects that are drawn can be copied, moved, deleted, aligned, resized, rotated, grouped, or layered using gestural commands or by menu selection, and can also be shaded or filled with various patterns. Lines or curves with rough edges can be automatically straightened or rounded if needed.

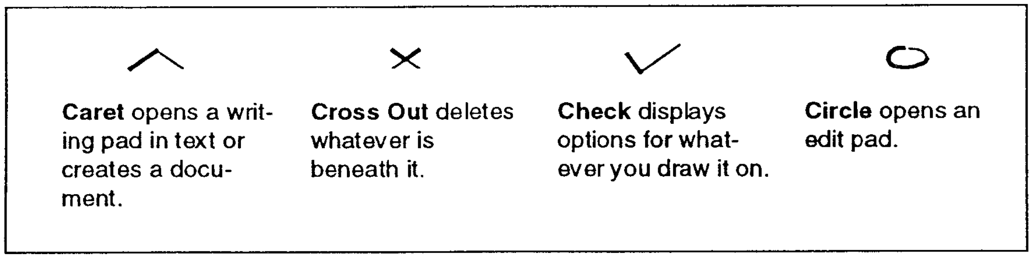
In addition, the notebook supports the input of scanned images (in TIFF format) and voice annotations. The capability to use voice annotations is supported by PenPoint™, however additional hardware is required. Notebooks can be created for individual projects and opened and viewed at the same time. This allows engineers to "carry" several notebooks with them at the same time.

Familiar applications such as a calendar, schedular, to-do-list, wordprocessor, spreadsheet, and database are integrated into the EEN. The following commercial software applications are integrated in the EEN and are described in more detail below: **PenApps™** - a form designer with a built-in database; **Perspective™** - a calendar, scheduler, to-do-list, address book; **Aha! InkWriter™** - a word-processing and sketching application; **Numero™** - a spreadsheet application; **PenASCII™** - a connectivity program. These applications are an integral part of the EEN because they support engineering design. If we are to encourage engineers to capture more information on the EEN we need to provide them with tools that are useful.

The PenPoint™ Operating System

The PenPoint™ operating system is an object-oriented, multitasking operating system that was solely designed for pen-based computing. The operating system supports handwritten input and gestural commands. Gestural commands are shapes or figures that the user draws on the screen to invoke an action or command. Over 30 different gestural commands are provided (see Figure 7). The primary input device is a pen and it is used for pointing, inputting data, and invoking commands.

Figure 7 Example of Basic Gestures



PenPoint uses a notebook metaphor to organize its information. Features of the interface include a table of contents for viewing and navigating to all the available documents, section dividers for organizing documents into subsections, page numbering and section tabs for direct random access, and a page turner for accessing information sequentially. In addition, a bookshelf is available for storing multiple notebooks.

PenPoint's system architecture consists of five layers: (1) kernel, (2) system, (3) component, (4) application framework, and (5) applications. The kernel layer provides multitasking support, memory management, and access to hardware. The system layer provides windowing, graphics, and user interface support as well as common operating system services like filing and networking. The component layer provides general-purpose code that can be reused as building blocks for other applications. The application framework layer defines the structure and behaviour of PenPoint applications. It takes care of installation and configuration, creation of new documents, spell-checking, search and replace, and printing.

PenApps™

PenApps™ is an application builder, developed by Slate Corporation, that is designed for mobile pen-based applications. It consists of an interactive form designer, the Slate PenBasic™ programming language, and a database engine. The database engine consists of a version of C-Tree from Faircom. It can store various types of data such as bit mapped images and can export and import data from popular file types such as .dbf, .wks, .db, and ASCII. The PenApps form designer tool is shown in Figure 8.

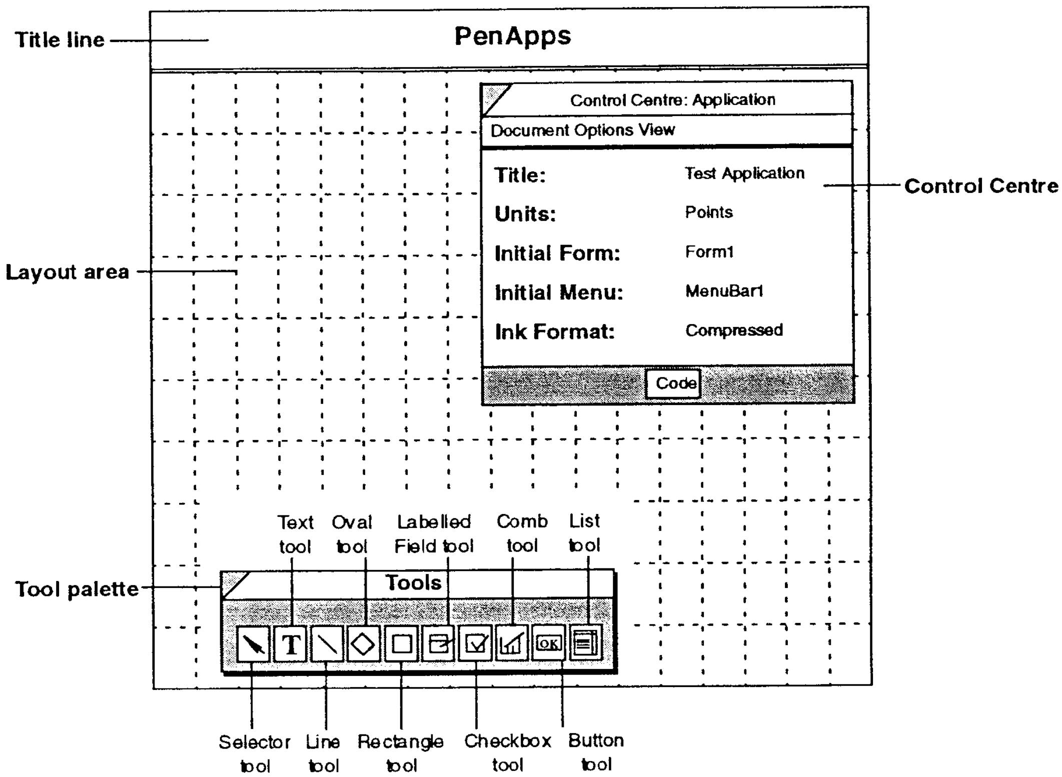
Perspective™

Perspective™ is a personal information manager, developed by Pensoft Corporation, that combines the functions of a calendar, address book, to-do-list, and notetaker. Figure 9 displays a sample page of the Day Planner.

InkWriter™

InkWriter™, developed by aha!™ Software Corporation, is an application that provides the power of a wordprocessor and a drawing application. InkWriter™ provides a user with the abil-

Figure 8 PenApps™



ity to: write, draw, and mark up text and objects anywhere on a page; translate handwriting during the time of input or at a later time; use gestures to move, copy or delete words; spell-check and search for words in text and handwritten form; bold, underline, italicize, and highlight selected words; draw rough sketches anywhere and have them converted to polished drawings; select, copy, move, delete, align, resize, rotate, group, or layer objects; customize ink properties such as thickness and grey scale; fill objects with various patterns, and select a style of paper (blank, line, grid). Figure 10 displays a sample interface of InkWriter.

Numer*o*!™

Numer*o*!™, developed by PenMagic!™ is an application that allows one to create customized spreadsheets and graphs. Line, pie chart, area, bar, stacked bar, and 3D graphs can be created and automatically updated when a change is made on the spreadsheet. It is compatible with other popular file types such as .wk1, .wks, .xls, .csv, and .txt. Samples of spreadsheets and PageMap are shown in Figure 11.

Figure 9 Perspective™

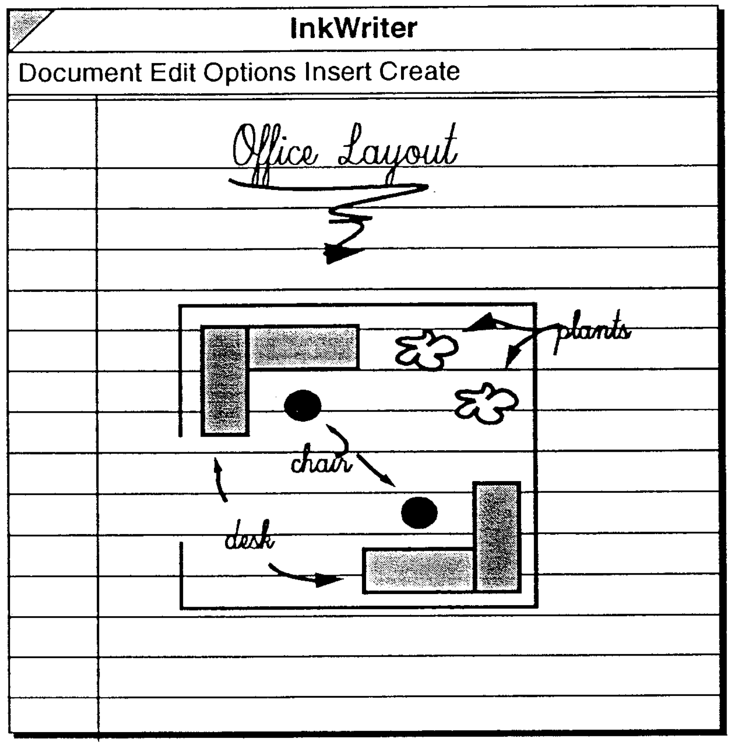
PenASCII™

PenASCII™, developed by Compsoft Services Inc., is a communications application for accessing application and data from systems such as HP, SUN, IBM, DEC and others that support ASCII terminals and industry standard file transfer protocols. PenASCII™ can emulate an IBM 3101, DECVT 100, or DEC VT220 terminal. It supports XMODEM, YMODEM, and ZMODEM file transfer protocol. PenASCII™ provides communication capability for transferring data from the EEN to the IKB (Integrating Knowledge Base, a central repository of knowledge and data).

Hardware

EEN applications are designed on a desktop computer (DECpc LPv 466d2) and are tested on a Toshiba DynaPad™ - T100X. The DECpc LPv 466d2 is equipped with an Intel i486 DX2 processor running at 66 MHz. The display is a 640 x 480 resolution VGA and measures 14 inches diagonally. A Wacom SD-510C Digitizer Tablet substitutes as a pen-tablet interface for the desktop computer. The DynaPad™'s processor is a AM386™SXLV/25 and has 8MB of RAM. The display is a 640x480 high resolution VGA, Trans Reflective sidelit LCD measuring 9.5 inches diagonally.The dimensions are 11.0 inches by 1.5 inches by x 8.3 inches and weighs approximately 3.3 pounds (see Figure 12).

Figure 10 InkWriter™



Integration of Applications

Applications such as a wordprocessor, sketching tool, spreadsheet, database, calendar, scheduler, to-do-list, and address book are integrated in the EEN. The standard page on the EEN provides wordprocessing and sketching capability. On this page, engineers can write and draw anywhere and perform various functions such as translate handwritten content to text, perform spell-checks, move objects, etc. Any application can be embedded on this page providing a "seamless" appearance as illustrated in Figure 13. For instance, a spreadsheet, a to-do-list, and a form can all reside on the same page. These applications can either be displayed in full (a window) or minimized (an icon) on a page. Unfortunately, as more applications are embedded on a particular page the time it takes to access that page becomes longer because each application must be opened before the page can be viewed.

Working from one application to another is simple because applications share a similar look and feel throughout. In most cases, the same gestural command can be used in any application, however, we noticed that some commands responded differently in certain applications. For instance, we noticed that a gestural command in the form of a flick left and right (two lines drawn horizontally parallel to one another with the top line drawn from left to right and the bottom line drawn right to left) would toggle between ink and gesture mode on one application (e.g. PenApps) and would align objects horizontally on another (e.g. InkWriter). These inconsistencies caused confusion at times, however, they were not that common.

Figure 11 Numero!™

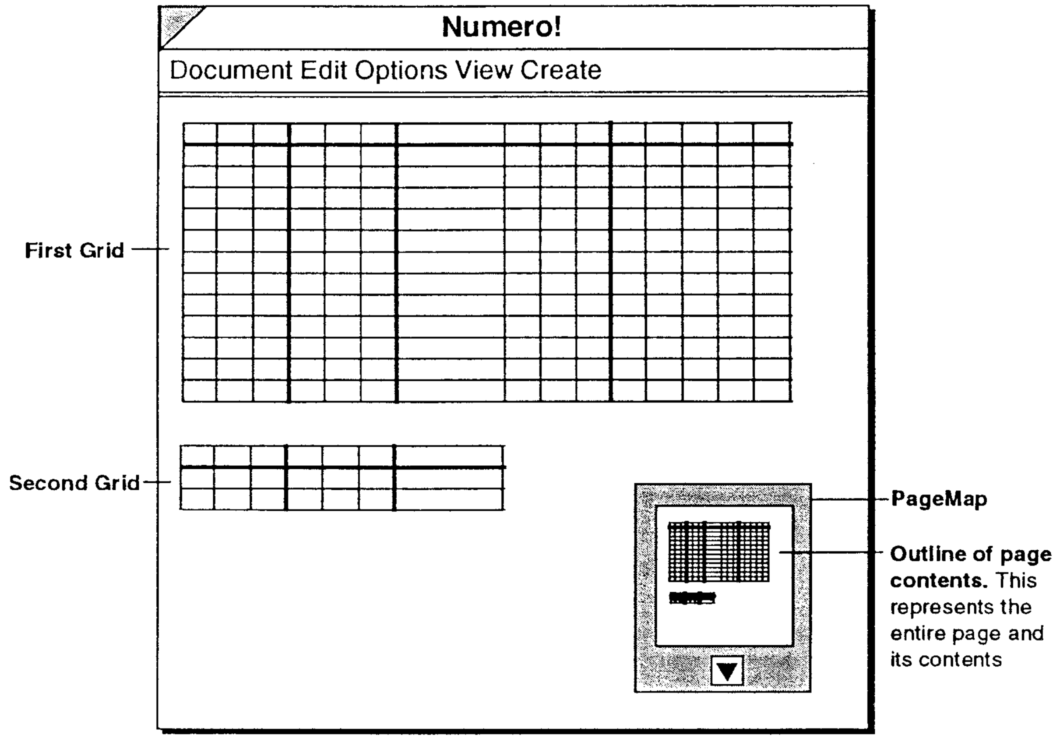
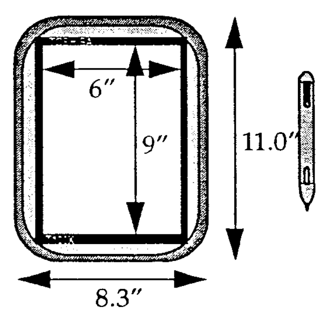
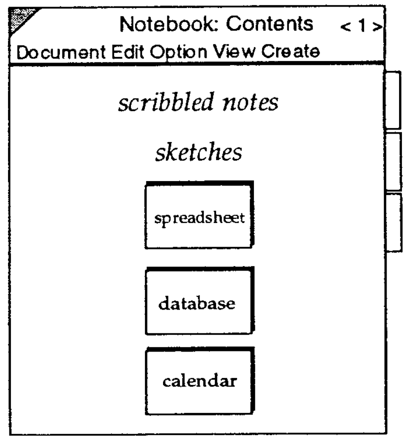


Figure 12 The Toshiba DynaPad™ - T100X



Although applications appeared to be integrated "seamlessly", some functionality could not be integrated completely. For example, in Perspective™ (the application that includes a calendar, scheduler, to-do-list, and address book) certain phrases such as "meet John" or "call Jane" are recognized and inserted automatically into applications like the to-do-list and calendar. Perspective recognizes keywords such as meet and call and places these entries in the appropriate applications. Unfortunately, keywords such as these can only be recognized from pages that have Perspective ™ applications running on them. For instance, a phrase such as "meet John" written on InkWriter™ cannot be recognized by Perspective™ because Perspective cannot recognize infor-

Figure 13 Embedded Applications



mation that is stored in another application. To integrate this functionality the source code of Ink-Writer™ and Perspective™ would be needed, unfortunately, they could not be obtained.

In addition to integrating off-the-shelf applications, we also provided customized features that help organize the various information that is recorded in notebooks such as *anchor and link* and *forms* that are described in the following section.

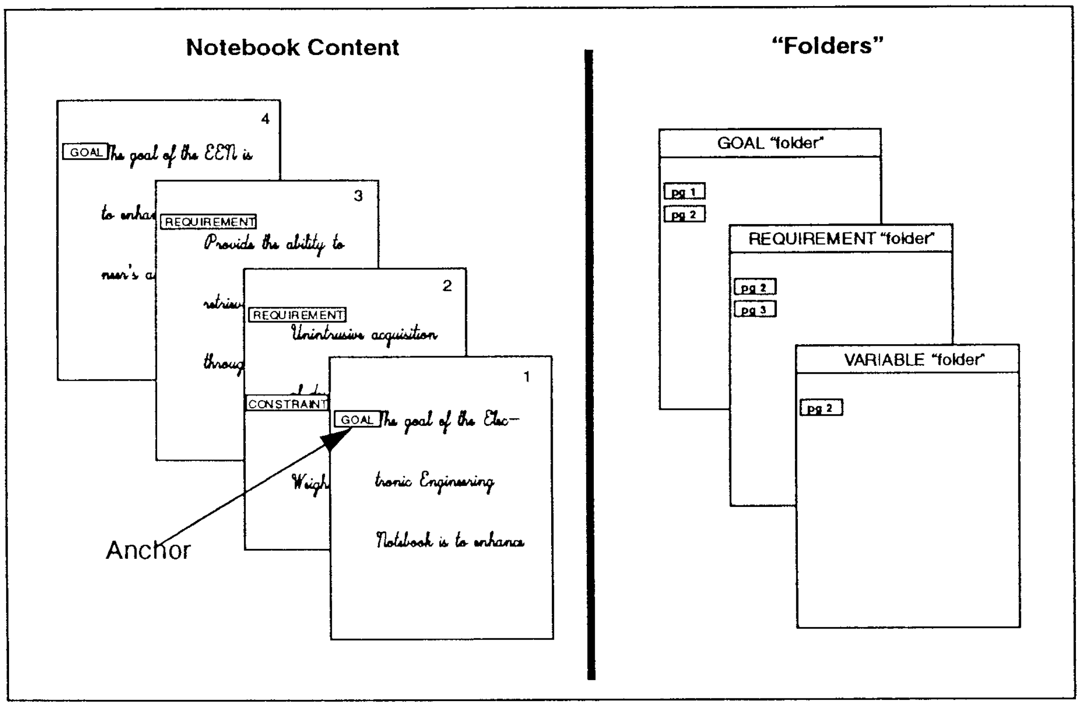
3.2.2 Information Organizing and Structuring

Information must be properly organized or structured on the EEN before it can be efficiently accessed by others. Simple and efficient methods for organizing information must be provided in order to encourage engineers to organize information in their EENs. The EEN provides several methods for organizing and structuring information. The simplest approach involves rearranging content using cut and paste methods. This approach which is similar to putting together a scrap-book is generally the most tedious and least efficient method of organizing information because the same information often ends up appearing in many places. A second approach involves using the linking and anchoring feature provided by the EEN (described in more detail below). This approach allows chunks of information to be identified and linked together. These links also provide paths that can be used to browse the notebook. A third approach is to enter information into pre-designed forms or templates. Forms provide an efficient means for capturing design information because information can easily be extracted from them.

Linking and Anchoring

The EEN provides a linking and anchoring feature that allows scattered chunks of information to be identified and linked with each other. *Linking* and *anchoring* is similar to a process known as "authoring" which involves partitioning selected content into self-contained chunks or nodes and linking these nodes with each other [Parsaye 93b]. Anchors are created by tagging or marking selected information with one of several labels provided such as goal, requirement, or constraint. The process of linking and anchoring involves "grabbing" a keyword from a pop-up menu list and then "dropping" it on the appropriate content. An analogy to linking and anchoring is rubber stamping; the process of rubber stamping involves "grabbing" a rubber stamp from a tray and then using it to "stamp" a document. Anchoring and linking also leaves an imprint on a page as does rubber stamping which appears as a keyword surrounded by a rectangular border (see Figure 18). This imprint provides a link to a folder that retains the location of related items in one place. Examples of anchors are: *GOAL, REQUIREMENT, ALTERNATIVE, VARIABLE,* and *CONSTRAINT* and a folder exists for each type of anchor. Figure 18 (left-hand side) shows several pages with anchors stamped alongside content. To its right are folders corresponding to these anchors. The folders contain a list of page numbers indicating where anchors are placed. For example, to find the location of all goal statements in the notebook, one need only open the GOAL folder and observe which pages they are in. A single tap of the page number icon brings the user to that page (i.e. current page is replaced with new page) whereas a double tap of the icon brings that page to the user (i.e page floats on top of current page).

Figure 14 Anchoring and Linking

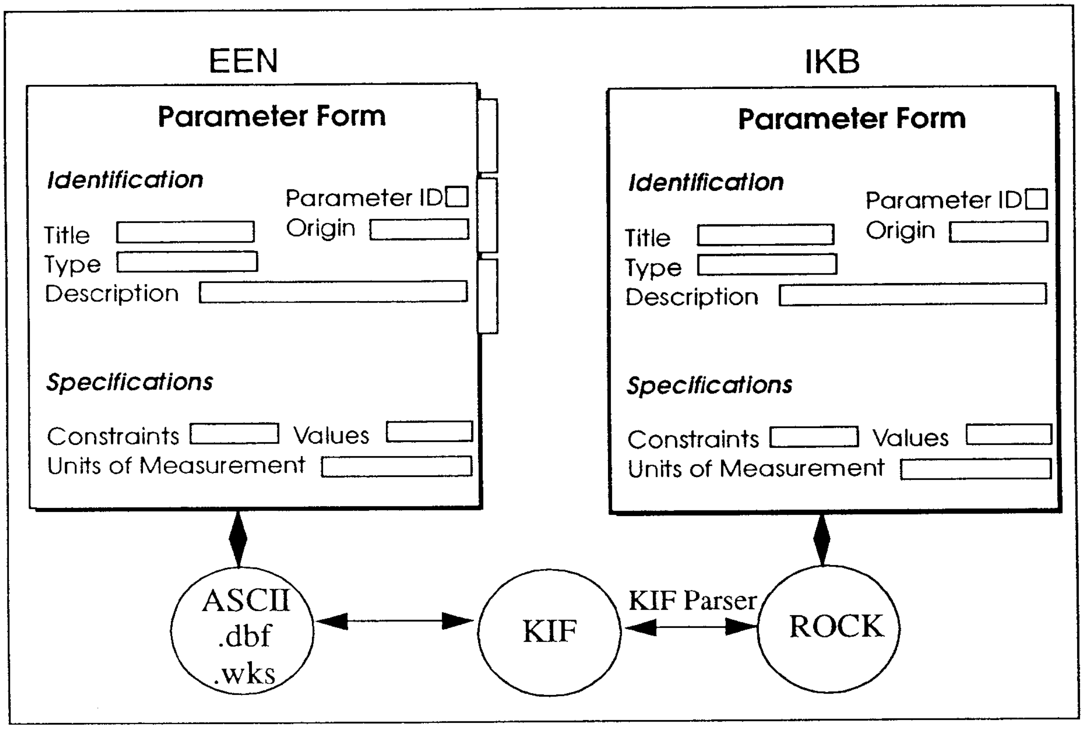


Users are able to customize anchor, however, several standard types are provided for some consistency. These were carefully selected after examining over 25 engineering notebooks and reviewing literature on studies involving documenting design information (see Anchoring and Linking Labels).

Form Filling

The EEN provides forms for capturing and structuring information because they provide an efficient method for capturing formal design information.The benefit of using forms is that information can easily be extracted from them automatically. The disadvantage is that they restrict users from entering additional pertinent information that may be useful. Generic forms with underlying databases are created using the PenApps™ Application Builder. Figure 15 (left-hand side) illustrates a form created for gathering information about a specific parameter. A similar form (i.e. same slot names) is also available on the IKB (Integrating Knowledge Base: a central repository of knowledge and data). Forms on the EEN are designed to be identical to those on the IKB so that data can be smoothly exchanged between the EEN and IKB (see Figure 15).

Figure 15 Flow of Data between the EEN and IKB



The Integrating Knowledge Base is composed of two parts: (1) a *data model* that links knowledge from various parts of an organization and (2) a *deductive reasoning* capability that aids in the search for relevant knowledge [Fox 94].

Anchoring and Linking Labels

A study was conducted in attempt to learn what types of information was being recorded in engineering notebooks. Approximately 30 engineering notebooks and engineering worksheets were sampled from a medium size aerospace company. Engineering notebooks were randomly selected from the storage facility located in the company's library. There were over 1000 notebooks in storage dating back to the 1960's. Only more recently dated notebooks were sampled. In examining each notebook page by page we were able to compile a list of the types of information that engineers typically recorded when they designed (refer to Table 1). The majority of the words on this list were composed of actual words or headers found in notebooks. Some words (indicated by an asterisk) were used to describe specific types of information recorded in notebooks (e.g. spreadsheet, photographs, drawings, etc.). With this information, we were able to derive some meaningful and useful anchor names for the EEN. Thus far, five anchor names (*alternative, assumption, constraint, goal,* and *variable*) have been adopted. These anchors will help users locate the answers to some of their questions such as "what is the purpose of this?" [*goal*], "what other methods have been explored?" [*alternative*], or "what is this decision based on?" [*assumption*].

Table 1 Types of Information Recorded in Engineering Notebooks

Accomplishments	Estimates	Methodology	Requirements - Informal
Algorithms	Experiments	Methods	Resolutions
Alternatives	Explanation	Milestones	Resources
Analysis	Feasibility study	Note (e.g. discussions)	Results
Applicable Documents	Flow chart *	Objectives	Reviews
Assumptions	Flow diagram *	Observations	Schedules
Budget	Formula	Parameters	Scope
Calculations	Gantt chart *	Performance trade-off	Solutions
Comparisons	Graph - Log *	Planning	Specifications
Concepts	Graph - Plot *	Problem statement	Spreadsheets*
Conclusion	Graphs *	Problems	Status
Constraints	Ideas	Procedure	Strategies
Costs	Insert (e.g. copies, photos) *	Proposal	Sub-Problem
Data	Instructions	Purpose	Suggestions
Definitions	Introductions	Queries	Summary
Description	Issues	Questions & Answers	Targets
Diagrams	Materials	Recommendations	Tests
Distribution List	Matrices*	References - People	Things to do
Drawings - CAD *	Measurement	References - Things	Validations
Drawings - Free-hand*	Meeting notes	Related document list	Variables
Drawings - Isometric *	Meeting - agenda	Reminders	Verification
Equations	Meeting - attendees	Requests	What-if
Equipment	Memo	Requirements - Formal	

Archiving Notebooks

Users can organize their work into several notebooks and store them on a 'bookshelf'. A 'bookshelf' is a special folder for storing notebooks that appears on the bottom of the page (see Figure 16). Typically a single notebook will be opened at any one time, however, multiple notebooks can be opened and viewed simultaneously. Individual notebooks that are no longer required on an on-going basis can be moved to an external 'bookshelf' for safekeeping (see Figure 17).

3.2.3 Information Browsing and Retrieval

Once information has been captured, organized, and structured properly in the EEN, engineers need ways to browse, search, and retrieve this information efficiently. The EEN provides several methods for accessing information. Users can browse the EEN and search for information the same way as they would in a notebook (see Figure 18), they can

- **use table of contents** - they can look up information on the table of contents and proceed to

Figure 16 PenPoint™ Bookshelf

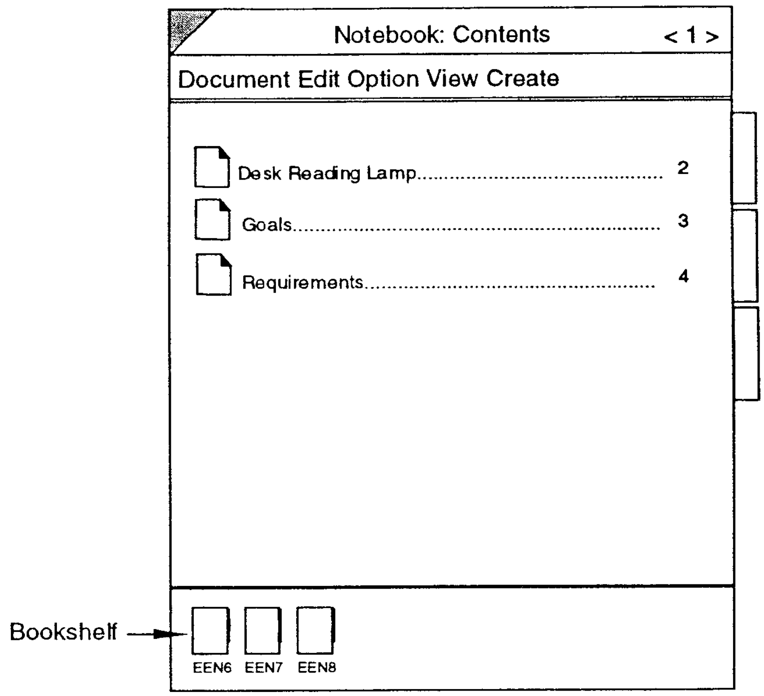
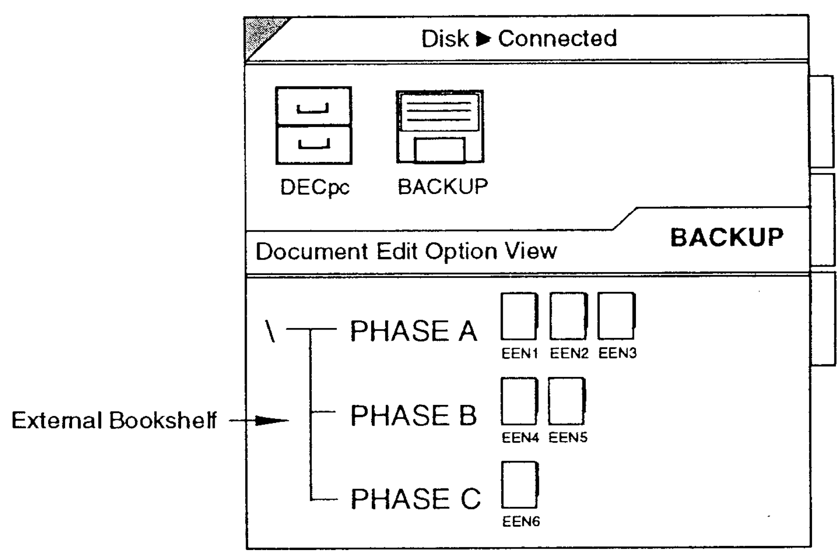


Figure 17 Archiving Notebooks



the page (random access),

- **use section tabs** - they can access specific sections of the notebook using the section tabs (random access),
- **turn page-by-page** - they can simply turn each page sequentially until they find what they are looking for (sequential access),
- **use paths** - they can also browse the notebook using the links they created from anchoring and linking (link access), or
- **search by word** - they can use the "Find" command.

3.3 Conclusion

The Electronic Engineering Notebook is equipped with various capabilities that enable engineers to capture, organize, structure, browse, and retrieve design information effectively and efficiently. The EEN which is packaged in a notebook-size computer appears to deliver all the advantages that both paper-based notebooks and computers provide such as (1) an easy-to-use interface that functions similarly to an engineering notebook, (2) desirable size and weight that makes it convenient to take along anywhere, (3) an input device (stylus) that provides quickness in entering information, (4) versatility - allows one to perform various tasks using the various applications (e.g. spreadsheet, wordprocessor, database, calendar) provided, (5) ability to organize information using visual anchors and links, (6) ability to structure information using forms, and (6) ability to browse and retrieve information.

The goals and functionality described in this paper are all a part of a ten phase project plan for constructing an EEN in the Design-in-the-Large (DITL) project at the University of Toronto [Fox 92]. The goals and functionality described here, constitute the first three phases of this project. They focus on basic functionality which includes inputting, storing, organizing, structuring, browsing, and retrieving information. The subsequent phases focus on more advanced functionality such as sharing, accessing, analyzing, and managing information. A brief description of all 10 phases is provided in Table 2. This chapter describes only the design and implementation of the EEN. The following chapters present the tests that we perform on the EEN.

Figure 18 Retrieving Content Stored in the EEN

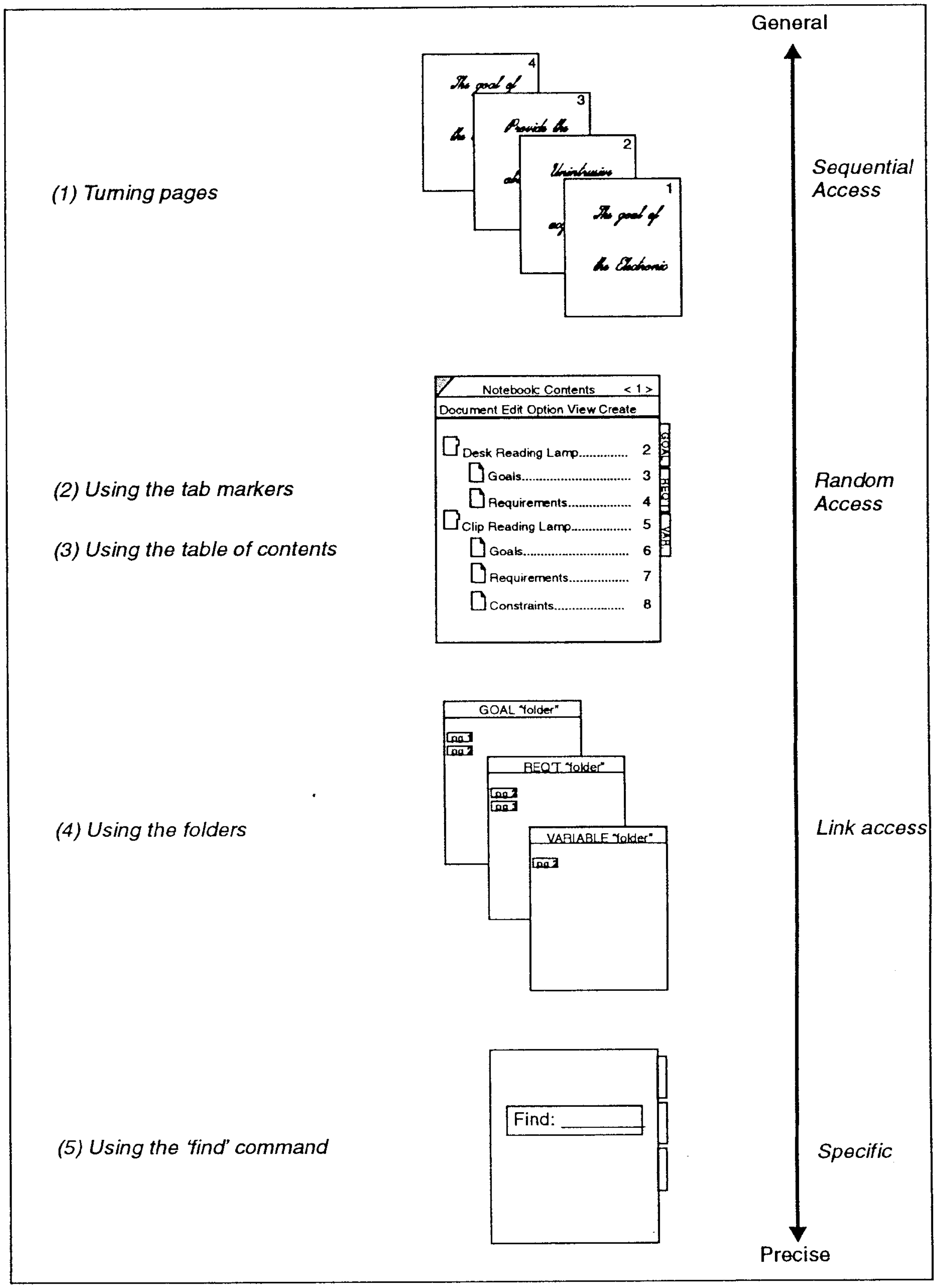


Table 2 EEN Developmental Phases

Phase 1	Provide the capability for unintrusive acquisition of design information
Phase 2	Provide the capability for structuring content in the EEN
Phase 3	Provide the capability for browsing and retrieving content in the EEN
Phase 4	Provide access (import and export data) to knowledge bases and data bases
Phase 5	Share information among design group members
Phase 6	Display and capture information during group meetings/reviews
Phase 7	Extract, analyse, and visualize EEN content
Phase 8	Communicate changes, alert constraint violations and formal communications
Phase 9	Manage change in design
Phase 10	Plan and control individual group engineering design activities

Chapter 4 Overview of Study and Methodology

4.1 Introduction

A major focus of this paper is to determine whether engineers can effectively use an EEN to capture design information. Because the EEN is constructed from technology that has not been widely used or tested in an engineering environment, it is uncertain whether engineers can use it effectively for this purpose. Three studies (2 usability studies and 1 controlled experimental study) were conducted to evaluate an engineer's ability to capture information on the EEN.

In the first study, we focus on evaluating the engineer's ability to perform basic tasks on the EEN such as reading, writing, and sketching. We expect that engineers will be able to capture information as effectively on an EEN as they can on a sheet of paper (our benchmark). Information that engineers capture can vary considerably and can include such items as meeting notes, memos, calculations, drawings, personal reminders, experimental results and data, etc. In the second and third studies, we concentrate our efforts on evaluating the engineer's ability to capture information in activities involving (1) problem design solving (analyzing, calculating) and (2) project/ time management (scheduling, action items).

With a relatively wide selection of pen-based computing hardware available, EENs can be constructed in various sizes ranging from a screen dimension of 4x3 to 9x6 inches. Smaller EENs are desirable in that they are more convenient to carry around than larger ones, however, we expect that smaller EENs will not be practical for engineers to use and furthermore will hinder their ability to effectively capture and document information. The following are our expectations and hypotheses that we will test in our studies.

4.2 Hypotheses

__Expectation:__ Engineers are able to capture information effectively on the EEN. To prove this we will attempt to falsify our null hypothesis

$H1_O$: Engineers can write on a sheet of paper more effectively (quickness and quality) than they can write on an EEN.

$H1_A$: Engineers can write on an EEN just as effectively (quickness and quality) as they can write on a sheet paper.

$H2_O$: Engineers can read from a sheet of paper just as effectively (quickness) as they read from an EEN.

$H2_A$: Engineers can read from an EEN just as effectively (quickness) as they read from a sheet of paper.

$H3_O$: Engineers can sketch on an EEN just as effectively (quickness and quality) as they can on a sheet of paper.

$H3_A$: Engineers can sketch on an EEN just as effectively (quickness and quality) as they can on a sheet of paper.

Expectation: Screen size affects reading, writing, and sketching performance.

$H4_O$: Engineers are able to write quicker and more legibly on large screen EENs (9x6) than on small screen EENs (4x3).

$H4_A$: Engineers are able to write just as quick and legibly on large screen EENs (9x6) as on small screen EENs (4x3).

$H5_O$: Engineers are able to read quicker from large screen EENs (9x6) than from small screen EENs (4x3).

$H5_A$: Engineers are able to read just as quick from large screen EENs (9x6) as from small screen EENs (4x3).

$H6_O$: Engineers are able to sketch better quality drawings on large screen EENs (9x6) than on small screen EENs (4x3).

$H6_A$: Engineers are able to sketch just as well (with the same quality) on a large screen EENs (9x6) as on small screen EENs (4x3).

4.3 Usability Testing

Human factors practitioners have relied on several techniques to evaluate user interface designs such as usability testing, heuristic evaluations, walkthroughs, and guideline reviews. Studies have shown that usability testing identifies the greatest number of problems as compared to other techniques [Karat 92][Jeffies 91].

Unlike techniques that solely rely on expert opinions such as heuristic evaluations, walkthroughs, and guideline reviews, usability testing involves representative or real users who perform typical tasks on a product under realistic conditions. The basic elements of a usability test includes [Philips 90][Rubin 94]: (1) developing problem statements or test objectives rather than hypotheses, (2) using representative end users, (3) using a representation of the actual work environment, (4) observing a user review or perform a set of tasks on the product, (5) collecting quantitative and qualitative performance measures, (6) recording problems encountered, (7) diagnosing the problems, and (6) recommending improvements to the design of the product.

Usability tests are conducted to get feedback from users to improve the overall usability and quality of a product. The intent is to ensure that the EEN is easy to use and provides the utility and functionality that engineers require [Rubin 94]. The primary objective for conducting usability tests is to discover problems relating to the user interface design so that problems can be corrected in future versions [Nielsen 93][Chapanis 81].

4.4 General Overview of Studies

Scope

The purpose of conducting these studies is to provide us with better insight about the performance of the EEN. These studies are not intended to evaluate the entire functionality and interactions of the EEN because to do this would require extensive long-term user trials.

Purpose

Two usability studies and one controlled experimental study were conducted.

The objective of the first study was to determine whether engineers can effectively use the EEN to capture basic information. Subjects were to perform three performance tests on the EEN that evaluate the fundamental skills used when capturing information. These skills included reading, writing, and sketching. We compared the effectiveness of writing, reading, and sketching on (1) an EEN to a sheet of paper (our benchmark) and (2) an EEN to a smaller version EEN (Newton MessagePad). In the second study, the objective was to evaluate the engineer's ability to use the EEN to solve design problems. Subjects were given a design problem with a set of requirements and constraints and were to create a complete design solution. In the third study, the goal was to evaluate the engineer's ability to use the EEN to perform project/time management tasks. Subjects were given four project/time management tasks to carry out.

Equipment

The EEN was based on a Toshiba DynaPad™ - T100X which was equipped with an AM386 SXLV/25 processor running at 25MHz (see Figure 19). The display was a 640 x 480 high resolution VGA and measured 9.5 inches diagonally. It was equipped with the PenPoint™ operating system and loaded with the following applications: *PenApps*- a form designer with a built-in database; *Perspective* - a personal planning application; *Aha! InkWriter*- a word processing and sketching application; *Numero!* - a spreadsheet application.

Two small version EENs, identified as (1) 4x3 EEN and (2) Newton, were used. The 4x3 EEN used identical hardware and software as the regular sized EEN except the display size was reduced to simulate a small version EEN (see Figure 20). The Newton was based on Newton MessagePad 100 hardware and software (see Figure 21).

Test Subjects

For each study, a different group of subjects was recruited. Twelve, eight, and three subjects were recruited for study 1, 2, and 3, respectively. The participants in the first study were engineering students studying at the University of Toronto. The subjects for the second and third study consisted of professional engineers all working in the electrical or mechanical engineering field at a medium sized aerospace company.

Figure 19 The 9x6 EEN

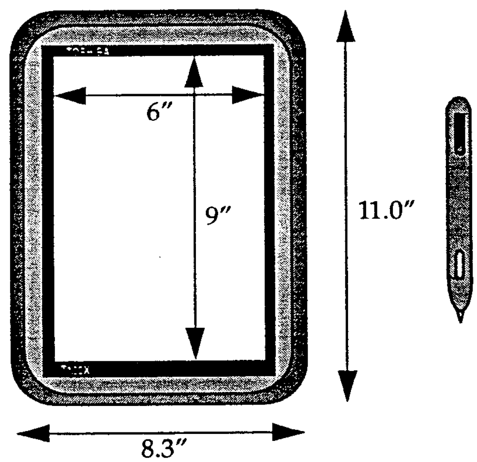


Figure 20 The 4x3 EEN

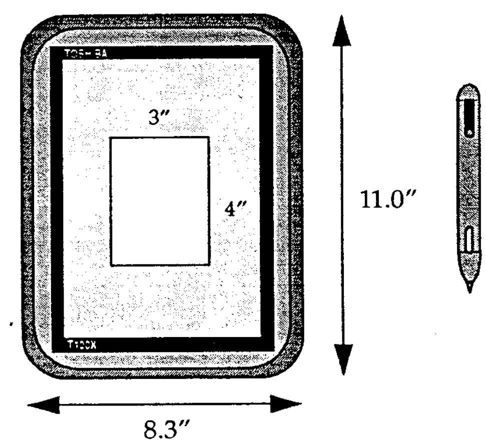
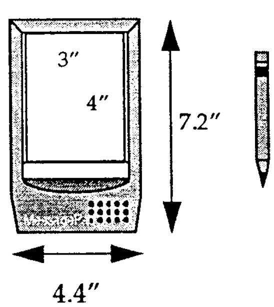


Figure 21 Newton (MessagePad 100)



Design of Studies

Study 1: Study 1 consists of (1) a training and practice session, (2) three performance tests, and (3) a debriefing session.

Study 2: Study 2 consists of (a) a training and practice session, (b) a design performance test, and (c) a debriefing session.

Study 3: Study 3 consists of (a) a training and practice session, (b) basic project/time management performance test, and (c) a debriefing session.

4.5 Conclusion

The studies described here were designed to help us evaluate an engineer's ability to capture and document design information on the EEN. In this paper, we focused our efforts on evaluating their ability to perform fundamental tasks (i.e. reading, writing, and sketching) on the EEN (see Chapter 5). We also evaluated their ability to capture information in activities that involved (1) problem design solving (analyzing, calculating) (see Chapter 6) and (2) project/time management (scheduling, action items) (see Chapter 7). These evaluations are described in further detail in chapters 5,6, and 7.

Chapter 5 Study 1

5.1 Purpose

The main purpose of this study is to determine whether engineers can effectively use the EEN to capture design information. In doing so, an experiment is conducted to evaluate their ability to read, write, and sketch on the EEN. Our expectation is that engineers will be able to capture information as effectively on an EEN as they can on a sheet of paper (our benchmark).

With a relatively wide selection of pen-based computing hardware available, EENs can be constructed in various sizes ranging from a screen dimension of 4x3 to 9x6 inches. Smaller EENs are desirable in that they are more convenient to carry around than larger ones, however, we expect that smaller EENs will not be practical for engineers to use and furthermore will hinder their ability to effectively capture and document information. The following are our expectations and hypotheses that we will test in our experiments.

5.2 Hypotheses

Expectation: Engineers are able to capture information effectively on the EEN. To prove this we will attempt to falsify our null hypothesis

$H1_O$: Engineers can write on a sheet of paper more effectively (quickness and quality) than they can write on an EEN.

$H1_A$: Engineers can write on an EEN just as effectively (quickness and quality) as they can write on a sheet paper.

$H2_O$: Engineers can read from a sheet of paper just as effectively (quickness) as they read from an EEN.

$H2_A$: Engineers can read from an EEN just as effectively (quickness) as they read from a sheet of paper.

$H3_O$: Engineers can sketch on an EEN just as effectively (quickness and quality) as they can on a sheet of paper.

$H3_A$: Engineers can sketch on an EEN just as effectively (quickness and quality) as they can on a sheet of paper.

Expectation: Screen size affects reading, writing, and sketching performance.

$H4_O$: Engineers are able to write quicker and more legibly on large screen EENs (9x6) than on small screen EENs (4x3).

$H4_A$: Engineers are able to write just as quick and legibly on large screen EENs (9x6) as on small screen EENs (4x3).

H5_O: Engineers are able to read quicker from large screen EENs (9x6) than from small screen EENs (4x3).

H5_A: Engineers are able to read just as quick from large screen EENs (9x6) as from small screen EENs (4x3).

H6_O: Engineers are able to sketch better quality drawings on large screen EENs (9x6) than on small screen EENs (4x3).

H6_A: Engineers are able to sketch just as well (with the same quality) on a large screen EENs (9x6) as on small screen EENs (4x3).

5.3 User Profile

In this study, twelve subjects comprising of engineering students studying at the University of Toronto are recruited. All participants have at least a combination of four years of engineering education and experience. Participants in this group have the following characteristic: (1) work with computers on a regular basis and are familiar with the operations of graphical user interfaces (e.g. familiar with menu selection, scrolling, etc.), (2) have at least one course of engineering graphics, and (3) have never worked with pen-based computers.

5.4 Methodology

The usability test consists of (1) a training and practice session, (2) three performance tests, and (3) a debriefing session.

1. Training and practice session

The training includes learning how to start the EEN, flip to pages, open applications (e.g. calculator), write and sketch with the stylus, invoke commands using gestures, page scroll, and edit content. A total of 10 minutes for training and practice is allotted to each subject.

2. Performance test

Three tasks representing the actions of capturing design information are selected for subjects to perform. The tasks involve *writing* a short paragraph (refer to Table 4), *sketching* a diagram (refer to Table 5), and *reading* a handwritten paragraph (refer to Table 6). To test our hypotheses we compare the EEN's performance to (1) paper (our benchmark) and to (2) a small version EEN. The small version EEN is represented by a Newton MessagePad 100. Because different technologies are used in constructing the EEN and Newton it will be difficult to determine if a difference in performance is a result of screen size, technology, or a combination of both. We therefore introduce a third medium into the experiment to help us control these variables. This third medium has the same technology as the EEN and the same screen dimension as the Newton.

Table 3 Medium vs. Task

Medium	Task 1	Task 2	Task 3
A: EEN (9x6)			
B: 4x3 EEN (4x3)			
C: Newton (4X3)			
D: Pen & Paper (8.5 x 11 - one sheet)			

Table 4 Study 1 - Task 1

Task 1: Handwriting Task - *Rewrite the following paragraph.*

A: The Industrial Engineering program was established in 1958 in response to the critical need in society for an engineering approach to solving problems relating to the interplay of people, productivity, information, and management.

B: Such problem situations occur in every type of industry or business enterprise. These problems occur in all parts and at all levels of the organization - finance, marketing, production, research and corporate administration.

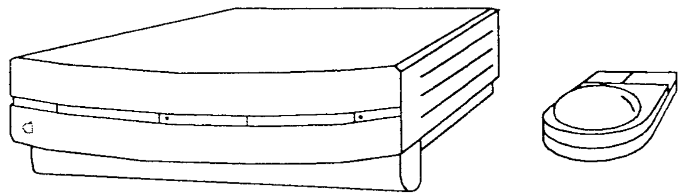
C: Today, the industrial engineer has an unusual combination of knowledge and skills for handling this interplay - a systems approach which uses appropriate combinations of mathematics, physiology, and computer technologies.

D: Industrial Engineering rests upon a substantial foundation in science and mathematics, and in fundamental engineering disciplines including applied thermodynamics, electrical science, mechanics, and materials science.

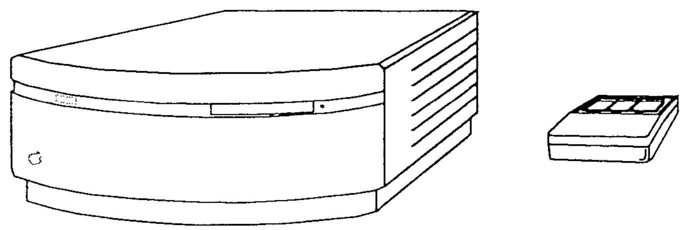
Table 5 Study 1 - Task 2

Task 2: Sketching Task - *Redraw the following figure.*

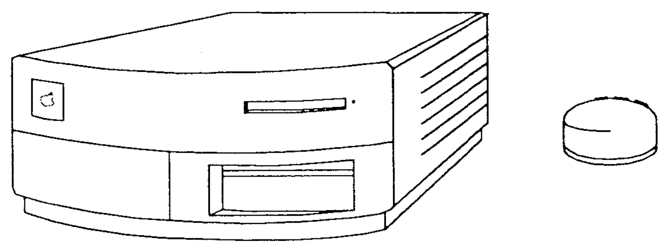
A:



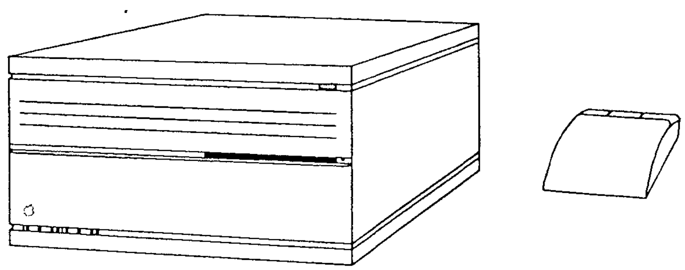
B:



C:



D:



Design of Experiment

This experiment requires each subject to perform three tasks (a. writing, b. sketching, c. reading) on four mediums (A. EEN, B. 4x3 EEN, C. Newton, D. sheet of paper) (refer to Table 3). Each subject performs 12 tests (3 tasks x 4 mediums) in total. The sequence of these tests are altered

Table 6 Study 1 - Task 3

Task 3: <u>Reading Task</u> - *Read the following paragraphs out aloud.*

A: Read the paragraph that was handwritten by the subject in ***Task 1 A:***

B: Read the paragraph that was handwritten by the subject in ***Task 1 B:***

C: Read the paragraph that was handwritten by the subject in ***Task 1 C:***

D: Read the paragraph that was handwritten by the subject in ***Task 1 D:***

(refer to Table 4) for each subject to minimize any possible transfer or carry-over effects. Furthermore, although subjects repeat each task four times, they are never exposed to the same experimental content (e.g. paragraphs, figures) because different content is provided each time.

Table 7 Sequence of Mediums Tested

Subject ID	Sequence of medium tested
S01	DABC
S02	DACB
S03	DBAC
S04	DBCA
S05	DCAB
S06	DCBA
S07	ABCD
S08	ACBD
S09	BACD
S10	BCAD
S11	CABD
S12	CBAD

3. Debriefing

After the test is completed, each participant is debriefed. Participants are given time to elaborate on the difficulties they experienced during the design task and to give comments on how the overall design of the EEN might be improved. Questions are guided using the following questions:

1.What is your overall impression of using the EEN?

2. How does it feel to write and sketch on the EEN?

3. How does it feel to read from the EEN?

4. What is your impression of the general user interface (table of contents, turning to pages,

opening applications, using gestural commands, moving, copying, deleting objects)

5. What improvements would you make to the EEN to make it easier and more practical to use?

5.5 Evaluation Measures

The following evaluation measures are collected and calculated:

1. The time to complete each task (Task 1, Task 2, Task 3)

2. The number of transcription or reading errors observed (Task 1, Task 3)

3. The judged ratings of each sketch (Task 2) (see Data Collection and Preparation)

5.6 Test Environment and Equipment

The study is conducted at the University of Toronto. Each performance test is performed in a laboratory environment. The equipment used are (1) an EEN and (2) a Newton MessagePad 100. The EEN is based on a Toshiba DynaPad™ - T100X which is equipped with an AM386 SXLV/25 processor running at 25MHz. The display is a 640 x 480 high resolution VGA and measures 9.5 inches diagonally. It is equipped with the PenPoint™ operating system and loaded with the following applications: PenApps, Perspective, Aha! InkWriter, and Numero!

5.7 Analyses and Results

Twelve subjects were tested under all 12 (4x3) possible combinations of task and medium (refer to Table 3). Twenty-five percent of the subjects (3 of 12) were female and thirty-three percent of the subjects (4 of 12) wrote with their left hands.

Data Collection and Preparation

The measuring criteria used to evaluate writing, sketching, and reading performances on the various mediums was time duration, quality ratings, and error counts. A total of 144 (12 subjects x 4 mediums x 3 tasks) time-related data points (see Appendix A), 7 error observations, and 576 (3 judges x 48 sketches x 4 criteria) quality-related data points were collected in all.

In task 1 and 3, time duration and error count were the criteria used to evaluate the user's ability to write and read on the mediums. The error observations noted in these tasks were, however, insignificant to provide any meaningful conclusion. Only seven errors were detected consisting of misspelled, misread or omitted words. In the writing portion of the experiment, one word was misspelled and another was mistakenly omitted while in the reading portion of the experiment, five words were misread possibly due to messy handwriting. Therefore, the single criteria used to evaluate writing and reading performances on the mediums was time duration.

An analysis of variance (a fully-within two factor experiment) was performed to compare the mean time to complete the writing and reading tasks. The factors are medium (EEN, 4x3 EEN, Newton, paper) and task (writing and reading). The analysis provides us with information about each factor and the possible interactions between them. The ANOVA shown in Table 8 indicates that the mean times are significantly different (F, $44.25 > F_{crit}$, 2.90) and that an interaction between the factors (F, $21.57 > F_{crit}$,2.90) exist. An interaction would indicate that none of the four mediums was uniformly quicker to write on and read from than any other medium. To illustrate this, a plot of this interaction (with 95% confidence intervals around the means) is shown in Figure 22. The upper line of points in the plot represents the writing task, while the lower line of points represents the reading task. If no interaction was detected, the 2 dotted lines in Figure 22 would be parallel to each other.

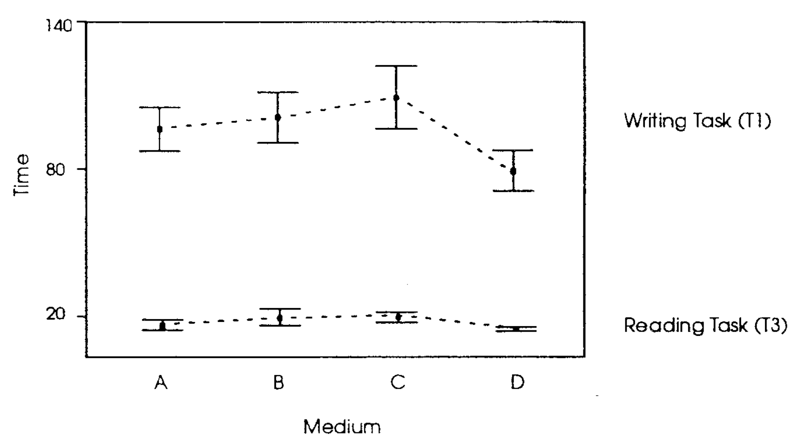
Table 8 ANOVA for two-factor (medium x task) experiment with repeated measures

Source of variation	*SS*	*df*	*MS*	*F*	*Fcrit*
Mediums (M)	4155.95	3	1385.32	44.25	2.90
Tasks (T)	161294.01	1	161294.01	339.77	4.84
Subjects (S)	5162.53	11	469.32		
M x T Interaction	2052.78	3	684.26	21.57	2.90
M x S Interaction	1033.18	33	31.31		
T x S Interaction	5221.86	11	474.71		
M x T x S Interaction	1046.84	33	31.72		
Total	179967.16	95			

note: only reading & writing tasks analyzed

Referring to Figure 22, considerably more variability can be seen for the writing task than the reading task. This result is not surprising, since people are generally accustomed to reading information from electronic screens such as computer monitors, but typically have less experience in writing on surfaces other than paper.

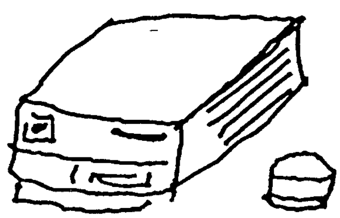
Figure 22 95% Confidence Interval Error Bars and Means



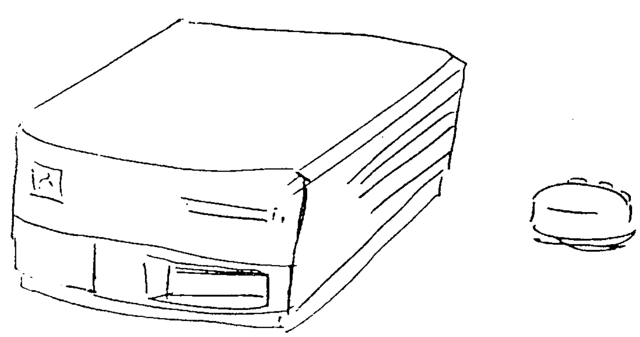
In task 2, time duration and judge ratings were the criteria used to evaluate the user's ability to sketch on the mediums. Four criteria were used to rate the quality of sketches. They were (O) overall impression, (S) stroke quality, (G) geometric resemblance, and (N) neatness. *Overall impression* represents the judge's first impression of the sketch (see Figure 23). *Stroke quality* represents the accuracy of the line segments drawn. Each sketch consisted of a combination of straight and curved line segments. A high stroke quality rating was given if straight lines appeared straight and if curved lines appeared curved (see Figure 24). *Geometric resemblance* represents the proportional and perspective elements of the object drawn. A high rating was given if the sketch was drawn with similar angles and dimensions as the given object (see Figure 25). *Neatness* represents a measure of the fine details in the sketch. A high rating was given to a sketch if it had lines and curves that were cleanly joined and well spaced (see Figure 26).

Figure 23 Overall Impression

POOR



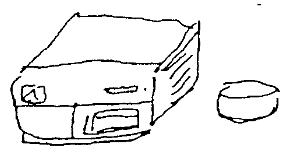
EXCELLENT



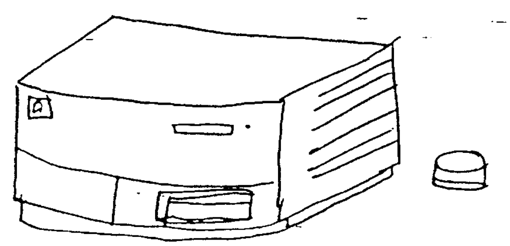
Three judges were recruited to rate all 48 sketches using the criteria described earlier. A rating scale from 1 to 5 was used: "1" indicated *poor*, "2" was *fair*, "3" was *OK*, "4" was *good*, and "5" was *excellent*. Each judge saw and rated the 48 sketches in a different sequence. The sketches shown to

Figure 24 Stroke Quality

POOR



EXCELLENT



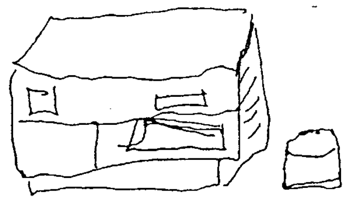
judge 1 were arranged by medium (i.e. rated all sketches drawn on Medium A first, then rated all sketches drawn on Medium B second, etc.). The sketches shown to judge 2 were arranged by subject first then medium (i.e. rated all of subject 1's sketches first in the sequence of Medium A sketch, Medium B sketch, Medium C sketch, and Medium D sketch, then rated all of subject 2's sketches second, etc.). Finally, the sketches shown to judge 3 were arranged in a reverse order of judge 2 (i.e. rated all of subjects 12's sketches first in the sequence of Medium D sketch, Medium C sketch, Medium B sketch, and Medium A sketch, then rated all of subject 2's sketches second, etc.). Each judge provided a total of 192 (48 x 4) ratings for the 48 sketches (see Appendix B). Judges were given approximately a dozen sketches to rate beforehand to determine if their ratings were relatively consistent with the ratings given by the other judges.

Analysis of Sketching Data

The results, as shown in Appendix C, indicated that Judge 2 and 3 consistently assigned ratings that were higher than Judge 1. The ratings of the three judges were intercorrelated to determine the reliability of the rating process. A strong intercorrelation was obtained, indicating that the

Figure 25 Geometric Resemblance

POOR



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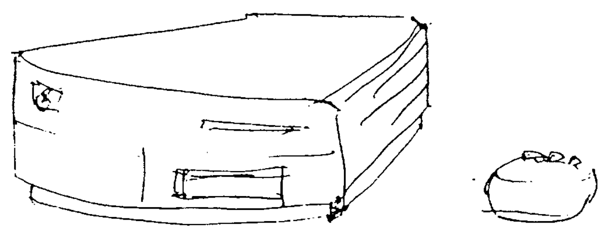
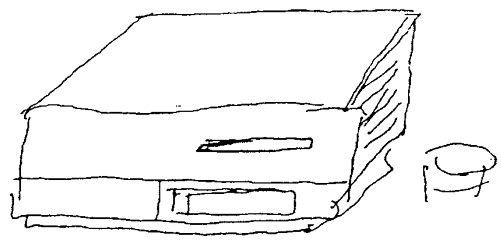


rating process was fairly reliable. A summary of the intercorrelation is provided below in Table 9. The data was then combined (averaged) into a single rating (see Table 10).

In task 2, subjects spent, on average, 60 to 80 seconds to complete each sketch. An ANOVA was performed to determine if there was a significant difference between the sketching times across the four mediums (refer to Table 11).

Figure 26 Neatness

POOR



EXCELLENT

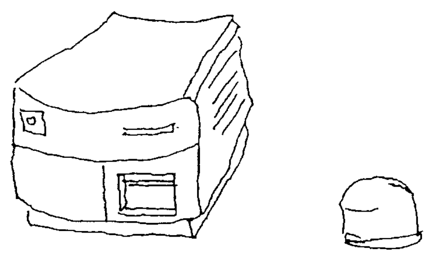


Table 9 Correlation Coefficients: Judge 1 vs. Judge 2 vs. Judge 3

	J1	J2	J3
J1	1		
J2	.93	1	
J3	.89	.93	1

Table 10 Sketching Task: Averaged Ratings

	A	B	C	D
O	3.3	2.8	1.7	3.7
S	3.7	3	2.2	4.1
G	3.1	2.6	1.8	3.4
N	3.5	2.9	1.8	3.6
AVG	3.4	2.8	1.9	3.7

The analysis shows no significant difference among the mediums with respect to sketching time ($F=1.07 \,!\!> F_{crit}=2.82$). A graph showing the 95% confidence intervals of time spent sketching on each medium is provided below. It illustrates that the time spent sketching was approximately the same across all four mediums. In other words, users did not spend significantly more time on any one medium compared to another.

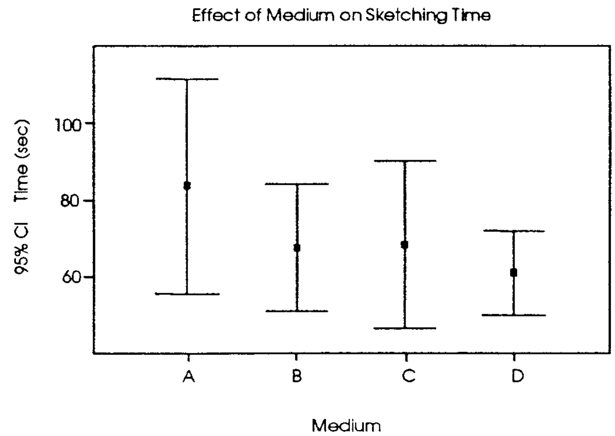


Table 11 ANOVA for sketching time across the four mediums

Mediums	*Count*	*Sum*	*Average*	*Variance*
A	12	1005	83.75	1926.21
B	12	813	67.75	672.39
C	12	822	68.5	1175.73
D	12	735	61.25	287.30

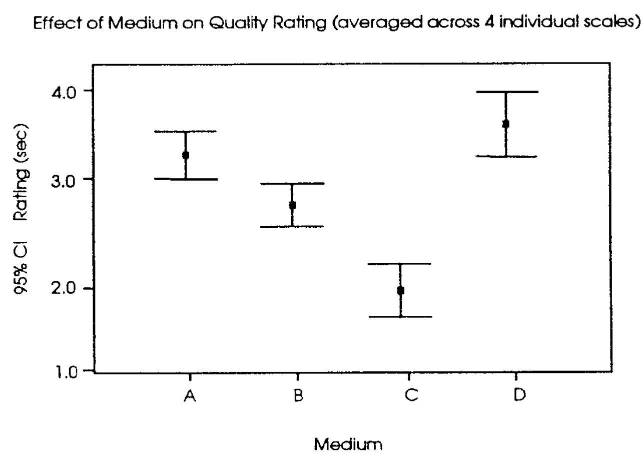
Source of variation	*SS*	*df*	*MS*	*F*	*Fcrit*
Between Mediums	3270.56	3	1090.19	1.07	2.82
Within Mediums	44677.75	44	1015.40		
Total	47948.31	47			

A second correlation analysis was performed to determine if a relationship existed between subjects who spent a lot of time sketching and sketches that received high ratings. The results showed that the amount of time spent drawing was not directly related to the quality of the sketch, however a fairly high intercorrelation existed between the four different types of rating. The results of this correlation analysis is shown in Table 12 and the data can be referred to in Appendix D. Sketching time was not considered further in the analysis because there were no significant differences in sketching time across the different mediums and also because sketching time was determined to be a non-factor with respect to sketch quality.

Table 12 Correlation Coefficients: Time vs. Quality Measure Ratings vs. Averaged Ratings

	Time (T2)	O	S	G	N	AVG
Time (T2)	1					
O	0.24	1				
S	0.16	0.88	1			
G	0.13	0.81	0.72	1		
N	0.34	0.86	0.80	0.73	1	
AVG	0.24	0.96	0.93	0.88	0.92	1

Since there was a high agreement between the different rating scales, an averaged rating (indicated as AVG in the table) was used instead to summarize the sketching performance. A 95% confidence interval graph is illustrated below showing the differences in sketch quality drawn on the four mediums. Sketching on the Newton was significantly worse than all other mediums. Sketching on the 4x3 EEN was worse than sketching on the EEN and paper, while the difference between the EEN and paper was not significant



Six individual hypothesis tests were performed. Because the chance of one of these tests being significant is greater as more tests are conducted, the alpha level was adjusted (using the Bon Ferroni method) from .05 to .01. The results of these tests are presented below.

Hypothesis Testing 1

H1: Engineers can write on an EEN just as effectively (quickness and quality) as they can write on a sheet paper.

Our hypothesis that writing on an EEN is no different than writing on a sheet of paper was rejected. The results of the analysis (refer to Table 13) indicates that a significant difference in writing time between the two mediums exists (t:5.74 > $t_{.01}$: 2.71). It took on average 96 seconds on the EEN and 78 seconds on the sheet of paper to handwrite the paragraph. The difference is approximately 20%. The data also shows a relatively strong correlation (0.71) in writing time between the two mediums. In other words, subjects who wrote quickly on paper also wrote quickly on the EEN and vice versa.

Users had to concern themselves with an extra task (page scrolling) on the EEN that they did not have to concern themselves with on paper. This may have contributed to longer time durations on the EEN. The quality of the handwritten content on the EEN was, in general, legible. Only five words in the entire study were found to be difficult to read which is insignificant considering that there were a few hundred words written in all.

Table 13 Writing Task - EEN (A) vs. Paper (D)

T1	A	D
S01	101	88
S02	79	64
S03	103	107
S04	117	82
S05	109	89
S06	114	94
S07	90	62
S08	72	65
S09	82	72
S10	105	76
S11	89	72
S12	95	75

t-Test: Paired Two-Sample for Means	A	D
Mean	96.3333	78.8333
Variance	203.152	184.697
Observations	12	12
Pearson Correlation	0.71415	
Pooled Variance	138.333	
Hypothesized Mean Difference	0	
df	11	
t	5.74926	
t Critical one-tail (alpha .01)	2.718	

Hypothesis Testing 2

H2: Engineers can read from an EEN just as effectively (quickness) as they read from a sheet of paper.

Our hypothesis that reading handwritten content from an EEN is no different than reading it from a sheet of paper was not rejected. The results of the analysis (refer to Table 14) do not indicate that a significant difference in reading time between the two mediums exist (t:2.16 !> $t_{.01}$:2.71). It took on average 13.25 seconds on the EEN and 11.5 seconds on paper to read the handwritten paragraph. There was insufficient evidence to indicate that users were able to read quicker from paper than from the EEN.The data also shows a relatively strong correlation (0.73) in reading time between the two mediums which implies that subjects who read quickly on paper also read quickly on the EEN and vice versa.

In general, subjects were able to read the handwritten content without much difficulty. Only five reading errors were observed in the study.

Table 14 Reading Task - EEN (A) vs. Paper (D)

T3	A	D
S01	11	10
S02	14	10
S03	14	12
S04	15	12
S05	12	11
S06	12	13
S07	11	10
S08	24	15
S09	10	12
S10	13	11
S11	11	11
S12	12	11

t-Test: Paired Two-Sample for Means	A	D
Mean	13.25	11.5
Variance	13.6591	2.09091
Observations	12	12
Pearson Correlation	0.73998	
Pooled Variance	3.95455	
Hypothesized Mean Difference	0	
df	11	
t	2.16494	
t Critical one-tail (alpha .01)	2.718	

Hypothesis Testing 3

H3: Engineers can sketch on an EEN just as effectively (quickness and quality) as they can from a sheet of paper.

Our hypotheses that sketching on a screen EEN is no different than sketching on a sheet of paper was not rejected. The results of the analysis (refer to Table 15) do not indicate that a significant difference in sketching quality between the two mediums exist (t:1.68 !> $t_{.01}$: 2.71). Sketches drawn on the EEN and on paper had an average quality rating of 3.36 and 3.70, respectively. There was insufficient evidence to indicate that users were able to sketch with better quality on paper than on the EEN. The analysis also indicates (variance = 0.03) that users who did sketch well on paper did not necessarily sketch well on the EEN and vice versa. As noted earlier, sketching time was not a factor in this experiment. Users spent an equivalent amount of time sketching on the EEN as they did on paper.

Table 15 Sketching Task - EEN (A) vs. Paper (D)

T2	A	D
S01	3.3	3.3
S02	3.1	3.6
S03	3.7	4.1
S04	4.4	3.4
S05	3.0	2.5
S06	3.2	4.6
S07	3.5	4.0
S08	3.3	3.3
S09	3.7	4.1
S10	3.3	3.4
S11	2.9	3.9
S12	3.1	4.3

t-Test: Paired Two-Sample for Means	A	D
Mean	3.36806	3.70139
Variance	0.16851	0.31497
Observations	12	12
Pearson Correlation	0.03266	
Pooled Variance	0.00752	
Hypothesized Mean Difference	0	
df	11	
t	-1.6871	
t Critical one-tail (alpha .01)	2.718	

Hypothesis Testing 4

H4: Engineers are able to write quicker and more legibly on a large screen EEN (9x6) than on a small screen EEN(4x3 - Newton).

The results of the analysis (refer to Table 16) indicate that a significant difference in writing time between the two mediums exists (t:4.3 >$t_{.01}$: 2.71). It took on average 96 seconds on the EEN and 109 seconds on the Newton to write the paragraph. The Newton took approximately 22% longer in carrying out the task. The data also shows a relatively strong correlation (0.87) in writing time between the two mediums which implies that subjects who wrote quickly on the Newton also wrote quickly on the EEN and vice versa. These results clearly indicate that users can write quicker on an EEN than on a Newton.

Although no additional analyses were done to evaluate the legibility quality between the handwritten content on the EEN versus the handwritten content on the Newton, subjects had no difficulty reading content from either one of these mediums. The difference in times was largely due to users spending time scrolling pages. On the Newton, subjects had to scroll 3 to 5 times more than they had to on the EEN.

Table 16 Writing Task - EEN (A) vs. Newton (C)

T1	A	C
S01	101	125
S02	79	85
S03	103	130
S04	117	146
S05	109	107
S06	114	131
S07	90	94
S08	72	88
S09	82	93
S10	105	113
S11	89	88
S12	95	113

t-Test: Paired Two-Sample for Means	A	C
Mean	96.333	109.42
Variance	203.15	411.17
Observations	12	12
Pearson Correlation	0.8736	
Pooled Variance	252.48	
Hypothesized Mean Difference	0	
df	11	
t	-4.334	
t Critical one-tail (alpha .01)	2.718	

Hypothesis Testing 5

H5: Engineers are able to read quicker from a large screen EEN (9x6) than from a small screen EEN (4x3 - Newton).

The results of the analysis (refer to Table 17) indicate that a significant difference in reading time between the two mediums exists (t:2.9 >$t_{.01}$: 2.71). It took on average 13 seconds on the EEN and 16.5 seconds on the Newton to read the handwritten paragraph. The difference is approximately 13%. The results clearly indicate that users can read quicker from an EEN than from a Newton.

Similar with the writing task, the time difference between reading on the EEN and reading on the Newton was largely due to time spent page scrolling. As mentioned previously, subjects had to page scroll 3 to 5 times more on the Newton than they had to on the EEN.

Table 17 Reading Task - EEN (A) vs. Newton (C)

T3	A	C
S01	11	11
S02	14	18
S03	14	21
S04	15	19
S05	12	14
S06	12	17
S07	11	16
S08	24	20
S09	10	21
S10	13	16
S11	11	12
S12	12	13

t-Test: Paired Two-Sample for Means	A	C
Mean	13.25	16.5
Variance	13.659	11.909
Observations	12	12
Pearson Correlation	0.4455	
Pooled Variance	5.6818	
Hypothesized Mean Difference	0	
df	11	
t	-2.987	
t Critical one-tail (alpha .01)	2.718	

Hypothesis Testing 6

H6: Engineers are able to sketch better quality drawings on a large screen EEN (9x6) than on a small screen EEN (4x3 - Newton).

The results of the analysis (refer to Table 18) indicate that a significant difference in sketching quality between the two mediums exists (t:14.3 > $t_{.01}$: 2.71). Sketches drawn on the EEN and on the Newton had an average quality rating of 3.36 and 1.89, respectively. The difference is approximately 61%. The results clearly indicate that users can sketch with better quality on an EEN than on a Newton.

The quality of sketches on the Newton was considerably poorer than on the EEN. One explanation is that the line weight of the sketches was heavier on the Newton which may have made the judges feel that the Newton sketches were messier.

Table 18 Sketching Task - EEN (A) vs. Newton (C)

T2	A	C
S01	3.3	1.7
S02	3.1	2.2
S03	3.7	1.8
S04	4.4	2.7
S05	3.0	1.5
S06	3.2	2.2
S07	3.5	1.4
S08	3.3	2.2
S09	3.7	2.5
S10	3.3	1.9
S11	2.9	1.4
S12	3.1	1.3

t-Test: Paired Two-Sample for Means	A	C
Mean	3.3681	1.8958
Variance	0.1685	0.1971
Observations	12	12
Pearson Correlation	0.6555	
Pooled Variance	0.1195	
Hypothesized Mean Difference	0	
df	11	
t	14.329	
t Critical one-tail (alpha .01)	2.718	

Control Variables

Our results show that users can write, read, and sketch more effectively on a large screen EEN (9x6) than on a small screen EEN (4x3).

The small screen EEN was represented by a Newton MessagePad 100. Because different technologies were used in constructing the EEN and Newton it was difficult to determine if a difference in performance was a direct result of screen size, technology, or a combination of both. A third medium (4x3 EEN) was added to the experiment to help us control these conditions.

A similar analysis was repeated for (1) EEN vs. 4x3 EEN (both based on the same technology) and (2) Newton vs. 4x3 EEN (both having the same screen dimension). Comparing the Newton to the 4x3 EEN, the results show sufficient evidence to indicate differences between these two mediums for the writing and sketching task but not for the reading task (see Appendix F). Comparing the EEN to the 4x3 EEN, the results show sufficient evidence to indicate differences between EEN and 4x3 EEN for the reading and sketching task but not for the writing task (see Appendix E).

To summarize, the results show clearly that large screen EENs are more effective than small screen EENs for reading and sketching, regardless of technology (refer to Table 19). On the other hand, for writing, the results show that large screen EENs are more favourable than Newtons but are not necessarily favourable than 4x3 EENs. A possible explanation is that with the 4x3 EEN, users had the luxury of being able to write with their hands rested on a bigger surface area (see Figure 27). This would have provided users with more stability in writing and as a result would allow them to write quicker.

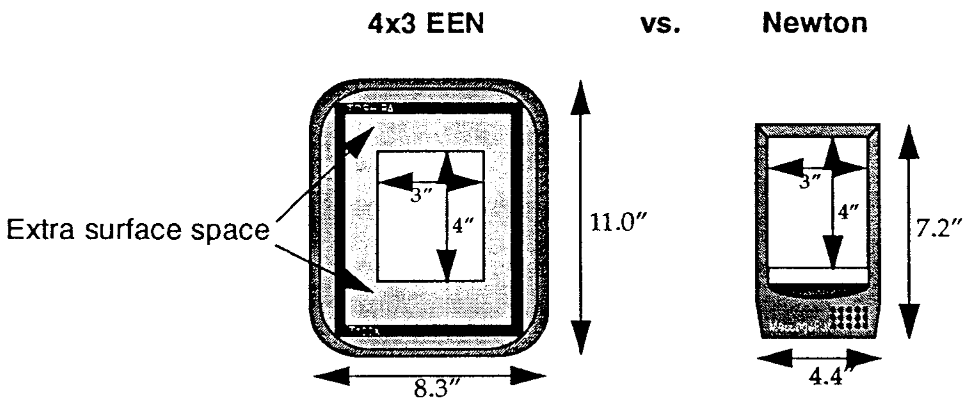
Table 19 Large Screen EEN vs Small Screen EEN

Writing	EEN > Newton	EEN ! > 4x3 EEN
Reading	EEN > Newton	EEN > 4x3 EEN
Sketching	EEN > Newton	EEN > 4x3 EEN

5.8 Summary of Results

Paper was a better medium for writing, however, for reading and sketching, the EEN fared just as well. Overall, users were able to write legibly without much difficulty on the EEN, however, they had to concern themselves with other factors such as page scrolling and view angle adjusting which could explain why users required more time on the EEN.

Figure 27 4x3 EEN Surface Space



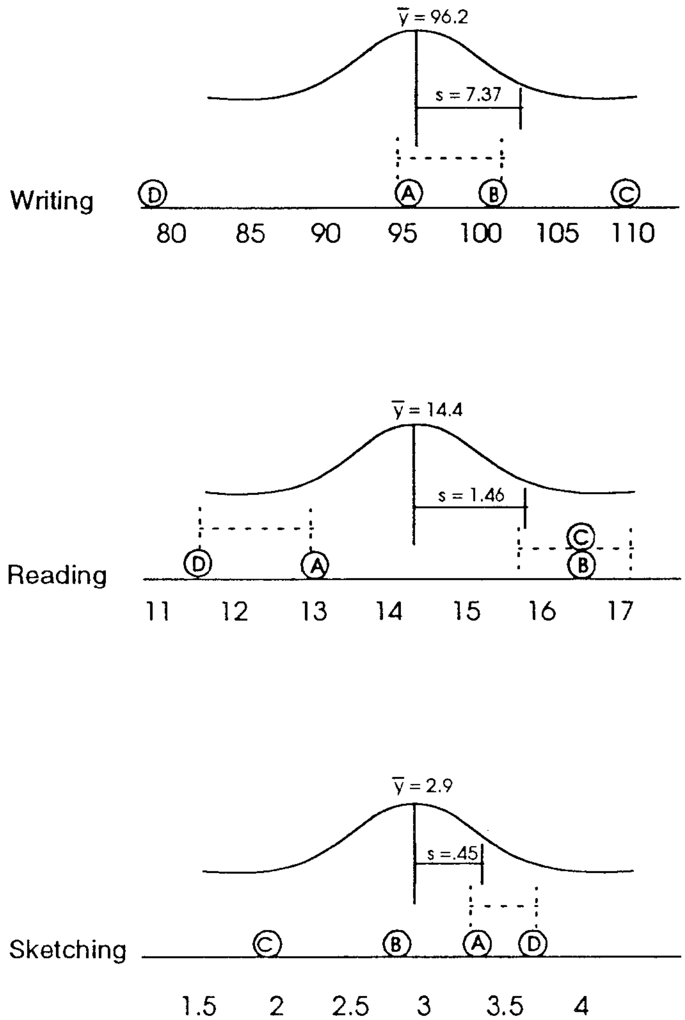
In comparing the EEN to the smaller screen versions, the large screen was clearly a better medium for reading and sketching while for writing, it was difficult to conclude because the Newton fared relatively poorer than the EEN while for the 4x3 EEN the same could not be said. Subjects also commented that the surface area on the 4x3 EEN and Newton was quite small and impractical for writing, reading, and sketching. Our interpretation of these results is that people need a comparatively large working space for writing, reading, and sketching.

The following table and dot diagrams summarizes the results of this experiment. The hash lines on the dot diagrams indicate that no significant difference between the mediums shown beneath this line.

Table 20 Summary of Analysis

Mediums	Tasks	Significant Difference Observed	Percent Difference
EEN vs. Paper	writing	yes	20%
	reading	no	
	sketching	no	
EEN vs. Newton	writing	yes	22%
	reading	yes	13%
	sketching	yes	61%
EEN vs. 4x3 EEN	writing	no	
	reading	yes	22%
	sketching	yes	18%
4x3 EEN vs. Newton	writing	yes	8%
	reading	no	
	sketching	yes	41%

Figure 28 Dot Diagrams for the three tasks



Chapter 6 Study 2

6.1 Purpose

The main purpose of this study is to evaluate the engineer's ability to use an EEN to solve design problems. The EEN will act as a notepad where engineers can write and sketch on it. This study which is intended to simulate an actual design process involves users designing an artifact on the EEN. Subjects are given a design problem with a set of requirements and constraints and are asked to create a complete design solution. The study will identify errors and difficulties encountered by the user.

6.2 Problem Statement

The specific questions that need to be answered:

1. Are there any difficulties in writing and sketching on the EEN?
2. Do engineers experience difficulty reading from the EEN?
3. Does the EEN provide enough surface space to work on?
4. Are engineers able to move effectively within and between pages?
5. Are engineers able to recover when they make mistakes?

6.3 User Profile

A total of eight participants will be tested. The participants comprise of professional engineers working in the electrical or mechanical engineering field. All participants have at least five years of engineering experience and have previous computer experience. Participants in this group have the following characteristic: (1) work with computers on a regular basis and are familiar with the operations of graphical user-interfaces (e.g. familiar with menu selection, scrolling, etc.) and (2) have never worked with pen-based computers.

6.4 Methodology

The usability test consists of (1) a training and practice session, (2) a performance test, and (3) a debriefing session. The performance test is designed to gather usability data through direct observation.

1. Training and practice session

The training includes learning how to start the EEN, flip to pages, open applications, write and sketch with the stylus, invoke commands using gestures, page scroll, tagging, and edit content. A total of 15 minutes for training and practice is allotted to each subject.

2. Performance test

The performance test consist of a single design task that the participants are asked to carry out while being observed. Subjects are asked to design a simple artifact on the EEN given a set of requirements and constraints. The instructions are as follows:

> You have been asked to design a bookshelf that is 1m high, 1.5m wide, and 0.5m deep. The bookshelf must have 3 shelves and be able to stand up books that are 30 cm high. The pieces are to be cut from a single sheet of wood with dimensions 2.5 m by 2.5 m x 2.5 cm. Only 20 screws are provided.
>
> Record all notes, calculations, sketches, etc. on the EEN. Note any assumptions that you make.
>
> Provide the necessary drawings and instructions for a carpenter to build the bookshelf. Lastly, provide a final drawing showing how the bookshelf should appear.

3. Debriefing

After the test is completed, each participant is debriefed. Participants are given time to elaborate on the difficulties they experienced during the design task and to give comments on how the overall design of the EEN might be improved. Questions are guided using the following questions:

1. What is your overall impression of using the EEN?
2. How does it feel to write and sketch on the EEN?
3. How does it feel to read from the EEN?
4. What is your impression of the general user interface (table of contents, turning to pages, opening applications, using gestural commands, moving, copying, deleting objects)
5. What improvements would you make to the EEN to make it easier and more practical to use?
6. Do you think mobile pen-based computers are practical for use in engineering design environments?
7. What would be an ideal size EEN (for writing, for carrying around)?
8. What would be a tolerable weight for an EEN?
9. Would you use an EEN if the above improvements that you stated above were made?

6.5 Test Environment and Equipment

The study is conducted at a medium sized aerospace company. Each performance test is performed in the subject's work environment. The equipment used is an EEN that is based on a Toshiba DynaPad™ - T100X which is equipped with an AM386 SXLV/25 processor running at 25MHz. The display is a 640 x 480 high resolution VGA and measures 9.5 inches diagonally. It is equipped with the PenPoint™ operating system and loaded with the following applications: *PenApps*- a form designer with a built-in database; *Perspective* - a personal planning application;

Aha! InkWriter- a word processing and sketching application; *Numero!* - a spreadsheet application. The primary applications used for this study are *Aha! InkWriter* and *Numero!*.

6.6 Observations and Comments

Subjects, on average, spent between fifteen to twenty minutes to complete the design problem. Each subject required approximately five minutes to get accustomed to the basic operations that were demonstrated to them. During the experiment, subjects asked questions, made comments, and gave suggestions about the EEN and the problem. The questions asked were mainly concerning the problem scenario such as "Does the bookshelf have a backing?" and about operating the interface such as "How do I move this line?" After completing the problem, subjects elaborated on the difficulties they encountered during the experiment. They also provided comments about what they liked about the EEN as well as suggestions for improving the EEN. The following sections summarizes our observations and answers questions that were posed in our problem statement.

Reading

Subjects were able to read what they were writing without much difficulty, however, they occasionally shifted their head position or repositioned the screen tablet to view certain parts of the screen. The view angle of the screen was small which made it difficult to scan the entire screen with a single glance. The majority of the subjects thought the resolution was adequate and one subject, who sat next to a window, mentioned that there was a lot of glare coming from the screen.

Writing and Sketching

Several subjects had difficulty while writing and sketching on the screen tablet. Users felt awkward writing on the screen because the tip of the pen was never in contact with the ink. This is know as a parallax problem. This occurs because the screen tablet has a transparent overlay which is a few millimetres thick. PenPoint had tried to minimize this problem by displaying a virtual pen on the spot where the tip would have touched. Another problem users complained about was that the pen did not provide any feedback on pressure. Writing with a pen or pencil on paper, a light or heavy line can be drawn by applying the appropriate amount of pressure, however, writing with a stylus on a screen/tablet, the line would appear the same regardless of the pressure applied to it.

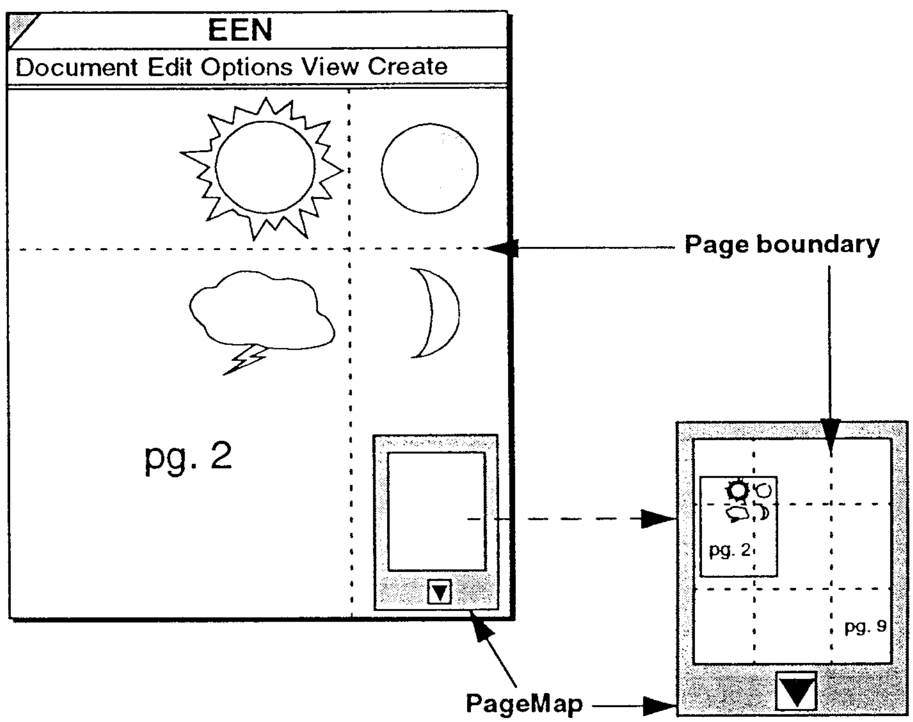
Erasing

One of the earlier problems that subjects experienced was erasing text and objects. Initially, there was only one way to erase content from the screen and that was to use a "cross-out" gestural command that was demonstrated to them beforehand. Because they found this function difficult to use, a tool palette which included an eraser and a pen tip was added onto the interface. Subjects preferred using the eraser on the palette over using the "cross-out" gestural command because it was more precise and intuitive. In the initial tests, the tool palette was purposely omitted to maximize screen space.

Navigating

The scenario was also designed to examine the user's ability to navigate around the EEN. The full solution to the problem required approximately two to three screen pages of writing, calculations, and diagrams. Subjects occasional referred back to previous screens using the scroll bars, however subjects complained that the scrolling rate was too slow. A PageMap (see Figure 29), occupying approximately 5% of the screen surface, was added to the interface to help users locate information on various pages. Several pages (super reduced) could be displayed on the PageMap at the same time. The current page was always highlighted with a black border. Although the detail of information on the PageMap was difficult to see, the user was able to navigate from one page to another much quicker and easier than without it. For example, referring to Figure 29, one is able to navigate from page 2 to page 9 in one step whereas if one had to page scroll it would take considerably longer. Another benefit of the PageMap was that it allowed pages to be magnified or reduced to suit the user's need. Users still preferred to use the scroll bars (as opposed to the PageMap) to move to various parts of the solution space possibly because they were more comfortable using them.

Figure 29 PageMap



Weight

The EEN used in this experiment weighed 3.3 pounds which is substantially heavier than most engineering notebooks. The subjects performed the experiment while sitting down with the EEN rested flat on their table because the problem was too lengthy to be solved in an upright position.

Although users did not use the EEN while standing, they thought it would be light enough to carry around in the office.

Screen Size

As mentioned earlier, subjects frequently navigated from one page to another to look for information to help them solve the problem. Because a lot of time was spent travelling from one part of the solution space to another, a larger surface area would have helped reduce some of this travel. Users felt that the size of the EEN screen provided adequate surface space to solve the given problem as well as solve other typical engineering problems. One subject mentioned that although the screen size was adequate he would typically solve engineering problems using several sheets of paper and spread them across his desk. This way he could reference specific information in parallel with a glance to another sheet.

User Comments

Subjects made comments on what they liked about the EEN such as the ease of erasing ink from the screen, moving, copying, and pasting objects, searching for specific notes, and the ability to cross-reference information. They liked the tagging feature in particular because it was not difficult to use and it provided some guidance to help them record what was important. They also liked the table of contents feature of the EEN because it organized the material in the notebook very well. It gave users the flexibility to see as much or as little information as they wanted to see. The ability to scan pictures such as military specifications into the EEN and cross-reference them with other material was thought to be useful by a couple of subjects. Users also liked the polishing features which translated sketched circles and rectangles into perfect geometric shapes. One other feature which they though would be useful was the ability to beam or handout meeting materials electronically during a meeting.

User Suggestions

Subjects provided feedback on what they thought would make the EEN attractive for engineers to use. Most subjects agreed that the EEN would be most desirable if it was compatible with their current desktop system (MS Windows) because information would then be easily exchanged between the two systems. Subjects wanted to see more specialized applications on the EEN similar to the ones they currently use on their desktops (such as a block building tool, a symbolic mathematical calculating tool, and sophisticated drawing packages with a library of objects). They also wanted a capability that would allow sketches drawn on the EEN to be reused directly in other drawing applications. This way, the EEN would serve as more than just a sketch pad. The EEN was capable of translating handwriting into normal text, however, a subject mentioned that Greek alphabets would also be important to have translated if necessary. Users felt than the EEN should handle colour because often times engineers record information in their notebooks using different colour ink to help them visualize information clearer.

Chapter 7 Study 3

7.1 Purpose

The main purpose of this study is to evaluate the engineer's ability to use the EEN to perform project/time management tasks. The EEN will act as a notepad and time management organizer where engineers can write on it as well as utilize time management functionality. Subjects are given four project/time management tasks to perform and are asked to carry them out. The study will identify errors and difficulties encountered by the user.

7.2 Problem Statement

The specific questions that need to be answered:

1. Are there any difficulties in entering information into the EEN?
2. Do engineers experience difficulty translating handwritten content into text?
3. Are engineers able to effectively drag and drop information between applications?
4. Do engineers experience difficulties in using gestural commands?

7.3 User Profile

Three participants will be tested. The participants comprise of professional engineers working in the electrical or mechanical engineering field. All participants have at least five years of engineering experience and have previous computer experience. Participants in this group have the following characteristic: (1) work with computers on a regular basis and are familiar with the operations of graphical user-interfaces (e.g. familiar with menu selection, scrolling, etc.), (2) are familiar with project time/management applications, and (3) have never worked with pen-based computers.

7.4 Methodology

The usability test consists of (1) a training and practice session, (2) a basic project/time management performance test, and (3) a debriefing session. The performance test is designed to gather usability data through direct observation.

1. Training and practice session

The training includes learning how to start the EEN, flip to pages, open applications (e.g. calculator), write and sketch with the stylus, invoke commands using gestures, page scroll, and edit content. In addition, subjects are given a demonstration of the operations of the project/time management application and given practice on how to: (1) enter and move information, (2) convert handwriting to ASCII, and (3) navigate to different windows like the Day Planner, Month

Planner, Address Book, and To-Do-List. A total of 20 minutes for demonstration, training, and practice is allotted to each subject.

2. Performance test

Four tasks representing typical project/time management tasks are selected for subjects to perform. These tasks involve the user to enter project related information, copy and paste entries into appropriate sections of the planner, translate handwritten input into text, update entries, and view appointments. The tasks are as follows:

Task 1: **Scheduling**

First, write "meet Jim at 2:00 today" on a blank page. Next, translate this statement to ASCII and copy and paste it on the appropriate day and time slot in the Day Planner.

Task 2: **Action Item**

Write "Perform Field Test with Jim" in the To-Do-List and change status to 'in progress'.

Task 3: **Address Book**

Enter your name and other relevant information into the Address Book.

Task 4: **Month View**

Use the Month Planner and find what has been scheduled for today and attach a note beside "meet Jim at 2:00 today" saying "the field test was fun" and change status of "Perform Field Test with Jim" in the To-Do-List to 'completed'

3. Debriefing

After the test is completed, each participant is debriefed. Participants are given time to elaborate on the difficulties they experienced during the design task and to give comments on how the overall design of the EEN might be improved. Questions are guided using the following questions:

1. What is your overall impression of using the EEN?
2. How does it feel to write and sketch on the EEN?
3. How does it feel to read from the EEN?
4. What is your impression of the general user interface (table of contents, turning to pages, opening applications, using gestural commands, moving, copying, deleting objects)
5. What improvements would you make to the EEN to make it easier and more practical to use?

7.5 Test Environment and Equipment

The study is conducted at a medium sized aerospace company. Each performance test is performed in the subject's work environment. The equipment used is an EEN that is based on a Toshiba DynaPad™ - T100X which is equipped with an AM386 SXLV/25 processor running at 25MHz. The display is a 640 x 480 high resolution VGA and measures 9.5 inches diagonally. It is equipped with the PenPoint™ operating system and loaded with the following applications: *PenApps-* a form designer with a built-in database; *Perspective* - a personal planning application; *Aha! InkWriter-* a word processing and sketching application; *Numero!* - a spreadsheet application. The primary application used for this study is *Perspective.*

7.6 Observations and Comments

The following sections describe the results of this study. Subjects required approximately fifteen minutes to complete the tasks. Each subject spent an additional fifteen minutes practicing the operations that were shown to them. These included opening the Day and Month Planner, Address Book, and To-Do-List, dragging and dropping text objects and translating handwriting to text. The subjects did not have difficulty familiarizing themselves with this project/time manager since the look and feel of this interface was similar to the ones they were using on their computers (i.e. WordPerfect Office).

Drag and Drop

Subjects complained about how long it took to drag and drop text objects from a text page to the planner. It took approximately ten seconds to extract information from a page into a slot in the planner. Users had to first copy the information from a page, open the planner, then drag the copied information to the appropriate slot. Furthermore, the user had to be precise when dropping text objects into slots because on a couple of occasions text objects ended up in the adjacent slot.

Handwriting Translation

Subjects were also required to translate their handwriting into text because the planner would not understand it otherwise. Users were able to translate their handwriting after a few attempts at it. On average, one or two letters would be translated incorrectly and the user would have to go back and make the corrections. This was reasonable considering that the translator was not customized for their handwriting style. It would have required approximately one hour to program the translator to accurately interpret each user's handwriting style.

Gestural Commands

Users had difficulty using the gestural commands because it was sometimes interpreted as text. For example, when a subject tried to open an edit pad using a "circular" gesture, a letter "O" would be drawn instead. A similar problem occurred when a user tried to apply a single tap command, it instead inserted a period. The system is very sensitive to the various types of input and because the gestural commands used similar strokes to letters and punctuations, users were sometimes confused.

Chapter 8 Conclusions

8.1 Summary of the Studies Conducted

Paper was a better medium for writing, however, for reading and sketching, the EEN fared just as well. Overall, users were able to write legibly without any difficulty on the EEN. Users, however, had to concern themselves with extra factors like page scrolling and view angle adjusting that were not issues with the paper medium. These extra factors, which did consume a bit of time, could explain why users spent more time writing on the EEN.

In comparing the EEN to the smaller screen versions, the large screen was clearly a better medium for reading and sketching. For writing, it was not definite whether large screens were better than smaller ones because the Newton fared relatively poorer than the EEN while the 4x3 EEN showed no signs of being inferior to the larger screen EEN. Our interpretation of these results is that people need a comparatively large working space for writing, reading, and sketching.

8.2 Observations

The observations of the studies are summarized below. In the three studies conducted several tasks were examined and are summarized below.

1. Reading

The results and feedback from the studies indicate that users prefer reading from paper than from EENs. Other studies have shown similar results that reading from a screen is generally slower than reading from paper [Gould 87].This is not very surprising considering that users have more experience reading from paper that from tablets. In general, users were quite impressed with the legibility of their handwriting on the tablets, but were dissatisfied with other factors. For example, users often had to adjust their screen position in order to see the display and, for those who sat near a window, they had to block off direct light sources to minimize the glare from the screen. Furthermore, the overall appearance of content displayed on the tablet was quite dull because all strokes appeared in the same colour and same thickness throughout.

2. Writing

The results from the studies show that users write quicker on paper than on the EEN. Users were capable of writing just as legibly on the EEN as on paper, however, they felt less comfortable writing on tablets. First, the surface of the EEN, made of hard glass, writes differently than on paper. On glass surface there is less friction than on paper that can cause the pen to slip at times. Some pen systems are equipped with an etched display glass, which provides more paper-like drag on the pen. Users have found it more comfortable writing on these surfaces and characters have been formed more precisely as a result [Crane 93]. Second, users have less control over the appearance of their writing. All strokes regardless of the pressure applied to it appear the same. These factors explain why handwriting on tablets, although legible, appeared slightly messier than on paper.

3. Sketching

The sketches drawn on paper were quite comparable, in terms of quality, to those drawn on the EEN. However, the differences in quality between paper and the smaller version EENs were more noticeable. With the smaller EENs, users were forced to scale down their sketches to fit more information onto the page. Because the screens were low resolution, lines appeared jagged when drawn small. The scaled down sketches appeared messier and more cluttered than the sketches drawn on the EEN and on paper. Furthermore, it was more difficult to erase lines on the smaller drawings because lines were closer together. It was difficult to target specific lines to be erased. Quite often, lines that were not intended to be erased were accidentally removed.

Parallax between the pen tip and the screen image occasionally mislead pointing. This problem was more evident on the Newton than on the EEN. The EEN compensates this problem by displaying a virtual pen in the image plane. There is less parallax because the virtual pen provides feedback in the image plane [Forman 94]. The results showed that drawings sketched on the EEN were of better quality than on the Newton. Referring to Figure 30, the line segments drawn on the EEN appear notably neater than on the Newton.

4. Erasing

Users prefer using an eraser tip over a "cross-out" gestural command for removing content on a tablet because it is much quicker and more precise. To erase an object, the "cross-out" gestural command requires two pen strokes, in the formation of a letter "X", whereas the eraser tip requires only a single tap. For example, to erase a single line using the "cross-out" gesture, two quick strokes over the line object will remove it. To erase the same line using the eraser tip, tapping any part of the line object with the tip will erase it. The eraser tip acts more of a stroke remover than a true ink eraser because it cannot remove sections of lines or objects. For objects that are drawn close together, the eraser tip provides more accuracy in erasing that the "cross-out" gesture. With the "cross-out" gesture, it is not always clear which objects will be erased. Several gestural commands were taught to subjects and the "cross-out" gesture was the most difficult to learn. Users found the other gestures to be easy to use and useful. One experiment comparing gestural and keyboard interfaces on spreadsheet found that users were faster with the gestural interface. Subjects performed the operations in about 72% of the time taken with a keyboard. These findings were explained in terms of the fewer number of movements required to carry out an operation with the gestural interface, the greater ease of remembering gestural commands, and the benefits of performing operations directly on objects of interest [Wolf 88]

5. Navigating

Users were impressed with the various methods available to help them navigate around the notebook such as (1) turning to specific pages using the table of contents, (2) tapping sections tabs, (3) turning pages sequentially, (4) using tags, (6) using the word finder, and (5) using scroll bars within a page. Users were however, frustrated with the speed at which it took to turn to pages and to page scroll during the three studies. In study 3, subjects were required to copy a line of content and paste it on a different page. It took a few seconds for the new page to appear. In study 2, subjects noticed that a large portion of their time was spent scrolling back and forth to various parts of their solution. In study 1, a possible explanation for why writing required more time on the tablet than on paper was because, on the tablet, a portion of the total time included scrolling time. In the sketching task, users did not need to page scroll nor turn pages on paper, and the results showed no significant difference in times across the four mediums. Other studies have shown that scrolling raw text files or tracing through long menu paths also can be tiresome and disorienting [McCall 92].

6. Editing

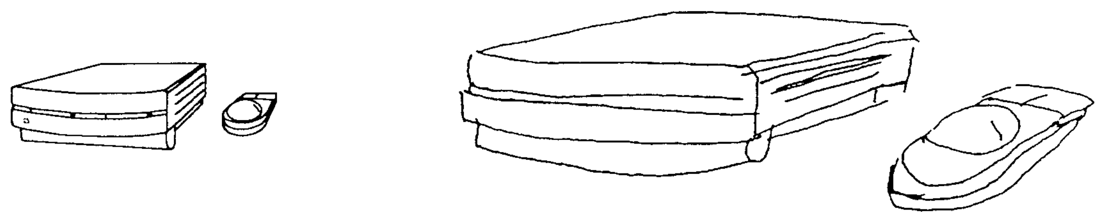
One of the advantages of using EENs for writing as opposed to using paper is the convenience of editing. Users were impressed with the ease of erasing, moving, and copying text and objects. In study 3, users were taught some editing gestural commands. Unlike the "cross-out" gesture, users found the editing gestures to be more intuitive and easier to use. For example, to move an object, one would tap the object and hold, then drag it to the destination. To cut and move an object, one would instead double tap, hold, then drag.

7. Translating

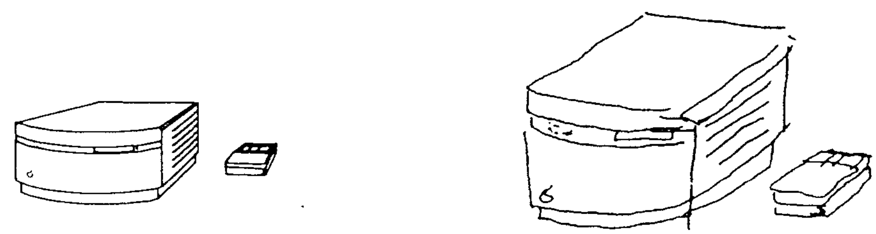
A few applications such as the Day Planner required that users translate their writing into ASCII first. The Newton had capability for translating handwriting in both cursive and block writing whereas the EEN could only recognize block letters. We found translating handwriting into printed text tedious because a lot of time was spent correcting what was translated incorrectly. Although it has been quoted that handwriting recognition rates are typically 96-98% accurate when trained to a specific user [Forman 94], we experienced rates that were much lower. The recognition rate was very good when printing block letters on an edit pad, however, when attempting to translate words written on a blank page, translation errors were abundant. It would have required approximately one hour to program the translator to interpret a user's handwriting style.

Figure 30 Sample of Sketches Drawn by the Same Person

Sketched on the EEN

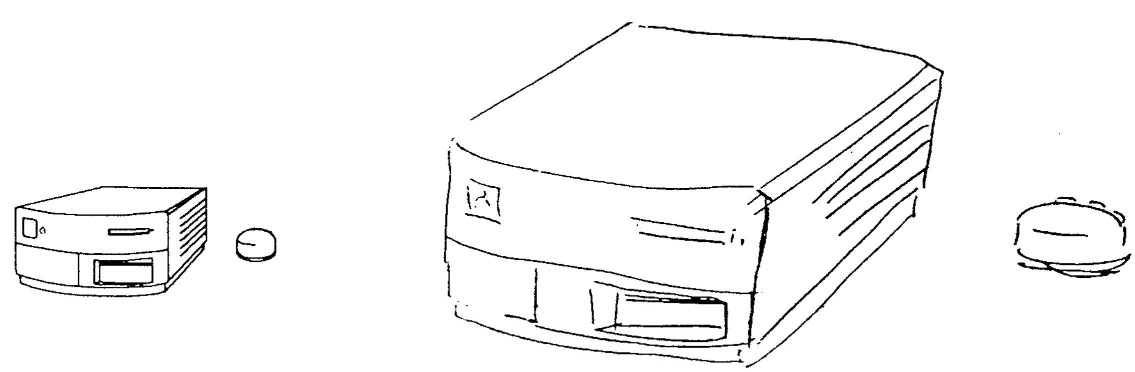


Sketched on the 4x3 EEN



Sketched on the Newton

Sketched on a sheet of paper



8.3 Recommendations

1. The effectiveness of reading and sketching can be enhanced by the size of the screen. Large screen EENs clearly provide a better medium for reading and sketching over smaller ones.
2. The effectiveness of navigating on the EEN can be enhanced by faster access rates. Page scrolling and page turning access rates on the EEN are quite slow and frustrating at times. In study 3, the access rate for turning a page was 3 seconds which is unacceptable. Access rates that are under one second are tolerable.
3. The effectiveness of handwriting translation on the EEN can be enhanced by the type of handwriting recognition software selected. Software such as Unistrokes or Graffiti that require the use of a modified version of the alphabet system provides a high rate of accuracy (Graffiti claims a translation accuracy rate of 100% after twenty minutes of practice). A handwriting recognition rate of 97% or higher is acceptable by most users.
4. The effectiveness of reading and writing on the EEN can be enhanced by the type of screen technology used. If the EEN is to be used in various places that have different lighting conditions, problems such as glare and contrast need to be addressed. As observed in study 2, reading content on the EEN was challenging in bright lighting conditions.
5. The effectiveness of writing, drawing, or gesturing on the EEN can be limited or enhanced by the type of writing surface available. Some pen-based tablets are equipped with an etched display glass, which improves writing by providing a more paper-like drag on the pen.
6. The effectiveness of long term use of the EEN can be enhanced by the availability of (1) generic and specialized applications (e.g. block building, symbolic mathematical calculating tools), (2) applications that are compatible with user computer systems (e.g. MS Windows), (3) applications that allow sketches drawn on the EEN to be reused in other drawing applications (EEN to serve as more than a sketch pad), and (4) colour to help visualize information more clearly.

8.4 Concluding Remarks

The EEN is designed to help engineers capture, organize, structure, browse, and retrieve design information. It permits engineers to enter information anywhere on a page and provides structuring capabilities that allows information to be retrieved and accessed. EENs are particularly well suited for capturing engineering design information. They eliminate some of the impediments that are imposed by existing systems, such as the inability to record information away from the desk (due to the lack of portability of most documentation systems) and the inability to write and draw quickly (due to keyboard constraints). Furthermore, EENs provide a "pen and paper" like interface that engineers prefer to use and provide the processing capability that engineers need to organize and structure design information.

EENs can also provide benefits to the work environment. "They encourage multi-person interaction by providing a high performance interface that users can carry. Instead of co-workers having to congregate at someone's workstation, interactions can occur more naturally at almost any place in the engineering laboratory. Face-to-face discussions can be augmented with electronic data exchange and markup, data can be retrieved from long-term storage and displayed, and graphs can be plotted on the spur of the moment. What was once verbal communication augmented with hand gestures becomes an opportunity for sharing visual information" - [Marsh 93].

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Appendix A

Table 21: Experimental Time Data: 4 mediums, 3 tasks, and 12 subjects

SubjectID	Medium	Task1 (sec)	Task2 (sec)	Task3 (sec)
S01	A	101	39	11
	B	111	33	13
	C	125	41	11
	D	88	53	10
S02	A	79	51	14
	B	81	55	11
	C	85	47	18
	D	64	44	10
S03	A	103	63	14
	B	126	58	17
	C	130	52	21
	D	107	60	12
S04	A	117	197	15
	B	115	111	28
	C	146	167	19
	D	82	52	12
S05	A	109	91	12
	B	109	77	15
	C	107	69	14
	D	89	79	11
S06	A	114	100	12
	B	121	83	14
	C	131	71	17
	D	94	86	13
S07	A	90	65	11
	B	89	59	11
	C	94	66	16
	D	62	49	10
S08	A	72	101	24
	B	81	106	23
	C	88	67	20
	D	65	67	15
S09	A	82	78	10
	B	98	75	25
	C	93	63	21
	D	72	57	12
S10	A	105	109	13
	B	98	78	12
	C	113	70	16
	D	76	87	11
S11	A	89	27	11
	B	76	25	15
	C	88	29	12
	D	72	32	11
S12	A	95	84	12
	B	107	53	13
	C	113	80	13
	D	75	69	11

Appendix B

Table 22: Experimental Sketch Ratings: 4 mediums, 1 task, 12 subjects, 3 judges, and 4 quality measures

Subjects	Medium	J 1				J 2				J 3			
		O	S	G	N	O	S	G	N	O	S	G	N
S01	A	2	2	3	3	4	4	3	4	3	4	4	3
	B	2	2	2	2	2	2	1	2	4	2	3	4
	C	1	2	3	2	1	1	2	2	1	3	1	1
	D	3	3	2	3	4	4	3	4	3	5	3	3
S02	A	2	2	2	2	4	3	4	3	4	4	4	3
	B	2	2	3	2	2	2	2	2	3	4	2	4
	C	2	3	2	2	2	3	3	3	1	3	1	1
	D	3	3	3	4	3	4	4	3	4	5	3	4
S03	A	3	3	2	3	4	5	3	4	4	4	5	4
	B	2	3	2	2	4	3	4	3	4	4	5	4
	C	1	2	2	2	2	1	2	2	2	3	2	1
	D	4	4	3	3	4	5	4	3	4	5	5	5
S04	A	4	5	3	4	4	5	4	5	5	5	4	5
	B	3	3	3	3	4	3	5	3	3	4	3	4
	C	3	2	3	3	2	3	1	2	3	3	3	4
	D	3	4	3	2	3	4	3	2	5	5	4	3
S05	A	2	3	2	3	2	3	4	3	3	4	3	4
	B	2	2	2	3	3	3	2	2	4	4	3	3
	C	1	2	1	1	1	2	1	1	2	3	1	2
	D	2	2	2	2	2	2	2	3	3	4	2	4
S06	A	3	2	2	3	4	4	2	3	4	4	3	4
	B	3	3	2	3	2	4	2	3	4	4	3	3
	C	2	2	2	2	3	2	1	1	3	3	2	3
	D	4	5	3	5	5	5	4	4	5	5	5	5
S07	A	3	3	3	4	3	4	3	3	4	4	3	5
	B	2	3	2	3	3	3	2	2	4	4	3	4
	C	1	2	2	1	1	1	1	1	2	3	1	1
	D	4	5	3	4	4	4	3	3	5	5	4	4
S08	A	3	4	3	3	3	3	2	3	4	4	4	4
	B	2	2	3	3	2	1	1	3	4	3	4	4
	C	1	2	2	2	3	2	3	1	2	2	3	3
	D	2	3	3	3	3	4	3	3	3	4	4	4
S09	A	3	4	2	3	4	5	2	4	4	5	4	4
	B	3	4	3	3	2	4	2	3	4	4	3	3
	C	3	3	2	2	2	2	3	1	3	4	2	3
	D	3	4	2	4	4	4	3	5	5	5	5	5
S10	A	2	3	2	4	3	3	2	3	5	4	4	5
	B	2	3	2	2	1	3	2	3	4	3	3	4
	C	1	3	2	2	1	2	2	2	2	1	2	3
	D	3	3	3	3	4	4	5	4	3	4	3	2
S11	A	2	3	3	2	3	3	4	3	3	4	3	2
	B	2	2	1	2	2	3	2	3	2	4	2	3
	C	1	1	1	2	1	2	1	2	1	3	1	1
	D	3	3	4	4	5	4	5	4	4	4	4	3
S12	A	2	3	3	3	4	4	3	4	3	2	3	3
	B	2	2	1	3	3	3	4	3	3	4	3	3
	C	1	1	2	2	1	1	2	1	1	1	2	1
	D	4	4	3	4	4	5	4	4	5	5	4	5

Appendix C

Table 23: Averaged Ratings of the 12 subjects given by the 3 judges:

Quality Measures	Medium	J1	J2	J3
O	A	2.6	3.5	3.8
	B	2.3	2.5	3.6
	C	1.5	1.7	1.9
	D	3.2	3.8	4.1
S	A	3.1	3.8	4.0
	B	2.6	2.8	3.7
	C	2.1	1.8	2.7
	D	3.6	4.1	4.7
G	A	2.5	3.0	3.7
	B	2.2	2.4	3.1
	C	2.0	1.8	1.8
	D	2.8	3.6	3.8
N	A	3.1	3.5	3.8
	B	2.6	2.7	3.6
	C	1.9	1.6	2.0
	D	3.4	3.5	3.9

Appendix D

Table 24: Task 2 Data: experimental time data vs. sketch ratings

SubjectID	Task 2 (sec)	O (1-5)	S (1-5)	G (1-5)	N (1-5)	AVG (1-5)
S01	39	3.0	3.3	3.3	3.3	3.25
S02	51	3.3	3.0	3.3	2.7	3.08
S03	63	3.7	4.0	3.3	3.7	3.67
S04	197	4.3	5.0	3.7	4.7	4.42
S05	91	2.3	3.3	3.0	3.3	3.00
S06	100	3.7	3.3	2.3	3.3	3.17
S07	65	3.3	3.7	3.0	4.0	3.50
S08	101	3.3	3.7	3.0	3.3	3.33
S09	78	3.7	4.7	2.7	3.7	3.67
S10	109	3.3	3.3	2.7	4.0	3.33
S11	27	2.7	3.3	3.3	2.3	2.92
S12	84	3.0	3.0	3.0	3.3	3.08
S01	33	2.7	2.0	2.0	2.7	2.33
S02	55	2.3	2.7	2.3	2.7	2.50
S03	58	3.3	3.3	3.7	3.0	3.33
S04	111	3.3	3.3	3.7	3.3	3.42
S05	77	3.0	3.0	2.3	2.7	2.75
S06	83	3.0	3.7	2.3	3.0	3.00
S07	59	3.0	3.3	2.3	3.0	2.92
S08	106	2.7	2.0	2.7	3.3	2.67
S09	75	3.0	4.0	2.7	3.0	3.17
S10	78	2.3	3.0	2.3	3.0	2.67
S11	25	2.0	3.0	1.7	2.7	2.33
S12	53	2.7	3.0	2.7	3.0	2.83
S01	41	1.0	2.0	2.0	1.7	1.67
S02	47	1.7	3.0	2.0	2.0	2.17
S03	52	1.7	2.0	2.0	1.7	1.83
S04	167	2.7	2.7	2.3	3.0	2.67
S05	69	1.3	2.3	1.0	1.3	1.50
S06	71	2.7	2.3	1.7	2.0	2.17
S07	66	1.3	2.0	1.3	1.0	1.42
S08	67	2.0	2.0	2.7	2.0	2.17
S09	63	2.7	3.0	2.3	2.0	2.50
S10	70	1.3	2.0	2.0	2.3	1.92
S11	29	1.0	2.0	1.0	1.7	1.42
S12	80	1.0	1.0	2.0	1.3	1.33
S01	53	3.3	4.0	2.7	3.3	3.33
S02	44	3.3	4.0	3.3	3.7	3.58
S03	60	4.0	4.7	4.0	3.7	4.08
S04	52	3.7	4.3	3.3	2.3	3.42
S05	79	2.3	2.7	2.0	3.0	2.50
S06	86	4.7	5.0	4.0	4.7	4.58
S07	49	4.3	4.7	3.3	3.7	4.00
S08	67	2.7	3.7	3.3	3.3	3.25
S09	57	4.0	4.3	3.3	4.7	4.08
S10	87	3.3	3.7	3.7	3.0	3.42
S11	32	4.0	3.7	4.3	3.7	3.92
S12	69	4.3	4.7	3.7	4.3	4.25

Appendix E

Table 25: Writing Task -EEN (A) vs. 4x3 EEN(B)

T1	A	B
S01	101	111
S02	79	81
S03	103	126
S04	117	115
S05	109	109
S06	114	121
S07	90	89
S08	72	81
S09	82	98
S10	105	98
S11	89	76
S12	95	107

t-Test: Paired Two-Sample for Means	A	B
Mean	96.3333	101
Variance	203.152	273.455
Observations	12	12
Pearson Correlation	0.79417	
Pooled Variance	187.182	
Hypothesized Mean Difference	0	
df	11	
t	-1.5988	
P(T<=t) one-tail	0.06909	
t Critical one-tail (alpha .05)	1.7959	

Table 26: Reading Task - EEN (A) vs. 4x3 EEN(B)

T3	A	B
S01	11	13
S02	14	11
S03	14	17
S04	15	28
S05	12	15
S06	12	14
S07	11	11
S08	24	23
S09	10	25
S10	13	12
S11	11	15
S12	12	13

t-Test: Paired Two-Sample for Means	A	B
Mean	13.25	16.4167
Variance	13.6591	32.9924
Observations	12	12
Pearson Correlation	0.39719	
Pooled Variance	8.43182	
Hypothesized Mean Difference	0	
df	11	
t	-2.0099	
P(T<=t) one-tail	0.0348	
t Critical one-tail (alpha .05)	1.7959	

Table 27: Sketching Task - EEN (A) vs. 4x3 EEN(B)

T2	A	B
S01	3.3	2.3
S02	3.1	2.5
S03	3.7	3.3
S04	4.4	3.4
S05	3.0	2.8
S06	3.2	3.0
S07	3.5	2.9
S08	3.3	2.7
S09	3.7	3.2
S10	3.3	2.7
S11	2.9	2.3
S12	3.1	2.8

t-Test: Paired Two-Sample for Means	A	B
Mean	3.36806	2.82639
Variance	0.16851	0.1281
Observations	12	12
Pearson Correlation	0.77953	
Pooled Variance	0.11453	
Hypothesized Mean Difference	0	
df	11	
t	7.21952	
P(T<=t) one-tail	8.5 E-06	
t Critical one-tail (alpha .05)	1.7959	

Appendix F

Table 28: Writing Task - 4x3 EEN (B) vs. Newton (C)

T1	B	C
S01	111	125
S02	81	85
S03	126	130
S04	115	146
S05	109	107
S06	121	131
S07	89	94
S08	81	88
S09	98	93
S10	98	113
S11	76	88
S12	107	113

t-Test: Paired Two-Sample for Means	B	C
Mean	101	109.417
Variance	273.455	411.174
Observations	12	12
Pearson Correlation	0.89251	
Pooled Variance	299.273	
Hypothesized Mean Difference	0	
df	11	
t	-3.1425	
P(T<=t) one-tail	0.00937	
t Critical one-tail (alpha .05)	1.7959	

Table 29: Reading Task - 4x3 EEN (B) vs. Newton (C)

T3	B	C
S01	13	11
S02	11	18
S03	17	21
S04	28	19
S05	15	14
S06	14	17
S07	11	16
S08	23	20
S09	25	21
S10	12	16
S11	15	12
S12	13	13

t-Test: Paired Two-Sample for Means	B	C
Mean	16.4167	16.5
Variance	32.9924	11.9091
Observations	12	12
Pearson Correlation	0.59392	
Pooled Variance	11.7727	
Hypothesized Mean Difference	0	
df	11	
t	-0.0625	
P(T<=t) one-tail	0.95131	
t Critical one-tail (alpha .05)	1.7959	

Table 30: Sketching Task - 4x3 EEN (B) vs. Newton (C)

T2	B	C
S01	2.3	1.7
S02	2.5	2.2
S03	3.3	1.8
S04	3.4	2.7
S05	2.8	1.5
S06	3.0	2.2
S07	2.9	1.4
S08	2.7	2.2
S09	3.2	2.5
S10	2.7	1.9
S11	2.3	1.4
S12	2.8	1.3

t-Test: Paired Two-Sample for Means	B	C
Mean	2.82639	1.89583
Variance	0.1281	0.19713
Observations	12	12
Pearson Correlation	0.49957	
Pooled Variance	0.07939	
Hypothesized Mean Difference	0	
df	11	
t	7.90102	
P(T<=t) one-tail	7.4E-06	
t Critical one-tail (alpha .05)	1.7959	