ABSTRACT

Title of Document: PAPIERCRAFT: A PAPER-BASED INTERFACE TO SUPPORT INTERACTION WITH DIGITAL DOCUMENTS

Chunyuan Liao, Ph.D, 2009

Directed By: Associate Professor, François Guimbretière, Department of Computer Science

Many researchers extensively interact with documents using both computers and paper printouts, which provide an opposite set of supports. Paper is comfortable to read from and write on, and it is flexible to be arranged in space; computers provide an efficient way to archive, transfer, search, and edit information. However, due to

the gap between the two media, it is difficult to seamlessly integrate them together to optimize the user's experience of document interaction.

Existing solutions either sacrifice inherent paper flexibility or support very limited digital functionality on paper. In response, we have proposed PapierCraft, a novel paper-based interface that supports rich digital facilities on paper without sacrificing paper's flexibility. By employing the emerging digital pen technique and multimodal pen-top feedback, PapierCraft allows people to use a digital pen to draw gesture marks on a printout, which are captured, interpreted, and applied to the corresponding digital copy. Conceptually, the pen and the paper form a paper-based computer, able to interact with other paper sheets and computing devices for operations like copy/paste, hyperlinking, and web searches. Furthermore, it retains the full range of paper advantages through the light-weighted, pen-paper-only interface. By combining the advantages of paper and digital media and by supporting the smooth transition between them, PapierCraft bridges the paper-computer gap.

The contributions of this dissertation focus on four respects. First, to accommodate the static nature of paper, we proposed a pen-gesture command system that does not rely on screen-rendered feedback, but rather on the self-explanatory pen ink left on the paper. Second, for more interactive tasks, such as searching for keywords on paper, we explored pen-top multimodal (e.g. auditory, visual, and tactile) feedback that enhances the command system without sacrificing the inherent paper flexibility. Third, we designed and implemented a multi-tier distributed infrastructure to map pen-paper interactions to digital operations and to unify document interaction on paper and on computers. Finally, we systematically evaluated PapierCraft through three lab experiments and two application deployments in the areas of field biology and e-learning. Our research has demonstrated the feasibility, usability, and potential applications of the paper-based interface, shedding light on the design of the future interface for digital document interaction. More generally, our research also contributes to ubiquitous computing, mobile interfaces, and pen-computing.

PAPIERCRAFT: A PAPER-BASED INTERFACE TO SUPPORT INTERACTION

WITH DIGITAL DOCUMENTS

By

Chunyuan Liao

Dissertation submitted to the Faculty of the Graduate School of the
University of Maryland, College Park, in partial fulfillment
of the requirements for the degree of
Doctor of Philosophy
2009

Advisory Committee:

Associate Professor, François Guimbretière, Chair
Associate Professor, Ben Bederson
Associate Professor, Matt Kirschenbaum
Associate Professor, Pete Keleher
Professor, Amitabh Varshney

Acknowledgements

I would like to appreciate many people who have helped me through these years to finally finish this dissertation. It would not be possible without their cordial and generous support.

Without doubt, my advisor, François Guimbretière, is the very person who has the most impact on my work presented in this dissertation, and more importantly, on my research journey exploring truths of the world. Among numerous things that I learned from him is the serious and rigorous attitude to science. “Obey Science” is the motto stamped on every book that he owns. Thanks to the role model by François, the motto has gradually become a part of my principle of life. Another thing that impressed me very much is his pursuit of perfection. Although it is not easy, some times quite painful, to push to one’s limit for better outcome, such efforts will eventually be rewarded with the relief and happiness rising from the external recognition and internal self-affirmation. The English maxim “no pains, no gains” or its Chinese counterpart 不劳无获 holds here. It has been a great experience working with François in the past five years, and I believe such experience will continue to shape my career and personal life into the future. Thank you, François!

I also would like to thank my committee members. Pete Keleher knew me long time ago, and, as an experienced faculty, has helped me go through the procedure of the preliminary examination, dissertation defense and revision. Ben Bederson paid a lot of attention to my dissertation and gave many insightful comments and suggestions, which greatly improve the quality of this work. Matt Kirschenbaum brought me fresh views about how techniques and humanities interact with and impact each other, which made me think more about innovations in a broader context. Amitabh Varshney is always nice and ready to help. His kindness and encouragement have made my life easier at the last stage in school.

Although officially Bobby Bhattacharjee is not in my committee, he helped me a lot find research directions, especially introduce me to my advisor Francois. I am very grateful to him. And I would truly appreciate Corinna Loeckenhoff. Her expertise in the psychology data analysis and English writing has helped ground this dissertation on solid and perspicuous scientific analysis.

I was very lucky to work with many excellent researchers in the HCI community. As two HCI veterans, Jim Hollan at UCSD and Ken Hinckly at Microsoft Research have collaborated with Francois and me for several years. We share the strong interests in interactive paper and, more broadly, bringing physical and digital worlds together. Jim and Ken's insightful thoughts and rich experiences in this field have inspired me in many ways. I also want to thank Jim's research assistants, Ron Stanonik, Timothy Sohn, Kevin Li, Brynn Evans, Roshni Malani and Jill Iwasaki, who helped deploy PapierCraft at UCSD and were extremely patient with the annoying software bugs.

Moreover, for the project ButterflyNet, I was honored to work with Scott Klemmer, Ron Yeh, Brian Lee, Boyko Kakaradov, Jeannie Stamberger and Andreas Paepcke at Stanford University. Scott and Ron spent much time with me discussing the interface design, prototype implementation and user study. It was particularly memorable for Ron and me to work at the Jasper Ridge Biological Preserve, with mosquitoes and bugs accompanying us in the sleepless summer nights. For the project

PaperCP, I was lucky to get a chance to work with Richard Anderson, Natalie Linnell, Craig Prince and Valentin Razmov at University of Washington. It was amazing how we could successfully collaborate remotely cross the country, without ever meeting face to face. I appreciate their great help in building and deploying PaperCP.

I am thankful to my fellow students too. My officemates, Hyunyoung Song, Nick Chen, Chang Hu, Alex Quinn and Morgan Dixon brought me lots of fun in the somehow long boring Ph.D. student life, and of course much help on various projects. Dave Levin built the original PADD system, one of the key supporting techniques for my dissertation project. And Yit Phang Khoo helped implement the first version of the multimodal feedback pen. Without their generous help, I might have had to struggle for a longer time.

Finally, from the bottom of my heart, I cherish the endless love, understanding, encouragement and support from my wife, Mei Huang, my parents, Guocong Wang and Zuode Liao, and my sister, Qiu Liao. They are truly the source of my happiness, courage and confidence in every day. I love you all!

This work is supported by Microsoft Research (as part of the Microsoft Center for Interaction Design and Visualization at the University of Maryland) and NSF under Grant IIS-0414699 and IIS-00447730. I would like to thank Anoto for their support with streaming pattern space, Logitech for streaming software, HP and the Lee company for hardware donations.

Portions of this dissertation were originally published by me and my colleagues. The specific involved sections include

Chapter 4, which is based on [Liao, et al. 2005] and [Liao, et al. 2008]

Chapter 5 and Section 6.1, which are based on [Liao, et al. 2006]

Section 7.1, which is based on [Ron, et al. 2006] and

Section 7.2, which is based on [Liao, et al. 2007].

Again, I thank all the co-authors (in alphabetic order), including Richard Anderson, François Guimbretière, Jim Hollan, Ken Hinckley, Boyko Kakaradov, Scott Klemmer, Brian Lee, Corinna Loeckenhoff, Natalie Linnell, Andreas Paepcke, Craig Prince, Valentin Razmov, Jeannie Stamberger and Ron B. Yeh, for their wonderful work toward these papers and this dissertation.

Table of Contents

The List of Tables

The List of Figures

Chapter 1: Introduction

Both paper and computers are widely used by people to interact with digital documents [Sellen and Harper, 2001]. This dissertation aims to understand the pros and cons of the two media, and to explore novel interaction techniques to combine them for a better user experience.

1.1 Problem Definition

Interaction with digital documents is an everyday activity to knowledge workers, such as researchers, lawyers, graduate students, and IT professionals, who analyze information within specific subjects, define problems, design and/or develop solutions [Adler, et al., 1998, Sellen and Harper, 2001]. A typical example of such interaction is Active Reading [Adler and Van Doren, 1972], which is a combination of reading with critical understanding and thinking. Active Reading usually consists of a series of read-understand-act cycles: People first read a document segment, try to understand the meaning, and then perform follow-up actions, such as annotation and note-taking, to reflect their own thoughts about the document. After that, they move on to the next segment for another cycle.

Looking into the Active Reading cycles, we find a set of sub-tasks which should be well supported for a good user experience. First of all, *reading* itself is the primary activity, for which high display resolution and contrast are two key factors. Active readers often *write* down annotations or notes, which are very useful for helping readers to concentrate on thinking, to re-visit the content later or to organize information [Adler and Van Doren, 1972]. Therefore, it is important to *capture and* *archive* these reader outputs. Unlike casual reading of novels, knowledge workers' active reading is often non-linear, and they often *browse* or *navigate* back and forth among sections and pages, to find specific content or to compare several different segments. For this purpose, flexible spatial arrangement of the documents is helpful for readers to quickly access and organize the documents [Mander, et al., 1992].

From a broader view, reading is often a part of document composition such as writing a summary [Adler, et al., 1998]. Information obtained from reading is *transferred*, digested, and synthesized into the new document. The copy/paste command is frequently used for this purpose [Morris, et al., 2007]. Further, it is also a key part of *retrieving external information*—e.g., finding additional documents that are complementary to the on-going reading via Web-search, dictionaries, or digital libraries. That is because the initial documents are usually not self-contained, and the reader needs, for example, extra references and details for some content in the documents [Norrie and Signer, 2003]. For these activities that are closely related to specific segments of the reading material, performing operations *in situ* is important to help users focus on the ongoing reading without the distraction of eye-focus switching between different displays [Hinckley, et al., 2007].

While examining available displays for the above sub-tasks, it is very interesting to note that, even in this age of computers, paper is still extensively used in conjunction with computers by knowledge workers [Sellen and Harper, 2001, William Powers, 2007]. This phenomenon can be attributed to paper's unique affordances[1] [Gibson, 1977] that existing computers still cannot match: comfortable

[1] Affordance refers to the functionality set supported by an object like paper or a computer.

reading and writing, flexibility to spread out on a desk for easy navigation, robustness, endless battery life, nearly ubiquitous availability, "always-on" accessibility, and wide acceptance in social settings [Sellen and Harper, 2001]. Nevertheless, paper does not provide powerful digital functions that are usually available only via computers, including rich editing facilities, in situ data manipulation like data copy/paste [Morris, et al., 2007], user input capturing and archiving [Schilit, et al., 1998], Web search facilities for finding external information [Hinckley, et al., 2007], and easy remote sharing and collaboration [Hardock, et al., 1993]. As a result, people tend to mix the use of paper and computers in the life cycle of digital documents. For example, many users begin with editing a digital document on a computer, then read and annotate its hard copy, and finally update and share the document on computers again.

However, this simple mixing does not work well, due to ***the gap between paper and computers***, in other words, their asymmetric roles in interacting with digital documents. At a lower level, although it is rather easy to bring information from computers to paper through printing, it is more difficult to bring information created on paper back to computers. Traditional capture methods, like scanning [Heiner, et al., 1999] and taking pictures with a camera, require extra time-consuming tasks besides reading, so are usually inefficient. Real-time video tracing [Wellner, 1993] might alleviate this issue, but the system setup and configuration are complex, and precise tracing with various light conditions and paper bending distortions still remain a challenge [Wilson, 2005].

At a higher level, unlike computers, paper usually does not have command systems; thus it is hard for a system to capture semantic information created during paper interaction or to perform digital functions, like copy/paste and keyword-search, which are very useful in working with digital documents. As a result, knowledge workers are left with three options, all inconvenient: If they work exclusively with paper (probably very few people do now), then they must give up the powerful digital utilities. If they do all their work on computers, they lose the flexibility of paper. Finally, if they endeavor to switch back and forth between the two media, they suffer much distraction.

1.2 Overview of Existing Solutions

The literature indicates that people try to address the paper-computer gap in two main directions. The first one is to simulate paper with computers. One step toward this goal are tablet-PC-based systems like XLibris [Schilit, et al., 1998], OneNote [Microsoft, 2003] and InkSeine [Hinckley, et al., 2007]. These systems allow people to annotate or take notes using a stylus on the screen. Although the systems demonstrate how the digital functions can facilitate Active Reading with efficient in situ operations like capturing, archiving, and search, they are still not competitive with paper in terms of screen resolution and contrast or display flexibility and robustness. Given the limitations of the existing computer interfaces and the unique advantages of paper, we believe that paper will continue to be used in conjunction with computers in the foreseeable future, and the two media should complement each other in supporting human-digital-document interaction [Sellen and Harper, 2001, William Powers, 2007]. Thus, this dissertation focuses on the second research direction, namely bringing digital functions to physical paper.

The literature portrays several tracks in this direction. First, systems like Digital Desk [Wellner, 1993] and Play Anywhere [Wilson, 2005] adopt carefully calibrated cameras and projectors to track and *augment* paper with projected digital content. Second, systems such as Intelligent Paper [Dymetman and Copperman, 1998] and Paper++ [Norrie and Signer, 2003]) employ a separate screen to render multimedia associated to hotspots on paper documents, achieving paper-computer *coordination*. Third, PaperPDA [Heiner, et al., 1999] and the like use paper as a *form-filling* tool, which extracts user input from the scanned forms and then performs user-specified actions, such as emailing or faxing. Fourth, Anoto [Anoto] uses a fountain-pen-like digital pen to trace user input in real time on paper with special dot patterns in the background. Using this technique, Fly Pen [LeapFrog, 2005] and LiveScribe [LiveScribe, 2007] allow users to interact with *pre-defined documents* by using a digital pen to draw or tap within designer-specified areas on paper.

The Anoto technique actually opened the door to the fifth track, which aims to establish a *co-habitation* relationship between paper and computers. With this technique, systems such as PADD [Guimbretiere, 2003] capture readers' freeform annotations on printouts and automatically merge them into the original digital copy. This actually enables paper to behave like a standalone computer interface for document manipulation, with no reliance on other computers (the back-end data processing still needs computers, but the interaction does not). As a result, users can choose either paper or computers to interact with digital documents. In other words, paper and computers play symmetric roles in such tasks. It well fits the issue of "paper-computer-gap" in Active Reading, therefore has been taken as our approach.

However, lack of an expressive and flexible command system, PADD can hardly capture the precise semantic of user inputs created during reading, or support digital functions beyond annotating. Toward the "co-habitation" goal, we have extended PADD by proposing PapierCraft, a pen-gesture-based command system well geared to paper.

1.3 Overview of PapierCraft

To address the paper-computer asymmetry issue, PapierCraft adopts a command system to capture readers' intention or semantic information. With the command system, a reader can explicitly select a target (e.g., a keyword, a paragraph or a figure) and choose an action (e.g., create hyperlinks or do a Web search), optionally with some parameters. Compared with non-command-system approaches such as automatic user intention inference from free-form user behavior [Sousa and Garlan, 2002, Wasson, et al., 2003], the manual command systems are much more robust, and therefore has been extensively adopted by most existing computer interfaces [Buxton, 1987]. PapierCraft extends this idea from conventional computers to paper.

We take pen gestures as the input of the command system, since pen gestures can be easily interwoven with free form annotations in Active Reading. Such an approach has been adopted by many computer-based interfaces like FlowMenu for wall-size displays [Guimbretière and Winograd, 2000] and Scriboli for Tablet PCs [Hinckley, et al., 2005]. We borrowed the idea of using pen gestures for PapierCraft.

With the pen-gesture command system, PapierCraft features the *Paper Proxy* notion: A printed page acts as a proxy of its corresponding digital copy, so that users can manipulate the digital content through pen interactions on the printout. Figure 1 illustrates this interaction paradigm: People use a digital pen to draw a *copy* gesture on a printed document page. Once the gestures are captured, the system exploits the PADD infrastructure [Guimbretiere, 2003] to retrieve the original digital page. With this digital page as the context, PapierCraft translates the captured strokes into the digital coordinates, and then interprets and executes the gesture commands. For cross-page or cross-device commands like copy-paste, the infrastructure also interacts, on behalf of the printout, with other PapierCraft printouts and/or computing devices.

In such interaction paradigm, the pen-printout alliance behaves as if it were a standalone static-display tablet PC. The pen gestures enables many digital operations on paper, such as copy/paste (see Figure 2), hyperlinking, keyword finding, and Web-search (with a nearby computer screen) [Liao, et al., 2007]. On the other hand, the

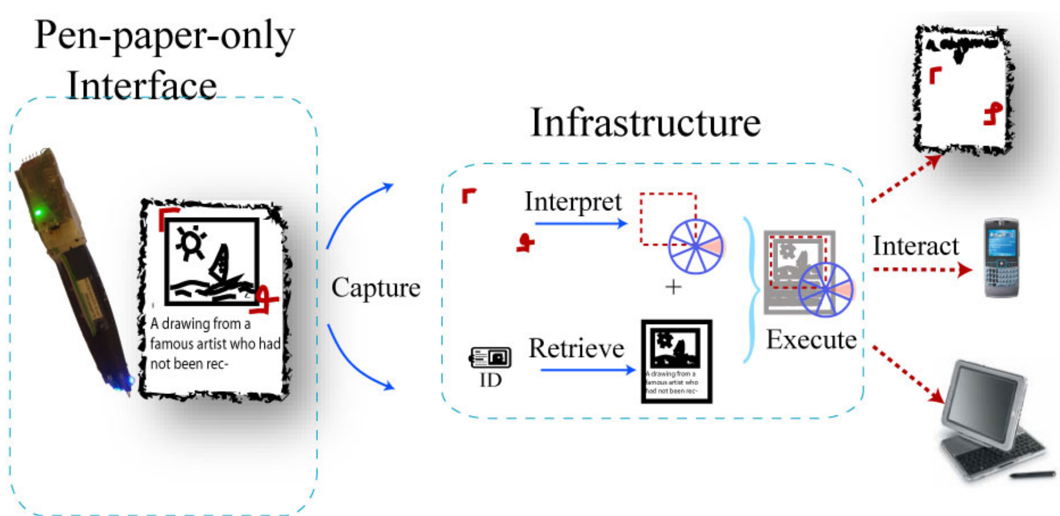


Figure 1. Proposed interaction paradigm in which a digital pen and paper act as a paper-based computer. While a user draws gestures (in red) on the printed document, the strokes and the printed document ID are both *captured*; the corresponding digital copy is *retrieved*, and the pen gesture is *interpreted* as commands to be *executed* within the digital copy; the infrastructure then *interacts* with other devices on behalf of the pen-paper interface.

light-weight interface retains all of paper's flexibility, which well supports reading, writing, navigating, and spatial arrangement. Therefore, we believe our design can smooth the information flow and reduce the asymmetry between paper and computers.

1.4 Contributions

We contribute to existing research by demonstrating the feasibility and usability of a pen-paper-only interface. In particular, we contribute in four aspects: namely, a *pen-gesture based command system well geared for paper*, an *infrastructure* enabling the interface, a set of *pen-top multimodal feedback* to support the command system, and an *empirical evaluation* of the system.

1.4.1 Pen-gesture Based Command System for Paper

The number one challenge in PapierCraft design is the paper's passiveness. Although this issue can be addressed by using devices like the projector of DigitalDesk [Wellner, 1993] which projects dynamic content on paper, such devices are often not present or accessible, not portable, or not precise and robust [Wilson, 2005]. An alternative way is to employ a separate PDA or cell phone, as in Paper++ [Norrie and

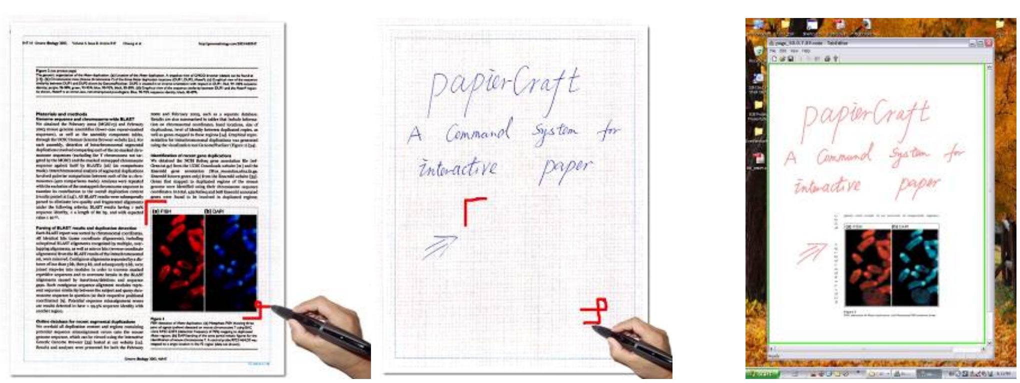


Figure 2. Copy/Paste Interaction in PapierCraft. A picture is copied from a printout (left), then pasted to a note (center). The result is shown on the PapierCraft viewer after pen synchronization (right). Marks are highlighted for clarity. Page taken from an Open Access document http://genomebiology.com/2003/4/8/R47 © 2003, Cheung et al. Used with permission.

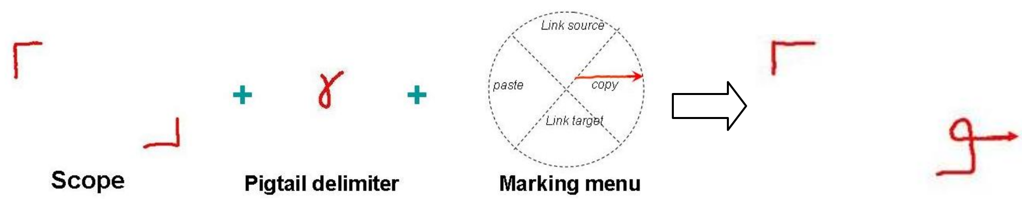


Figure 3 The basic components of a PapierCraft command—scope, delimiter and type—which can be drawn in one single stroke.

Signer, 2003], to render the dynamic information related to paper interactions, but this approach falls short of supporting in situ manipulations, and users have to switch eye focus between the paper and the screens. Given this situation, we focused on the ink left on paper and the pen to overcome the passiveness issue.

We started our investigation by using pen ink as a means of feedback. As Figure 3 illustrates, PapierCraft gestures are designed in such a way that they are self-explanatory, without any other feedback. In the basic mode, the system is able to work without any extra input other than the ink left on paper (Figure 2). The idea of self-explanatory gestures was borrowed from existing pen-gesture commands on computers such as Marking menus [Kurtenbach, 1993] and Scriboli [Hinckley, et al., 2005], which use the direction of a gesture mark to select a menu item without any other feedback. PapierCraft is the first such system to extend this kind of gesture commands to a paper-based interface.

PapierCraft highlights "late-interaction-binding", in that it allows end users to manipulate arbitrary document segments (e.g. any words and figures), with no constraints set by the application designers or manufacturers. This fine-grained manipulation is important for Active Reading, which requires the flexibility for readers to freely organize and manipulate any contents in order to understand the details. This feature distinguishes PapierCraft from other existing paper-based interfaces like PaperPDA [Heiner, et al., 1999], Fly Pen [LeapFrog, 2005] and

LiveScribe Pen[LiveScribe, 2007]. They just support "early-interaction-binding", since end users can only interact with pre-defined document segments such as hot spots in a map, but not select an arbitrary set of text lines or a part of a figure for copy/paste.

Furthermore, to choose a specific action applied to the selected document segment, PapierCraft users directly draw a marking menu following the scope gestures, in contrast to tapping a separate printed button slip as used by Anoto [Anoto, 2002], Fly Pen [LeapFrog, 2005] and LiveScribe Pen [LiveScribe, 2007]. This feature makes the command issuing more fluid, and leaves on paper visual clues of interaction history, which serves important feedback for the paper-based interface.

1.4.2 Supporting Infrastructure

To make the gesture commands functional on paper, an infrastructure is needed to map the paper strokes to digital ones, to interpret the strokes and to execute pen gestures within the corresponding digital pages. The challenges include how to support increasingly mobile users and mixed-media document interaction. We designed a distributed infrastructure composed of a light-weight client device (e.g., a digital pen and some printouts) and central servers which can be accessed from anywhere on the Internet. For mixed-media interaction, we designed a uniform communication protocol for both paper and computer based interfaces to talk with the central server and exchange data. The idea is similar to Pick&drop [Rekimoto, 1997] and Stitching [Hinckley, et al., 2004], which adopt a central server to monitor user inputs on multiple devices to support cross-screen operations like copy/paste between two computers. Our work extended this idea from the digital world to the physical world. As a result, PapierCraft presents users with a seamless workspace spanning the two worlds and offering easier information flow between paper and computer, and hence the combined advantages of each.

1.4.3 Pen-top Multimodal Feedback

Although the above ink-as-feedback approach works for lots of commands, it is hard for users to explore or recall the menu items, discern real-time system status, and perform interactive tasks like word-finding. To address this situation and explore the potential applications of a mobile feedback mechanism, we have systematically studied multimodal feedback for the pen-paper interface. We believe this to be the first such exploration in the literature.

We identified three feedback categories that are essential to a general computer interface: namely *interface discovery*, *system status indication,* and *application-specific feedback*. Interface discovery feedback, such as a popup menu on a computer, helps a novice user to learn a command system; system status indication feedback, like an icon for the current digital pen color and error messages for gesture recognition, informs users of the status of the current interaction and processing; and application-specific feedback helps accomplish a specific function of an application—for example, feed-back for keyword finding within a document and for dictionary look-up.

The challenge is how to support these categories of feedback in the form factor of a pen, which is required to retain the inherent paper flexibility in a paper based interface such as PapierCraft. Existing paper interfaces like LeapFrog [LeapFrog, 2005] and LiveScribe [LiveScribe, 2007] explored how voice and sounds could be used as feedback, as the hardware can be compact and fit in a pen. Their auditory feedback is expressive and easy to use, but relatively slow because of the linear nature of auditory modality. In the domain of computer interfaces, Haptic Pen [Lee, et al., 2004] takes a solenoid on the pen to provide haptic feedback for button clicks on screens. This feedback is quick to sense and intuitive, but not as expressive as voice.

To further study the pros and cons of different modalities, we have built a multimodal feedback pen as an experimental platform (Figure 4), which is equipped with a hardware button, several LEDs, vibration motors, and simulated voice/sounds. With the feedback pen, we investigated the properties of individual modalities and their combinations, and derived design principles to guide our pen-top feedback for PapierCraft commands [Liao, et al., 2006]. For example, long-time motor vibration or LED flashing should be used parsimoniously to avoid distraction to users; informative but relatively slow voice messages should be reserved for interaction with a long time frame. These principles are applicable not only to PapierCraft, but

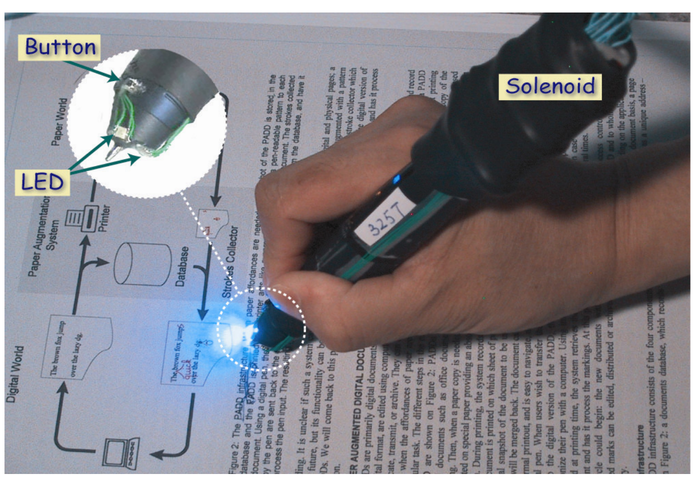


Figure 4: A prototype of the multimodal pen working on paper. It provides pen-top visual, tactile, and auditory feedback through LED around the pen tip, solenoids at the top and an earphone (in this prototype connected to a PC for simulation), respectively. A button is used to switch between ink and gesture mode.

also to other multimodal interfaces like earPod for eye-free menu selection [Zhao, et al., 2007].

1.4.4 Evaluation and Applications

We believe our work to be the first systematic user study in the literature on such a paper-based interface. We evaluated the system at three levels based on the scope of involved user actions—namely *command-component* level, *whole-command* level, and *application* level. Accordingly, our user tests were carried out at each level.

To evaluate PapierCraft in comparison with existing interfaces, we adopted controlled experiments to compare PapierCraft against Tablet PC interfaces in all three level evaluations, and against traditional paper in the *command-component* level and *application* level evaluation. The comparison reveals pros and cons of different interfaces in terms of, for example, display quality, pen-and-gestures design, document navigation, and spatial layout. The findings may give insights for the design of future reading devices.

For more details, at the command-component level, we put particular stress on one of the three components of a PapierCraft gesture (Figure 3), command type selection, and examined the impact of feedback on the command system recall and accuracy. The experiment has successfully shown that the multimodal feedback pen, compared with the non-feedback pen, can not only significantly improve the menu-selection accuracy of expert users, but also significantly encourages error correction of both novice and expert users.

We also evaluated the user experience in accomplishing *whole* commands, which typically consist of three components, namely command scope, delimiter, and type (Figure 3). The experiment was placed in the context of Active Reading tasks, and the results demonstrate that after some training (~30min), average users can grasp PapierCraft gestures and achieve a skill level comparable to that with a Tablet PC interface.

At the application level, we compared PapierCraft with a normal paper-based interface and a dual Tablet PC-based one in a read-summary-quiz scenario, to test how the system can be used in real-life Active Reading tasks. The results suggest the positive effect of two main design factors, paper affordances and in situ digital functions, on the user experience. And these two factors contribute to the advantages of PapierCraft, which retains a full range of paper affordances while supporting a flexible pen-gesture command system.

To demonstrate the potential of PapierCraft, we also applied some PapierCraft techniques to specific application fields. For example, in ButterflyNet [Yeh, et al., 2006], we used PapierCraft gestures to help field biologists organize multimedia data centered on paper field notepads. In PaperCP [Liao, et al., 2007], we integrated the PapierCraft infrastructure with an E-learning Classroom Presenter [Anderson, et al., 2003], allowing students to communicate digitally with their instructor through printed handouts. These applications suggest that the paper interface can be combined with computer interfaces in practical systems, and also let us understand more real-life issues in deployment—for example, that error-prone printing is probably the bottleneck of the work flow.

1.5 Broader Impact

Although the focus of this dissertation is on supporting digital document interaction by combining paper and computers, what we have learned in PapierCraft can be adapted to more general fields and can contribute in broader ways.

Our research on paper interfaces is tightly connected with work on ubiquitous computing [Weiser, 1993]. By introducing a digital command system onto paper, we have expanded people's workspaces from size-constrained desktop screens to more open spaces across digital and physical documents. It is a step toward a Ubiquitous Document Environment (UDE), in which people can access documents "anywhere, anytime via any media" [Weiser, 1993].

Our study on pen-top feedback provides design guidelines for general mobile interfaces that have similar weak visual-feedback constraints. For instance, similar tactile feedback can be used to enhance the handheld devices of small screens. As exemplified by EarPod [Zhao, et al., 2007], auditory feedback can be used for eye-free circular menu browsing.

By comparing PapierCraft and Tablet PCs in our experiments, we reaped many design implications and confirmed some previous findings in the literature. For example, the participants complained about the slippery screens and difficult coordination of the button-pressing and gesture-drawing, which indicates a direction for improving the existing Tablet PC interfaces; the varying relative navigation advantage of paper and computers at different quantities of pages suggests a new computer interface adaptive to the involved information amount; and the snippet context issues unveiled in PapierCraft annotation management suggest that a computer interface supporting convenient switching between snippets and their contexts may improve user experiences.

1.6 Dissertation Organization

In the following sections, we first discuss the related work in Chapter 2, giving a road map of efforts in addressing the paper-computer combination problem. In Chapter 3, we discuss digital document interaction and model the interaction with a Personal Document Interaction Space (PDIS). The analysis of the existing techniques for PDIS shows the motivation of PapierCraft.

Then, in Chapters 4 and 5, we present the key design of PapierCraft, including the command system, pen-top feedback, and the infrastructure. Indeed, such organization reflects the information processing in the system: PapierCraft first ***captures*** strokes, ***maps*** them onto corresponding digital pages, and then ***interprets*** the input as commands and annotation. Meanwhile, PapierCraft ***informs*** users of its interface capabilities, system status, and task-specific messages via multimodal feedback. Finally, PapierCraft ***executes*** the commands and manages the digital documents via the infrastructure.

Chapters 6 and 7 evaluate PapierCraft with three lab experiments and applications respectively. Also we discuss some important issues in a real life deployment. Finally, we discuss some future work and conclude the dissertation in Chapter 8.

Chapter 2: Previous Work

We drew upon previous work in several areas: mixed paper-computer interaction, multimodal feedback, pen-gesture commands, and multiple-device interaction.

2.1 Bridging the Paper-Computer Gap

Much research effort has been invested into bridging paper and digital media, which falls into two categories: digital-based approaches and paper-based ones.

The digital-based approaches attempt to simulate paper with computers. Systems like Wang Freestyle [Francik and Akagi, 1989] and MATE [Hardock, et al., 1993] allow users to annotate a document with a stylus on an electronic pad. Xlibris [Schilit, et al., 1998], OneNote [Microsoft, 2003] and InkSeine[Hinckley, et al., 2007] use Tablet PCs to capture and manage users' free-form stylus input, simulating traditional pen-paper practices. While this approach allows ready access to digital functions (e.g., search, recording of interactions, and "linking by inking" [Price, et al., 1998]), many paper affordances, like easy navigation and flexible display layout, are either missing or just insufficiently supported. Large high resolution displays like the Stanford Mural [Guimbretière, et al., 2001] can relieve such problems, but their low portability precludes their use in mobile settings.

The paper-based approaches try to bring digital affordances to physical paper. Figure 5 presents an overview of the literature in this field, in which existing systems can be categorized along three dimensions: namely, "paper-computer coupling," "document content diversity," and "processing mode." The first dimension can be segmented broadly into three bands, known as "Augmented Paper," "Paper-Computer

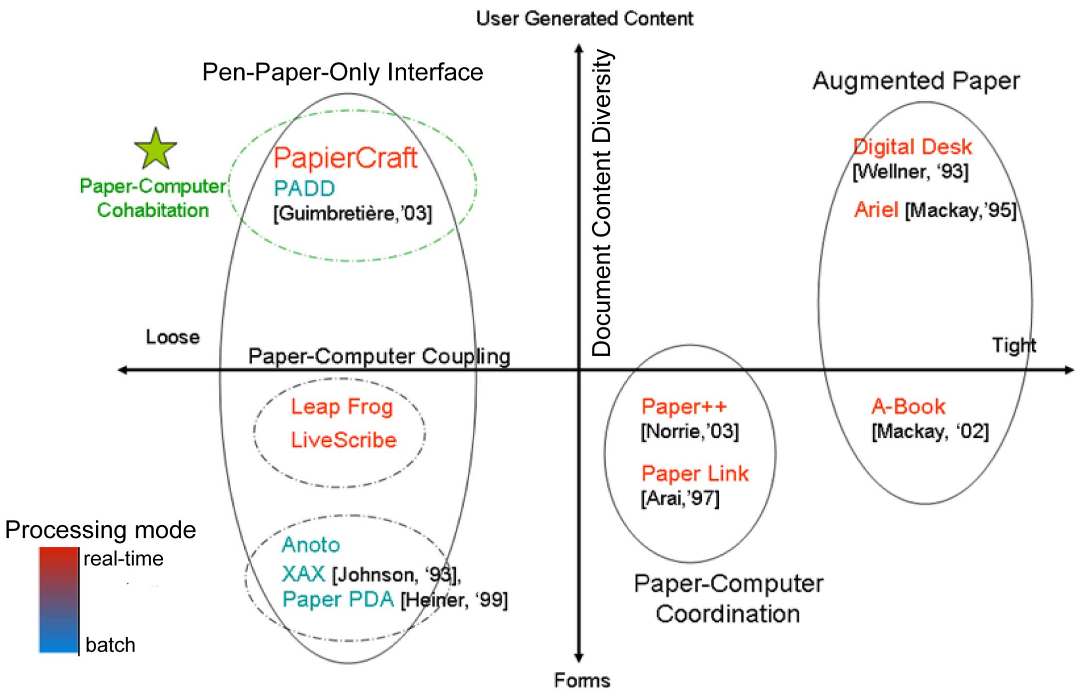


Figure 5. An approximate overview in the space of paper-based bridging. We focus on three dimensions, namely "paper-computer coupling," "document content diversity," and "processing mode."

Coordination," and "Pen-Paper-only Interface," with descending degrees of the paper's dependency on computer interfaces.

The *Augmented Paper* approach uses digital devices to augment physical paper, tightly coupling paper and digital displays. It provides full digital affordances but limited paper affordances. Typical systems include Digital Desk [Wellner, 1993], Video Mosaic [Mackay and Pagani, 1994], Ariel [Mackay, et al., 1995], and EnhancedDesk [Koike, et al., 2000]. They augment paper documents with spatially overlapping digital content by using overhead projectors, and capture users' pen-and-paper interaction with cameras. These systems allow people to use the desk and paper as computer displays and support a full range of digital functions, such as dynamic content rendering. However the complex hardware configuration constrains the paper's portability. A-Book [Mackay, et al., 2002] relieves such hardware constraints by using a PDA placed on top of paper, which renders digital information to augment the paper content underneath. But the A-Book digital interaction relies on the PDA, which may interfere with the existing pen-paper-only practices.

The second approach, *Paper-Computer Coordination,* loosens the paper's reliance on computers from "augmentation" to "coordination," using computer screens and paper side by side. For example, Intelligent paper [Dymetman and Copperman, 1998] and PaperLink [Arai, et al., 1997] use a separate computer monitor to dynamically present predefined content associated to certain regions within paper documents. Paper++ [Norrie and Signer, 2003] and Books-with-Voices [Klemmer, et al., 2003] utilize a portable PDA for similar function. Compared with the "Augmented Paper" approach, this one is more flexible in terms of hardware settings, but the interaction is bound to the extra monitor or PDA, which is not compatible with many existing pen-paper-only activities in document-related tasks.

Our work falls into the third approach, *Pen-Paper-Only Interface*, aiming to retain the full range of paper affordances. The existing research in this direction can be further divided into three folds based on the content diversity of the involved paper documents. In the first fold "Paper Form" systems such as Xax [Johnson, et al., 1993] and PaperPDA [Heiner, et al., 1999] take only paper and pens for an interface of form-filling tasks. Although having all paper affordances, the users need to spend extra time to scan the forms after finishing their tasks on paper and have no way for real time interaction.

To address this issue, recent Anoto [Anoto, 2002] digital pen technique digitizes handwriting while the user drawing on paper, by using a built-in camera to recognize special patterns in the paper background (see Figure 6). Besides the high efficiency in capturing pen strokes, the digital pen can also provides extra information, such as unique IDs of paper sheets and stroke timestamps. These features open the door to a set of powerful pen-paper-only interfaces. These interfaces can be further categorized into two folds, depending on the flexibility of the document content. The first one is called "Pre-defined Interactive Paper", including FlyPen [LeapFrog, 2005] and LiveScribe [LiveScribe, 2007] pen. Users can tap, with the pen, hotspots on paper maps or user-drawn buttons and receive real time feedback. However, the main content of the paper documents is pre-defined by manufacturers or developers. It is too restrictive to be used by knowledge workers in real life.

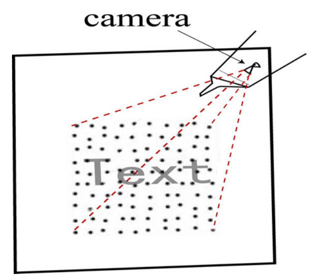


Figure 6, mechanism of the Anoto digital pen: The pen uses a built-in camera to recognize a visually unobtrusive dot pattern in the paper background to trace the pen tip's position within the page coordinates and the unique ID of that piece of paper.

In contrast, systems in another fold "Paper-Computer Cohabitation," like PADD [Guimbretiere, 2003], are able to work on printouts of arbitrary user-specified documents, analogous to a normal computer which may manipulate any user files. PADD exploits Anoto digital pens to associate printed documents with their original digital copies, and then automatically merges users' annotations on paper back to the digital documents. As a result, it puts paper and computers on the same footing in annotating digital documents, and people can choose either media to work on.

Following the steps of PADD, PapierCraft has advanced the concept of "Paper-Computer Cohabitation" by introducing a command system onto paper. It makes available on paper many useful digital document operations, like copy/paste, hyperlinking, Web search, and keyword finding, therefore, improve the user's experience in interaction with digital documents via hardcopies.

2.2 Multimodality Feedback

To provide feedback for a paper interface that is inherently weak in visual feedback, we turn to a broad range of modalities, including tactile, voice, and non-speech sounds, and explore design guidelines to combine them to render feedback for the PapierCraft command system.

Tactile sense allows precise and fast motor control [Geldard, 1960] with low demands on cognitive load (e.g., eye-free) from users [Poupyrev, et al., 2002]. The rendering hardware, like vibration motors and Braille cells [Kyung and Park, 2007], can fit in the form factor of mobile devices, so it is well adapted to PapierCraft's light-weight interface. In the field of tactile feedback mechanisms, Haptic Pen [Lee, et al., 2004] is the closest work to ours. It installs a longitudinal solenoid at the upper end of a pen to enhance button-clicking on a computer. Ambient Touch [Poupyrev, et al., 2002], Haptic Touch screen [Poupyrev and Maruyama, 2003], and Haptic feedback for pen computing [Poupyrev, et al., 2004] instead employ a movable screen (in the direction perpendicular to the screen) to give vibration feedback for specific applications, such as map browsing, painting, and "feeling" GUI elements like buttons. THMB [Luk, et al., 2006] installs piezoelectronic actuators at a side of a handheld device to support tasks like list selection, scrolling and direction signaling.

These applications demonstrate the effectiveness of tactile/haptic feedback and inspire us to adopt it in PapierCraft for warning and simple system status.

Besides the above mobile yet low-fidelity tactile feedback devices, high fidelity ones can be found in systems like haptified GUI [Miller and Zeleznik, 1998] and PC-Access system [Ramstein, et al., 1996]. They use force feedback devices for ambiguity warnings and gesture accuracy. While able to control precisely the force direction, amount, and duration, these devices require a stable base and are too bulky to fit in a pen. So we excluded such configurations in our design.

Voice and sound are widely used in mobile devices due to their eye-free nature, hardware-compactness and expressiveness [Kristoffersen and Ljungberg, 1999]. For example, the Leapfrog FLY pen [LeapFrog, 2005] features an auditory-only interface. It is based on the Anoto technique and can play various sounds/voice when the user taps on printed or user-drawn "buttons" on paper. Although powerful in rendering rich information, the auditory interface is inefficient and distracting for serious tasks by adults. In the literature, Nomadic Radio [Sawhney and Schmandt, 2000] uses a wearable and spatialized audio interface to present email and notifications to mobile users. It demonstrated the usefulness of auditory feedback for personal mobile applications. MOTILE [Kristoffersen and Ljungberg, 1999] studied interface design implications for mobile Computer-Supported Collaborative Work (CSCW) and pointed out the potential use of audio feedback. These works give us insights about using auditory feedback in PapierCraft, such as using voice to present "keyword search" results.

In contrast to voice feedback, non-speech sounds are particularly good for conveying simple and quick messages, such as confirmation or error indication. Systems like ARKOLA [Gaver, et al., 1991] and Mercator [Mynatt and Weber, 1994] have adopted everyday-sounds as "auditory icons" and metaphors for GUI elements and operations, like a "shredder" sound for the "delete" command, which are believed to be easy for users to understand. Currently, PapierCraft does not use many auditory icons, but it would be interesting to explore efficient ways to use such techniques in the future.

2.3 Pen Gesture Commands

PapierCraft drew on research of computer-based pen gesture commands, at both the gesture and the application levels. At the gesture level, special pen strokes are designed to indicate the two basic command components, namely the command type and scope. to specify a command type, researchers have proposed Marking Menu [Kurtenbach, 1993] and later Compounded Marking Menu [Zhao and Balakrishnan, 2004], which identify stroke directions to designate command types. To specify a command scope, CrossY [Apitz and Guimbretiere, 2004] takes a pen stroke across a target (e.g., a menu item or an icon) as the selection gesture, which avoids the inaccuracy of point-and-click interaction with pen-based computer interface.

An immediately related issue is how to naturally concatenate the command type and scope gestures without ambiguity. GEdit [Kurtenbach and Buxton, 1991] uses the position of the ending stroke (relative to the proceeding lasso selecting a command target) of a gesture to indicate the intended action, such as *delete* when ending the stroke inside the lasso or *move* when outside the lasso. Scriboli [Hinckley, et al., 2005] advanced this area by proposing a pigtail as the delimiter between the command scope and the following Marking Menu, which can be drawn in one single stroke fluidly.

Given the common situation where gesture commands are drawn with the same pen as free form annotations, pen mode switching (command vs. annotation) is also an important aspect. Fluid Inking [Zeleznik and Miller, 2006] uses punctuation to indicate gesture strokes. Li [Li, et al., 2005] suggests using a hardware button in the non-dominant hand for pen mode switching. These previous works inspired our design of PapierCraft gestures, such as the lasso selector, the pigtail delimiter, and the hand-written commands.

At the application level, research on pen-based digital document interaction started in the 1980s. For instance, Wang Freestyle [Francik and Akagi, 1989] allows users to annotate a document with a stylus on an electronic pad. MATE [Hardock, et al., 1993] goes further by recognizing users' proofreading marks. These systems combine natural and flexible pen input with powerful digital document processing. PapierCraft goes further by adopting structured gestures on physical surfaces to support more general functions like word-finding. Pen-based input is also extensively used in graphic design and ideation due to its informal and intuitive nature. SILK [Landay and Myers, 1995] and DEMAIS [Bailey, et al., 2001] interpret pen-sketching for quick early-stage interface design on computers. Stanford Mural [Guimbretière, et al., 2001] explores fluid structured pen commands for ideation on wall-size displays. PapierCraft technique could be used to implement some similar functions with physical artifacts, such as Post-it-based ideation on a wall. Such a tangible interface is believed valuable for exploratory and creative tasks [Klemmer, et al., 2001].

2.4 Multiple-Device Interaction

One motivating design model for PapierCraft is to conceptualize each piece of paper as a separate "mobile device" displaying information and capturing users' strokes. From this perspective, the implementation of a "copy and paste across pages" facility for PapierCraft faces technical challenges similar to those confronted in developing distributed interaction techniques to support "copy and paste between mobile devices," such as Pick-and-Drop [Rekimoto, 1997] and Stitching [Hinckley, et al., 2004]. PapierCraft demonstrates how similar forms of interaction can be extended to physical paper interfaces.

Taking printouts as a kind of displays, PapierCraft is similar to that of other fully digital multiple-display systems. UbiTable [Shen, et al., 2003] and Dual-display E-Book Reader [Chen, et al., 2008] emphasize on coordinating multiple displays to maximize spatial flexibility. Pebble [Myers, 2001] commits itself to using a mobile device to interact with conventional PCs. And Impromptu [Biehl, et al., 2008] endeavors to support multiple user coordination in a multiple-display environment. It is interesting to integrate these ideas into PapierCraft in the future.

Of course, PapierCraft is fundamentally different from the above fully digital systems in that it supports mixed-media interaction. From this aspect, PapierCraft bears similarities with the system proposed by Brandl [Brandl, et al., 2008], which forwards user input from Anoto paper to a digital whiteboard and combines input from different media. Rekimoto's Augmented Surfaces [Rekimoto and Saitoh, 1999], is another example of mixed paper-computer systems worthy of notice. The essential difference between PapierCraft and these systems is that PapierCraft allows for loosely-coupled components. For example, the pen-paper interface can continue to function in the basic mode (with batch processing and no multimodal feedback) without any access to a nearby computer.

At the lower level of cross-device communication, PapierCraft borrows ideas from systems handling input/output events among multiple displays and machines. PointRight [Johanson, et al., 2002] allows multiple computers to share a single mouse and keyboard by monitoring and redirecting the input events among computers. GEM [Mansouri-Samani and Sloman, 1997] and SIENA [Carzaniga, et al., 2001] adopt a distributed architecture to monitor network event monitoring, which inspired our design of an event server to coordinate interaction happening on different displays.

Chapter 3: Interaction with Digital Documents

In this age of computers, more and more documents are created, updated, shared, and archived in digital formats. Interaction with digital documents becomes a key part of knowledge workers' lives. There has been a rich literature about human interaction with digital documents in reading and writing [Adler, et al., 1998, Khan, 1993], information retrieval [Rao, et al., 1995], organization [Dourish, et al., 2000, Malone, 1983], and personal information management [Whittaker and Sidner, 1996]. In this dissertation, we focus on using portable computing devices such as digital pens and laptops to support Active Reading [Adler and Van Doren, 1972], the combination of reading with critical thinking.

For a better understanding of general user requirements in Active Reading, we model the typical interaction scenario with a *Personal Document Interaction Space (PDIS)*. It characterizes the typical documents involved in Active Reading, and helps analyze the corresponding interface design space, whose key dimensions include display physical quality and in situ digital functions. By examining the design space and the properties of paper and computers, we are motivated to propose PapierCraft to combine the merits of paper and computers for Active Reading.

3.1 The Personal Document Interaction Space (PDIS) for Active Reading

Active Reading [Adler and Van Doren, 1972] is a procedure mixing reading, deep thinking, and understanding, as well as a set of supporting actions, such as navigation and search. Figure 7 illustrates a typical Active Reading scenario. The involved documents are grouped into four categories based on their functions and related

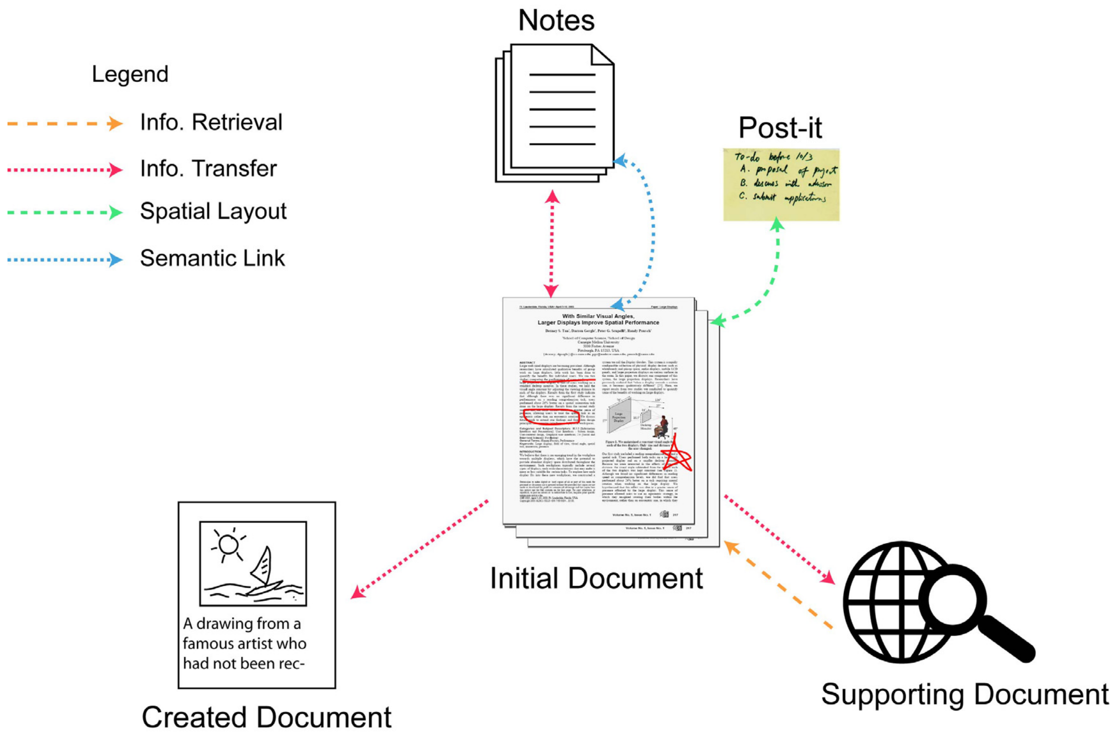


Figure 7. The model of the Personal Document Interaction Space. The arrowed lines are examples of the connections and information flows among documents.

interaction: *initial documents, notes, supporting documents* and *created documents*. By understanding the roles of these different documents in Active Reading, we can have more insights about what features are needed in an interface. Note that an active reader may not use all the four types of documents in a specific session, but we try to characterize all possible important information related to Active Reading in general.

Initial Documents are the primary content from which the reader initiates Active Reading. An example could be technique articles for computer scientists, which can be downloaded from the ACM Digital Library. Many times, the reader may directly mark up the documents to help with reading or re-visiting. To distinguish these marks on the initial documents from those on separate notebooks, we call the former "*annotation*" and the latter "*note,*" like the convention used by XLibris [Schilit, et al., 1998]. A kind of special annotation is Post-it notes, which are not on the initial documents but are physically attached to it, providing complementary information to specific document segments [Sellen and Harper, 2001].

Notes are usually created in blank notebooks separate from the initial documents. The main purpose of notes is to gather and organize information from multiple sources, to record overall comments that do not rely on specific document segments, or simply to avoid contaminating the initial documents [Khan, 1993, Wilcox, et al., 1997].

Supporting Documents refers to a broad category of documents, of which the use is usually not planned ahead but is initiated during reading—for example, a Wikipedia page for an unfamiliar term in the prepared document, a dictionary entry, or another document cited by the initial one. The retrieval procedure for the supporting documents is closely related to information foraging [Pirolli and Stuart, 1995], but here we focus on the interaction techniques to capture and manage information gathered during the read process, not on the retrieval technique.

Created Documents. Sometimes, the purpose of Active Reading is to create a new document, such as a summary, a report, or a survey [Adler, et al., 1998]. These are different from notes, in that the notes are more informal and less structured, and are often used as a *personal* intermediate information buffer or an ideation tool. In contrast, a created document is usually formal and is used to *communicate* with other people. Importantly, the composition procedure is not separate from reading, but often accompanied by re-reading the initial documents and notes, as well as searching for new supporting documents. So it is crucial to integrate seamlessly the use of all these documents.

For simplicity of description, we call the combination of these documents Personal Document Interaction Space (PDIS), in which the reader performs various interactions for Active Reading.

3.2 Key Interactions in Personal Document Interaction Space (PDIS)

To identify the user requirements and key features of an Active Reading interface, we looked into more details of the sub-tasks involved.

Read. During Active Reading, people spend most of the time looking at the initial documents. High resolution, high contrast, thin form-factor, and out-door readable displays are desired for good reading experiences [Sellen and Harper, 2001].

Write. People also write annotations and notes. The writing surface and the pen should be precise to capture user input and comfortable for long-term writing. A closely related issue, then, is how to capture and use the input.

Capture and Archive User Input. A reader in Active Reading is not only a forager of information, but also an active producer. After reading a chunk of information in the document, the reader performs a deep processing of information and often writes some words around the document chunk to express her or his own opinion (e.g, "good!"), to record understanding of the reading material (e.g., "point one, two…."), or to structure information by associating document segments with special symbols or written reference words (e.g, "see also paper XX…."); or the reader may attach a Post-it note to a main document [Adler, et al., 1998, Price, et al., 1998]. The created information has at least two functions. First, some of it is aimed at the reader's later review. For instance, the reminder symbols, written cross references, and spatial organization may form a semantic web [Price, et al., 1998], which is very useful for users to review the documents and quickly re-construct the context of previous Active Reading sessions. Thus, it is important to capture and archive such user input.

Second, different from the review-supporting marks, some annotations (e.g. the opinion word "good!") may serve only as a means for the reader to concentrate on the reading material or to simply indicate what has been skimmed, and will never be read again. However, such markers do imply somewhat important document segments around these annotations [Brush, et al., 2002]. The markers from previous readers can be collected and aggregated to help other first-time readers locate key points and understand the material more quickly. Thus, it is useful to save these annotations too [Marshall, 1997].

An interface to support these kinds of interaction should help users easily capture, manage, and retrieve all the annotations. Without doubt, the digital media has advantages in duplicating, retrieving and processing annotations. One thing to note, though, is that the capturing tools should not distract readers from the central reading task.

Navigate/Browse. Active Reading is not a one-way, linear action. Instead, people often read back and forth, for instance, to review previous pages, to search for specific information, or to compare two segments [Adler and Van Doren, 1972, O'Hara and Sellen, 1997]. These actions can be performed in the physical world by manually flipping and moving paper sheets, which can provide better tangibility and bi-manual support than digital media can [Sellen and Harper, 2001]. The same tasks can be carried out in the digital domain, with different interactions, including skimming thumbnails [Cockburn, et al., 2006], scrolling pages with Speed-Dependant Automatic Zooming [Igarashi and Hinckley, 2000], Rapid Serial Visual Presentation [De Bruijn and Spence, 2000] and Flipper [Sun and Guimbretière, 2005], or following hyperlinks [Price, et al., 1998]. The digital interfaces offer higher efficiency than printouts in handing a large amount of pages.

Create Spatial Arrangement. To quickly navigate and browse documents, arranging documents in a 2D space, such as on a (real or virtual) desk or on a white board, is an important means of organization [O'Hara and Sellen, 1997]. Moreover, the spatial layout can depict the information structure among documents, which is believed important to information organization, analysis, and creation [Guimbretière, et al., 2001, Jones and Dumais, 1986, Klemmer, et al., 2001]. Thus, a considerate interface should well support this important task.

The user experience in this task is significantly affected by the physical properties of displays. Paper has inherent advantages, due to its thin, light, and ductile nature [O'Hara and Sellen, 1997]. Therefore, the paper-based interfaces can benefit from this property. Existing electronic displays can hardly beat paper for this aspect [Sellen and Harper, 2001], but much research has been done toward simulating paper. Large displays [Guimbretière, et al., 2001] or multiple-display [Chen, et al., 2008] computers are two typical approaches, and the latter has the relative advantage of portability.

Transfer Information. Previous study on Active Reading indicates that readers often work on multiple document pages simultaneously, for instance, composing a document while reading [O'Hara and Sellen, 1997]. In such multiple-page interaction, there are various pieces of information to transfer, such as copying a figure from a Wikipedia page to a report in Word, or typing a keyword "Affordance" from a printout into a web browser on a screen. Sometimes this task may involve multiple devices and media if the documents do not resident in one single device. Research for easy cross-device information transfer, like Pick&Drop [Rekimoto, 1997], Stitching [Hinckley, et al., 2004], and the ubiquitous clipboard model [Slay, et al., 2005], can be applied to improve interaction in PDIS. Obviously, the digital media is more efficient than paper in supporting this task.

Retrieve Supporting Documents. In a broader view, the initial documents are just a small part of the knowledge body, and they are far from self-contained. For example, almost all research papers come with references to previous works. To fully understand the background or specific details about such a paper, readers often need to download the cited articles, visit the authors' Web sites or Google related keywords. Many times, the retrieval of the external information is not planned ahead, but occurs on the fly during Active Reading. Thus, it is crucial for a reader to conveniently initiate the retrieval from within the reading context and transfer back the resulting information to the ongoing tasks. The Web is one of the primary sources for the external supporting documents. Dynamically rendering additional Web pages [Norrie and Signer, 2003] or multimedia [Back, et al., 2001] available for use with paper documents has proven effective for better user reading experience.

3.3 The Design Space of Active Reading

There are many design factors affecting Active Reading user experience. We currently focus on four key factors affecting user experience of the major tasks in

Active Reading—namely, *display physical quality*, *in situ digital functions*, *support of multiple displays,* and *portability*.

Display Physical Quality. It comes without question that the user's reading and writing experience is deeply affected by the display's physical properties, such as resolution, contrast, reflectivity, surface friction, and so on. The display's weight, thickness, and elasticity also have great influence on user's comfort during document navigation, browse, and spatial arrangement. Therefore, physical characteristics of displays constitute a very important design factor. Indeed, the use of Tablet PC [Schilit, et al., 1998] and paper-like displays [E-Ink] are two steps along this track.

In situ Digital Functions. It has been broadly accepted that a digital approach has advantages over paper to capture and archive user input, transfer information among pages, and retrieve external supporting information. Many previous works on interactive paper have brought some of these digital functions to paper [Norrie and Signer, 2003, Schilit, et al., 1998, Wellner, 1993]. The key point of our research is to investigate the potential of pen-paper-only interfaces in realizing digital functions..

We emphasize the qualifier "*in situ*" since we believe that the on-paper digital functions should not be interruptive or obtrusive but should help the reader "stay in the flow" of focused attention [Csikszentmihalyi, 1991]. A good PDIS for Active Reading should allow for operations "in place"; for example, when a user wants to excerpt an interesting picture in an initial document while reading, she should be able to perform a copy operation easily right at that place without switching eye-focus to another display for that operation. This motivation is similar to that of "Active Note-taking" proposed by Hinckley [Hinckley, et al., 2007], which allows users to initiate web search on handwritten keywords directly from digital notes,

Multiple Displays. Compared with single small displays adopted by existing Tablet PCs, the multiple-display setting can offer more display real-estate and can mitigate inconveniences such as overlapped windows and small fonts. Further, it can provide more flexibility in spatial arrangement, improving user experience in navigation and browsing [O'Hara and Sellen, 1997]. Paper inherently supports such a setting, and we believe the multiple-display computer is a promising direction to go.

Portability. The high portability of the interface is necessary for the goal of accessing digital documents at "any time, anywhere via any media," which is the ultimate goal of this dissertation. So the portability is a key factor defining our design space. Indeed, high portability is the feature that distinguishes PapierCraft from many of the existing works on paper-computer integration, such as DigitalDesk [Wellner, 1993] and A-Book [Mackay, et al., 2002].

The above four design factors play a critical role in the Active Reading user

Tasks / Design Factors	Tasks better supported by paper	Tasks better supported by computers
Display Physical Quality	read, write, navigate, browse and spatially arrange	
In Situ Digital Functions		capture, archive, transfer and retrieve
Multiple Displays	read, write, navigate, browse and spatially arrange	
Portability	potentially any tasks (Portability affects the place, therefore the overall context, of active reading)	

Table 1. The cross-matrix of Active Reading interface design factors and their affected tasks

experience. Table 1 summarizes the relation between these factors and the tasks that are significantly affected by a specific design factor. We can use the table to examine typical existing systems in the literature and, more importantly, to provide guidelines for our research.

3.3.1 The Design Space of Active Reading Interfaces

Due to the importance of the above mentioned four key factors—*display physical quality*, *in situ digital functions*, *support of multiple displays* and *portability*, we focus on them and define a sub-space based on the four aspects (Figure 8). We explore existing representative Active Reading interfaces and identify a possible research direction.

Normal Paper. All documents are printed or written on paper, the most traditional setting for Active Reading. The configuration retains all inherent paper affordances, like high-quality physical display (high resolution and contrast), flexible multiple-display layout, and portability (to a degree). However, it does not support

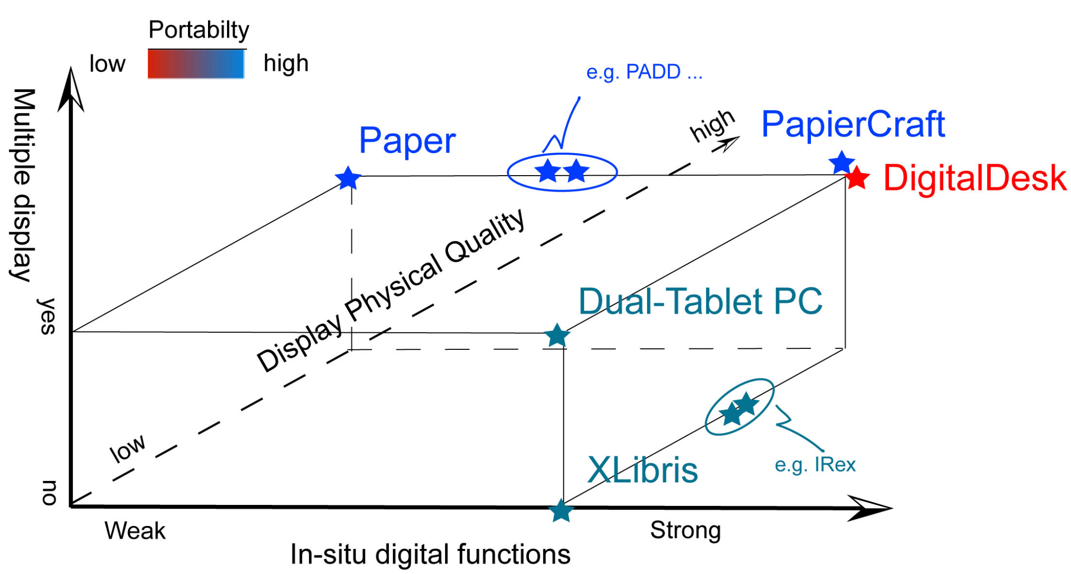


Figure 8. The design space of Active Reading interfaces

any in situ digital functions, so the rich information created on paper is trapped in the physical world, and the users have no handy on-paper means for information transfer and retrieval of external supporting documents.

1-Tablet PC (Single-display Tablet PC). Xlibris [Schilit, et al., 1998] is a representative interface for this configuration. It has full digital affordances, but is limited by the small single display area, inflexible spatial arrangement, and lower display quality than paper. The recent IRex [IRex] reading device, based on bi-stable screens [E-Ink], is an effort to improve such a configuration with better display physical quality.

N-Tablet PC (Multiple-display Tablet PC) is an advance of the 1-Tablet PC configuration. Exemplified with the dual-display e-book reader [Chen, et al., 2008], it features multiple displays to improve user experience in navigation, browsing and spatial arrangement. This setting represents recent efforts to simulate paper with pure computer interfaces. Expecting the persistence of paper in the foreseeable future, we believe that it is interesting to explore how multiple-display readers can be seamlessly integrated with paper-based interfaces. But this dissertation focuses on the latter.

PADD [Guimbretiere, 2003], enabled by the Anoto digital pen technique [Anoto, 2002], can capture annotations right where they are drawn within paper documents, so it supports "in situ digital function" to some degree. It reflects an advance in paper-based approaches along the lines of "in situ digital function." ProofRite [Conroy, et al., 2004] and PaperProof [Weibel, et al., 2008] improves on the concept of PADD by executing, not just capturing as PADD, proofreading marks on printouts to update the corresponding digital copy. Note that systems in the *paper-*

computer-coordination category, such as Paper++ [Norrie and Signer, 2003], enable digital functions on paper (e.g., browsing related multimedia) too, but they need a separate screen to perform the operations, which is not in accord with our "in situ" notion, and are not presented in the design space.

DigitalDesk [Wellner, 1993] supports full digital affordances on paper, combining paper's high display quality, inherent multiple-display support, and in situ digital functions, but its mobility is limited due to non-portable hardware and complicated configuration. The challenge is how to achieve a configuration similar to DigitalDesk but with a more portable interface.

3.4 Motivation of PapierCraft

Looking at the design space, it is clear that paper-based approaches are very competitive at *Display Physical Quality* and *Multiple Display Support*, while computer-based ones are better in *In situ Digital Functions*. Less clearly, *Portability* of systems vary in both paper and computer domains, depending on specific designs. There are several possible paths, e.g. dual-display computers and paper-based interfaces, to reach the point where all four factors are well embodied. We focus on the latter due to the hardware availability.

To approach the ultimate design goal, we need to improve the support of the "in situ digital functions" of paper-based interfaces, and, at the same time, retain the original paper advantages in other dimensions. Using a pen-paper-only interface can keep the inherent paper affordances in general, but we did not know to what extent such minimal interface hardware could serve "in situ digital functions," which is one of the research problems that this dissertation tries to answer.

We believe that it is meaningful to explore how far we can go by using only pen and paper to support Active Reading. From a scientific research view, we may understand better the affordances of the paper and the pen, the role of the multi-modal feedback on a static display, and the pros and cons of the digital and physical interfaces. From a practical perspective, such research can help optimize the paper-computer cohabitation and can provide users with the combined merits of the two media. We believe this cohabitation situation will last into the foreseeable future, since computers can hardly replace paper completely at any time soon [Sellen and Harper, 2001]. Further, with a better understanding of the existing paper and computer interfaces, we may obtain guidelines toward other paths in the design space—for instance, the next generation multiple-display computer interface for Active Reading.

Motivated by the analysis, we have proposed PapierCraft, a pen-gesture interface geared to static paper. We have explored the design of the gestures, the feedback mechanism for a pen-paper-only interface, the supporting infrastructure, and finally have evaluated it in the setting of Active Reading.

Chapter 4: Pen Gesture-based Command System for Paper[2]

Toward the goal of better user experience for interaction with digital documents, PapierCraft adopts a flexible and powerful command system that just needs a digital pen and paper for the interface. The command system is based on Anoto digital pen [Anoto, 2002], of which the light-weight form factor makes it possible to keep the paper flexibility while providing rich digital functions to support Active Reading. The core of the command system is pen gestures. Despite many ideas of pen gestures can be borrowed from Tablet PC gestures like Scriboili [Hinckley, et al., 2005], PapierCraft must handle a unique challenge: the passive nature of paper, and it should be compatible to existing pen-paper practices. As our solution, the key design principle of PapierCraft gestures is in two folds: First, reducing the reliance on feedback by using gestures easy for users to master and robust for computers to recognize; Second, exploiting self-explanatory gestures on paper as feedback and relieving the difficulty caused by the lack of dynamic screen feedback.

Underlying the gesture command system is the infrastructure that translates, interprets and executes the gestures. To accommodate the increasing need of mobile computing and mix-media operations, we extended existing cross-computer operation systems like Pick&Drop [Rekimoto, 1997] and Stitching[Hinckley, et al., 2004] to physical paper, and adopted a distributed and multi-tier architecture.

---

[2] Portions of this chapter were originally published by the author, François Guimbretière, Ken Hinckley and Jim Hollan in [Liao, et al., 2008]

In the rest of this chapter, we will discuss the design following steps of the data process: the stroke mapping from paper to digital domain, the components of a PapierCraft command, a sample command set for Active Reading, the supporting infrastructure and finally an early stage user testing.

4.1 Mapping Pen Interaction from Physical World to Digital World

PapierCraft follows the concept of ***Paper Proxy*** initiated in PADD [Guimbretiere, 2003]. It reflects two facets of the PapierCraft interface: First, as "paper", it adopts a pen-paper-only interface, and achieves the same level of flexibility as conventional paper; Second, as "proxy", the pen-paper interactions can be mapped to the corresponding digital manipulations. To realize the Paper Proxy concept, the first two enabling techniques are capturing pen inputs on paper and mapping them to corresponding digital copies.

4.1.1 Identify and Trace Paper Documents

In order to manipulate more than one different document pages, which is almost always the case, it is important to uniquely identify each piece of paper. The simplest method, manual identification, is problematic. For example, IBM CrossPad [IBM, 1998] requires users to tap a hardware button whenever a different paper sheet is used, which is often neglected and leads to mis-placed data. Thus, we center on the automatic identification methods.

Most of the automatic approaches identify paper document pages by recognizing photos of a page or a part of it, which are obtained by cameras or scanners. For example, SIFT (Scale-Invariant Feature Transform) [Lowe, 2004] calculates low level feature vectors from a paper image, and compares it against a pre-calculated feature database to determine from which digital page the hardcopy is made. SIFT does not require any special paper or pens, so has been broadly used in systems like [Kim, et al., 2004]. However, the image-capturing devices may hinder the interface portability (e.g. cameras), and the complex calibration and configuration make it further difficult for mobile users.

Another approach is to augment paper with special visual markers, such as the barcodes used by Augmented Space [Rekimoto and Saitoh, 1999] and Paper PDA [Heiner, et al., 1999]. This method is usually more computing-efficient and robust than SIFT, but the marker itself is visually obtrusive and wastes the space for document content. An alternative is "fiduciary pattern", the visual markers spread all over the background of paper documents, which can be recognized by pens with a built-in camera. Data Glyph [Hecht, 2001] and Anoto [Anoto, 2002] fall into this category. Compared to SIFT and 2D barcode, this method can be implemented with a light-weighted digital pen and the markers in the background are much less obtrusive.

Other non-optic approaches are possible for paper identification, such as RFID's embedded in each book page in ListenReader [Back, et al., 2001]. It has no issue of the visual obtrusiveness, but needs extra efforts to embed RFID's in paper pages.

Taking into account of the portability, user visual experience and robustness, we decided to adopt the commercialized Anoto technique for the paper identification, and for capturing the pen interactions.

4.1.2 Capture Pen Interaction

Active Reading involves both without-pen and with-pen actions. For example, people browse, flip paper and lay out paper on desktop, read and compare documents without explicit input onto paper. Although important, such interaction is difficult to capture and analyze with existing techniques. For now, we focus on pen stroke capturing.

There are several categories of pen stroke capture techniques. Scanning-based methods, used in XAX [Dymetman and Copperman, 1998] and PaperPDA [Heiner, et al., 1999], can work on arbitrary paper and normal pens. However, it is hard to record strokes' temporal information, which is essential to recognize multiple-stroke gestures, especially those across multiple document pages such as the copy/paste command between two paper sheets in PapierCraft (see Figure 2 on Page 8). Graphics tablets, as used in A-Book [Mackay, et al., 2002] and Audio Notebook [Stifelman, et al., 2001], can record time information, but the extra tablet may interfere with the inherent pen-paper interactions. Anoto digital pen has no such issues.

Considering the above issues and the hardware/software availability, we decided to use Anoto technique to identify paper sheets and capture pen strokes. Although the special pattern paper might an issue for real life deployment, we assume such paper will be available like normal print paper, and people can easily purchase at their convenience.

4.1.3 Bringing Pen Interaction to Digital Domain

Although Anoto digital pens can identify paper sheets and capture strokes, to map the pen inputs from a printed document to its digital counterpart, there must be a mechanism linking the printouts and the original digital files. This is done by incorporating PADD (Paper Augmented Digital Document) system [Guimbretiere, 2003] into PapierCraft.

Figure 9 illustrates the PADD work flow. When a user prints a digital document onto Anoto paper, the system associates the printout IDs (unique Anoto patterns) and the digital page IDs (unique document ID plus page numbers). The association information and coordinate transforming matrix are then stored in a database. The user can then use the digital pen to draw arbitrary marks on the printout. Afterwards, she just needs to synchronize the pen with PADD, which in response automatically downloads the strokes from the pen, retrieves the corresponding digital pages, and inserts the strokes into the digital documents based on the previously stored mapping information.

PADD system is a key step toward the goal of paper-computer co-habitation, in that it eases the information flow from paper back to the digital world and improves PDIS in terms of "Capture and Archive User Input". Nevertheless, PADD

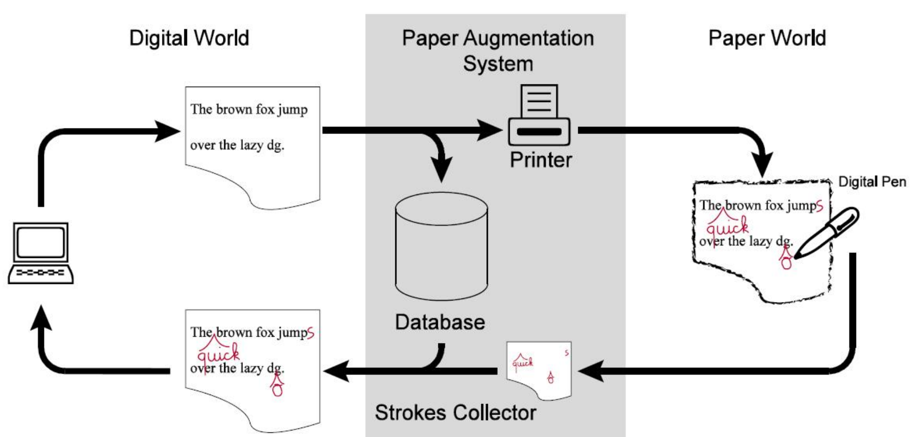


Figure 9. Work flow of PADD. A digital page is printed through PADD, which captures and stores the physical-digital mapping information. Then one can annotate the printout as if using a normal pen and paper. Upon pen synchronization, captured strokes are merged back into the

just captures stroke level information, e.g. annotations, on paper, not the semantic level information such as cross-references and spatial organization. Moreover, it does not provide enough support for the "Information Transfer", "In-Situ Operations" and "Retrieval of External Information."

In response, we propose PapierCraft command system. With the help of PADD, PapierCraft first captures and maps the pen gestures from paper into the digital domain, and then interprets and executes them like Tablet PCs do with digital ink [Hinckley, et al., 2005]. Of course, the static nature of paper has a great impact on the design of the command system and related feedback mechanism, which are the two main contributions of this dissertation and about to be discussed as follows

4.2 Design Goals of PapierCraft Gesture Commands

Although we can borrow ideas from rich literature of pen-based command system for computers, the passiveness of paper impose specific design goals for such a system:

Respect current paper practices. This was the main design goal. The general principle is that users should be able to do whatever they could before with no new constraints but also be able, with minimal extra effort, to access new facilities enabled by a paper-digital linkage. The key idea is to bridge the paper-computer gap while maintaining both digital and paper affordances. We have focused on several common paper-based practices including annotating sections of documents, excerpting passages, relating documents, and creating information collages.

Provide flexible, simple, and reliable commands. The command system should be as flexible as possible to accommodate the informal and unstructured nature of conventional pen-paper interactions, and impose minimal restrictions on the shape or location of command marks. In case of no computer nearby, the ink left on paper may be the only feedback. A simple and reliable command system may help reduce the reliance on strong feedback for correction and disambiguation.

Ensure commands are human-readable. Although the gesture commands are intended for computer interpretation, it is equally important that they also be easily understood by people. For example, the execution scope of a paste-command should be clear so that the region will not be overlapped by subsequent notes or other commands. Human-readability is also helpful for information recovery in the event of pen failure (e.g. out-of-battery). This way, we can achieve graceful degradation [Yeh, et al., 2006], in that the digital pen can still be used at least as a normal ink pen working with paper in a conventional way, not stopping users from doing tasks like note-taking and proofreading.

Design an extensible command system. Although we initially focus on paper-only interactions, the system should be extensible to accommodate varying computing resources and multiple devices. For example, in case of no computers nearby, the marks may be the only immediate feedback, the system should be able to still support a certain set of facilities; with a computer nearby, the system be able to coordinate with the computer for a larger command set to support more interactive tasks like web search. Furthermore, if multiple displays (either paper sheets or screens) are available, the system should support cross-display operations like copy/paste and hyperlinking.

4.3 Design of the Pen-Gestures for Paper

Guided by the design goals, we decided to use gesture-based commands in respect to existing pen-paper practices. There are two main reasons: Firstly, the pen gestures can be easily interwoven with normal annotations and notes. The low cognitive load helps reducing the chance to interrupt users' thought flow while working on paper. Secondly, the gestures can be draw at an arbitrary[3] place within a printout. Compared to fix-positioned checkbox/button-based paper command systems like PaperPDA [Heiner, et al., 1999], the gesture commands are more suitable for Active Reading, as readers may mark and perform operation for nearly any segments.

Thus, we borrowed ideas from Scriboli [Hinckley, et al., 2005], a Tablet PC gesture command system. Similarly, PapierCraft also needs to distinguish between annotations and commands, designate the scope of commands, select command types, and support command modification and subsequent execution.

4.3.1 Distinguishing Annotations and Command Gestures

Many solutions have been proposed to distinguish ink intended as content (annotations) from ink intended to be interpreted by the system (commands). Some systems use an implicit approach [Zeleznik and Miller, 2006] in which the computer automatically distinguishes the two. Other systems employ an explicit approach [Hinckley, et al., 2005, Li, et al., 2005] in which users indicate the current stroke type (e.g., by pressing a button). A mixed approach, in which the computer and the user collaborate to resolved ambiguous input, is also possible [Saund and Lank, 2003].

[3] Any place with pre-printed dot pattern so that the digital pen can trace the stroke.

Given the limited feedback possible with a digital pen and paper, we concluded that both implicit and mixed approach would be problematic because they require immediate feedback for correction or disambiguation. Instead, PapierCraft takes an "explicit" approach, using a "gesture" button present on the pen or in the environment (e.g. a foot pedal). This approach requires only weak synchronization. A stroke is considered a gesture stroke as soon as the gesture button is pressed for some duration during stroke drawing.

With the gesture button down, a gesture can be drawn to specify a PapierCraft command. It consists of three basic components: a command scope, an intermediate delimiter, and a command type. Several commands, possibly on different paper sheets, can work in coalition to fulfill a task such as copying and pasting a section or hyperlinking two document sections.

4.3.2 Specifying Command Scope

The absence of real-time feedback influenced the design of scope selection. Consider the simple example of a copy-and-paste operation. When this operation is performed on a computer (e.g., using a system such as OneNote), one first selects the object to be copied, often using a marquee selection with instant feedback of the area selected. Once the selection is complete, the paste location can be specified. As soon as the paste command is issued, visual feedback is immediately provided to show the result of the operation. Of course, on paper neither type of feedback can be provided. To address this issue, we require users to draw the intended scope of all commands. In the case of the copy operation for example, the scope identifies the region to be copied.

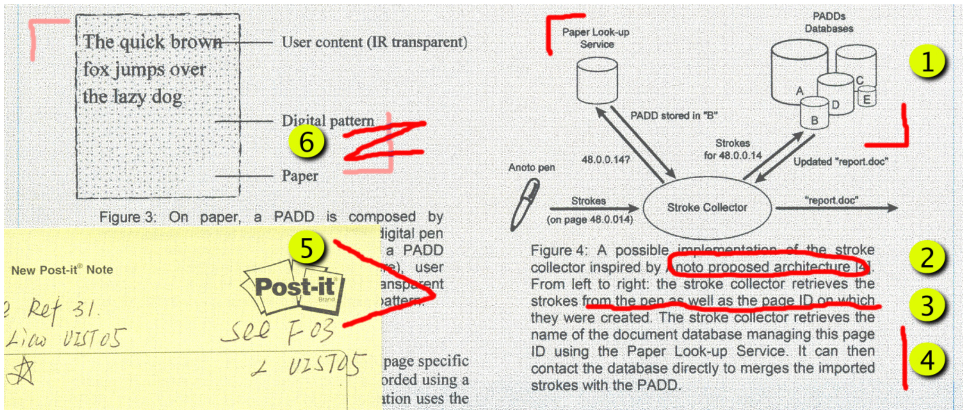


Figure 10. PapierCraft scopes and eraser command: (1) crop marks, (2) lasso, (3) underline, (4) margin bar, (5) stitching mark across two paper sheets, and (6) a "Z" eraser gesture deleting an unwanted crop mark. Its orientation could be arbitrary. Gestures are highlighted in red for clarity.

Inspired by typical marks found on manuscripts (Figure 10), PapierCraft offers five types of scope selectors. One can select content by "cropping" a graphics region, underlining a passage of text, creating a margin bar to select several lines, or simply lassoing an arbitrary document area. We also offer a special "stitching" mark, a "V" reminiscent of the mark carpenters draw on two pieces of wood to specify their alignment. Much like Stitching [Hinckley, et al., 2004], which exploits cross-screen strokes to initialize a connection between displays. PapierCraft uses a sticking mark to indicate that the two adjacent paper sheets should be stitched together in the digital view. It can also be used to "pin" a small Post-It note on a document (Figure 10 item 5).

As pointed out above, during a copy-and-paste operation, a scope gesture is needed to indicate the size and position of the information to be pasted. Before synchronization, the drawn scope serves as a placeholder reminding the user that some information will appear at that location upon synchronization. At synchronization time, the scope is used to scale the content so that it fits into the scope (Figure 2, middle).

Operators such as copy-and-paste only require a simple scope. Other operators, such as the "copy with keyword" command that assigns a keyword to a specific area of a document, use a scope involving multiple parameters to select the target area as well as an assigned keyword (see

Table 2). Note that currently, PapierCraft views scope as a region of space. Some systems (e.g., ScanScribe [Saund, et al., 2003]) extract information from images and other document elements to provide object-level selection. We expect to explore this in the future.

After the command scope strokes are made, a delimiter is required to distinguish them from subsequent command-type strokes. We have adopted the Pigtail approach proposed for Scriboli [Hinckley, et al., 2005]. Like Scriboli, our system considers all strokes between the first gesture stroke and a gesture stroke containing a pigtail as part of the scope selection, and all gesture strokes after the pigtail as the command selection (see Figure 2 for an example). An advantage of the pigtail notation is that it is familiar to proofreaders and, as shown in Hinckley et al. [2005], yields performance comparable to presenting a "handle" (menu box) at the end of any stroke to specify part of the scope.

4.3.3 Specifying Command Types

Existing paper-based interfaces usually employ a dedicated region on paper for command selection, such as printed buttons in Anoto [Anoto, 2002] and Fly Pen [LeapFrog, 2005] and Guided Gestures in Paper PDA [Avrahami, et al., 2001]. Although easy to learn, this approach typically separates the selected command type and the associated scopes. And, the involved content on paper usually remains unchanged and gives no command feedback. As a result, users may lose clues about what actions have been applied to the document segment. Stroke-based command selection approaches (e.g., marking menus as in [Hardock, et al., 1993] and Sensiva [Sensiva, 2005]) address this issue. Command marks can be drawn right beside the scopes and thus do not require additional feedback.

Given our choice of the pigtail as a scope-command separator, it was natural to pick marking menus for specifying command types. However, single-level marking menus typically offer only 8 different commands. For a richer command set, one option was to use hierarchical marking menus [Hinckley, et al., 2005, Zhao and Balakrishnan, 2004] but there are a number of reasons to expect this to be problematic on paper. First, without any immediate feedback it would be difficult for users to discover and learn the different marks without extra references. Second, it might be even more difficult to remember the meaning of a mark drawn on paper after some time had passed. Finally, a reader cannot discern the temporal order of the marks, violating our design principle of human-readability.

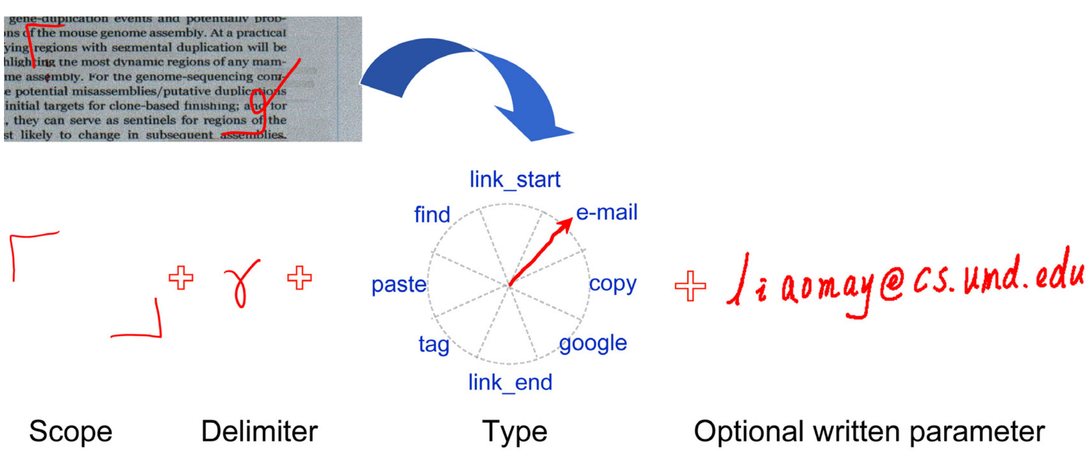


Figure 11. The structure of an example "email" command. Top left corner is the command drawn in a document page (highlighted in red for clarity.); below are its four components, namely Scope, Delimiter, Type (selecting one out of eight menu items using the marking menu direction) and the optional written parameter.

We decided to use a mixed approach for command selection (Figure 11). The commands we expect to be most frequently used, including copy, paste, hyperlink source, and hyperlink target, are accessed directly from the eight cardinal directions of the marking menu. The full command set can also be accessed by simply writing down an unambiguous prefix of the command name immediately after the pigtail. For example, one can directly write the word "Paste" to take precedence over the mark direction which might otherwise be taken as "Copy".

Writing command names allows for a larger command set. Since our system will recognize unambiguous prefixes, command prefixes can naturally assume the status of shortcuts. This approach makes it easy for people to read the commands they issued on paper. While having to write a full command name has a cost, we expect that it will be accepted by users as it fits naturally into the context of proofreading or annotating a document during active reading. We also considered the possibility of character/word recognition errors, but given the small vocabulary in the present application we did not expect this to be a significant practical problem. A similar technique known as "mnemonic flicks" has been proposed for a TabletPC-based marking interface [Zeleznik and Miller, 2006]. PapierCraft demonstrates how this technique is particularly well-suited to working on paper.

4.3.4 An Example: Issuing a Copy/Paste Command in PapierCraft

To further explain the PapierCraft command interface, we describe a simple copy/paste interaction in PapierCraft (Figure 2). To copy an image, the user first indicates the area of the document to be copied. To do so, she presses the gesture button and draws cropping marks around the area of interest. Keeping the gesture button pressed down, she draws a pig tail followed by marking to the right (East). Note that the last stroke of the cropping mark, the pigtail, and the command mark can be issued as one continuous mark, making the interaction fluid. While the current prototype does not support multiple-source-copy, such functionality could be implemented using the existing PapierCraft infrastructure.

To paste, the user follows a similar pattern. First, she indicates the area where the paste will take place by drawing a crop mark and a pigtail. This mark serves as a placeholder such that the user will avoid placing notes or other content there. Then she selects the paste command by marking to the left (West). For multiple-strokes commands, the system is flexible in use of the gesture button. The user may decide to hold it down during the full operation or simply click it each time she is drawing a "command" stroke. During this procedure the user may, as described more fully below, abort any command or remove undesired strokes.

Table 2 in section 4.5 gives an example command set for Active Reading. Of course, for different applications, developers can define their own command sets with the same command structure.

4.3.5 Command Modification

From time to time, one may want to change, abort, or cancel a command operation. To address this issue, it is useful to first look at the way users currently deal with errors when using pen and paper. According to Khan [1993], few people use an eraser for correction while taking notes. Instead users simply rewrite or leave errors as they are. This fact reflects the informal and unstructured characteristic of note-taking tasks.

Following this practice and factoring in paper's static nature, PapierCraft adopts a "lazy" approach for command modification: one can implicitly abort the current in-progress operations at any time and reissue a command from scratch. For example, one may abort an on-going copy command by simply ignoring the current scope selection and reselecting a new scope.

One might also want to delete a command after finishing it. PapierCraft supports explicit cancellation with a special "Z" eraser gesture as shown in Figure 10 (item 6). Any gesture stroke is considered void if it is overlapped by an eraser gesture to an extent greater than a specifiable threshold (e.g., being crossed by all the three segments of the "Z"). This eraser gesture is the same as the standard "Scratch Out" gesture in Microsoft Tablet PC handwriting recognition pack [Microsoft, 2005], bearing high user familiarity.

4.3.6 Error Handling

Error handling is important to any UI. As in the basic mode PapierCraft can only provide ink and physical engagement as feedback, error handing is postponed until pen synchronization. When a user synchronizes her pen, a potentially large number of commands need to be recognized and executed. Instead of alerting users during synchronization, our system adopts a best effort strategy for command recognition and does not report any errors during this initial phase. As users read their notes, they may discover that errors have been made (for example, that a "Paste" command was

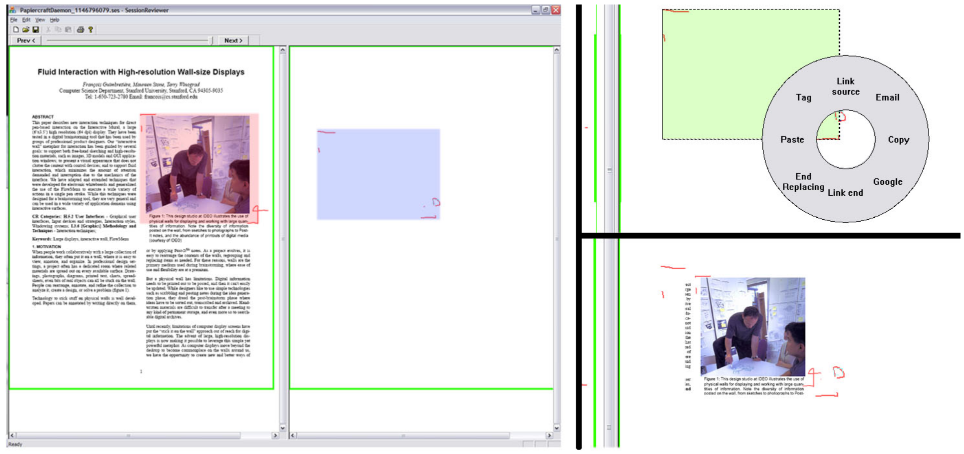


Figure 12. (left) An example of the interface for session review and error correction. A user tried to copy a picture in printout (highlighted in red) to an area in another note sheet (highlighted in blue), but failed due to unrecognized strokes for "paste". (top right) The user then selects the incorrect strokes and replaces them with a marquee selection in the target area, followed by a pie menu selection for command "paste". (bottom right) After re-execution, a new version with the desired picture in the note is created.

not executed). The system provides a simple recovering mechanism to rapidly correct such interpretation errors.

Our approach is based on the observation that while command recognition might be error prone, each stroke is accurately time stamped. Using this information, it is very easy to recover a given stroke's temporal context including the strokes that immediately precede it. When an error is found, simply clicking on strokes that were not correctly interpreted will automatically launch a Session Reviewer (Figure 12) that allows users to play back the strokes in the context in which they were made. This technique is similar to the Time-Machine Computing approach proposed by Rekimoto [1999] to allow users to restore an earlier context. Once the source of the problem is identified, a user can correct it using the digital interface without returning to paper. For some incorrect gestures, it may be faster to re-issue the commands using standard GUI facilities. Figure 12 illustrates the correction procedure when a "copy" command is mistaken for another gesture. One can select the two strokes and easily replace them with a correct "Copy" command by using PapierCraft gestures or, in traditional way, using a mouse marquee selection and popup menu. In order to retain the correct command sequence, the system will automatically assign the new command with the timestamp of the replaced one. Finally, the user can have the system re-execute the updated command stream for the correct result.

4.4 A Command Set for Active Learning

To demonstrate the potential of PapierCraft command system, we are presenting an example command set designed for Active Reading. The design is inspired by the observation on Active Reading [Adler, et al., 1998]:

> *Reading occurs more frequently in conjunction with writing than it does in isolation. Thus, it appears that writing (in a variety of forms) is an integral part of work-related reading. Designers need to seriously consider the importance of developing reading devices which also support the marking or writing of documents during the reading process.*

Almost half of all the document activities which involved reading involved the concurrent use of multiple "display surfaces" for reading, or reading in conjunction with writing. This points to the need to consider how single display devices can support the range of cross-document activities people carry out. It also emphasizes the importance of considering the benefits of designing devices which are based around the use of multiple, digital displays. [Adler, et al., 1998]

In this section, we describe how the PapierCraft command system was designed to support active reading. This includes managing annotations, linking paper documents, working with a mix of paper and computer media, and handling errors.

4.4.1 Managing Annotations

The simplest way to support active reading is to capture annotations. All annotations made on any PADD document are stored and automatically merged into the associated digital version of the document. Similar to the Xlibris Reader's Notebook, all annotated sections can be gathered in a special "Digital Snippets" panel to facilitate review. While our current system only identifies one pen type, it would be easy, since each pen has a unique ID, to create a special category for snippets of information associated with a specific pen. This would support the common practice of using highlighters of different colors to identify different types of information or grouping together annotations made by specific individuals.

4.4.2 Tagging segments of text

Using a different pen for different types of annotations has drawbacks. First, it requires users to carry several pens around and constantly jungle between them. Second, it offers only limited flexibility. Observing that many annotations are often

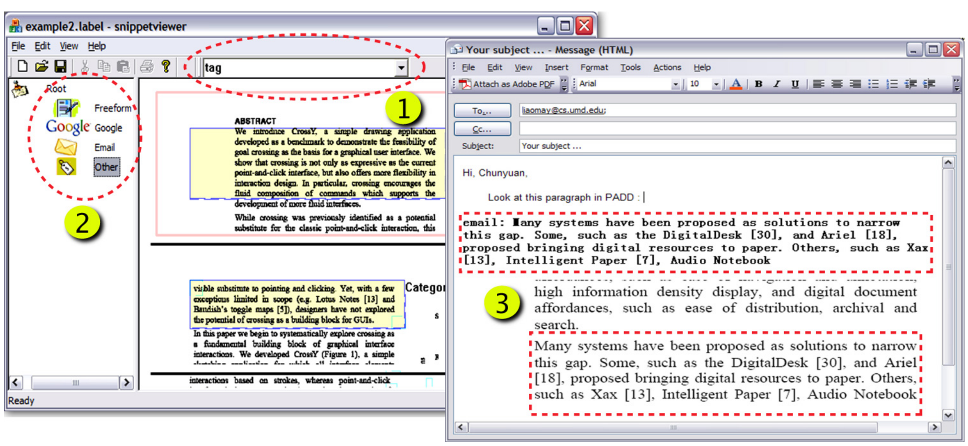


Figure 13. The interface to browse, search and manage snippets: (1) keyword filter, allowing users to type in keywords or to choose one from the list to select specific snippets. (2) a list of the valid categories. (3) an outlook email interface brought by clicking an "email" snippet. The top red rectangle indicates the text extracted from the snippet, and below is an image cropped from the original document (it has been extended to include surrounding content for more context information).

tagged with text (or a symbol) identifying them, we have provided a simple tagging capability. One can select any specific region in a printout or notebook page, and issue a "tag" command using a pigtail, in one of the four secondary directions, and optional written keywords (

Table 2). In the current implementation, pigtails towards "North West (NW)" and "South West (SW)" are designated to two user-configurable tags, "tag1" and "tag2" by default. Also, to provide additional flexibility, one can write any overriding tag words after these two pigtails.

Upon pen synchronization, one can review, manage, or search the annotated and tagged document segments, snippets, in an interface (see Figure 13). The snippets are organized into categories, and one can browse and review them under selected category nodes. In all cases each snippet is automatically linked to its location in the original document to help users rapidly access its context.

The other two secondary directions are used for advanced features. For example, a NE pigtail indicates text to be emailed to a specified address indicated by written words afterward, and a SE pigtail indicates text to be used as parameter to a search engine like Google (see

Table 2). If the pen is connected through a real-time link, processing can be executed in real time (see section 5.3); otherwise, commands are executed after synchronization. For example, upon double clicking an email snippet an email program will appear with the snippet embedded in the mail body and the written email address in the recipient field. Note, besides "Google" and "Email", other commands can be implemented with the same PapierCraft command structure.

4.4.3 Linking Paper Documents

As described earlier, PapierCraft makes it easy to copy information from a PADD document to one's notes. It is important to note that the results of any earlier commands present in a copied area are also included. This makes it possible to transfer complex collages from one page to another. It also facilitates importing content from legacy documents not printed with the Anoto pattern. For example, an architect could use a piece of translucent vellum with the Anoto pattern to trace a portion of a floor plan from a document. The traced image can then serve as a source for later copy operations.

One issue we address is how to maintain appropriate contexts of the pasted snippets. We do this in two ways: (1) The system always copies a slightly larger area than was selected so that the original surrounding text and annotations can still be seen in the destination document. (2) The system automatically creates a hyperlink from the pasted region back to the associated section of the source document. This makes it possible, for example, to create thumbnails of several pages by simply copying each to small regions on a single piece of paper. Upon synchronization, one can then use the thumbnails as quick indexes to the associated pages.

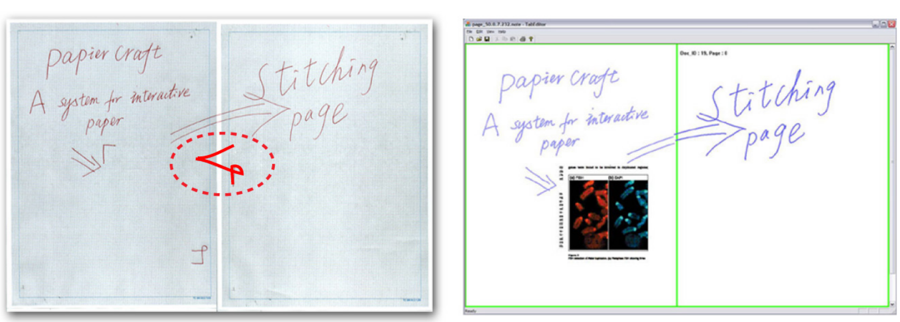


Figure 14. (left) "stitch" in the red circle to extend space. (right) The resulting digital document

4.4.3.1 Capturing Physical Collages

Arranging pieces of paper in a collage is an effective way of organizing information from multiple sources. PapierCraft allows users to create digital versions of paper collages by drawing stitch marks (see Figure 14) across page boundaries. This is similar to the Stitching system that allows stitching across Tablet PC displays [Hinckley, et al., 2004]. After synchronization, the content of the two pages are shown as a single page in the viewer interface. Similarly, one can effectively pin a smaller piece of paper (such as a Post-it note) onto a larger one (Figure 15). The corresponding digital version includes an “anchor region” around the position of the stitching mark vertex. Clicking on an anchor in PapierCraft viewer (Figure 2) allows users to review an attached Post-it note in a separate window.

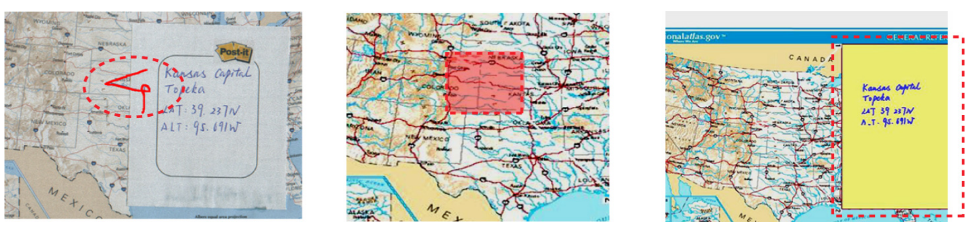


Figure 15. Stitching a post-it note to a map. (left) Draw the stiching mark on paper. (middle) The resulting “anchor” region in the digital version. (right) Expanded “anchor” region for details. Figures are highlighted for clarity.

4.4.3.2 Explicitly Linking Paper Documents

While our system offers many ways to create implicit links, it is sometime useful to be able to create explicit link between documents. For example one might want to create a link between a reference in a text and the corresponding paper or between a graph and the corresponding data table. PapierCraft supports this practice through the notion of “hot spots”. One can select a region of a document with, for example, a cropping mark and draw a gesture “hyperlink start” followed by another gesture "hyperlink end" on a separate document. The region "hot spot" will be highlighted in the PapierCraft viewer and users can double-click it to open the linked document.

4.4.4 Working with Paper-Computer Mixed Media

So far we have focused on paper-only operations, but in a typical work environment, paper and digital media coexist and people often use both simultaneously. For example, users may review a paper document and search for a reference or take notes on a PC. While early digital pens only supported synchronization through USB connections, the current generation of pens are able to stream strokes in near real-time through Bluetooth connections. PapierCraft provides support for a streaming interface. This permits users to execute computer commands via gestures on paper. For example, we support a "Google" search on paper. One can select any region in a paper document and issue a pigtail command "google". The underlying text of the specified region is extracted and sent as a search request to a web browser running on an associated host computer. In this way, users do not have to drop the paper document and switch to a computer to type in keywords, but can immediately review the search results on a screen.

Table 2 summarizes the prototype command set for Active Reading. With the same infrastructure, developer can define application-specific command set.

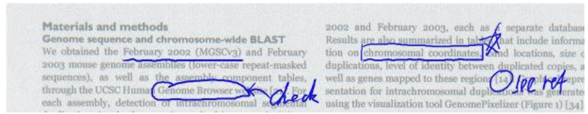
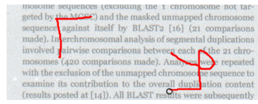
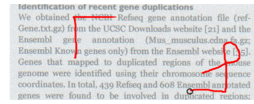
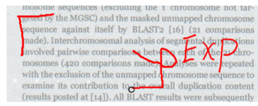
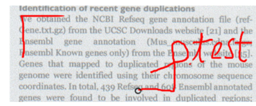
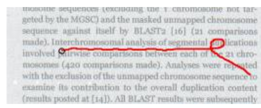
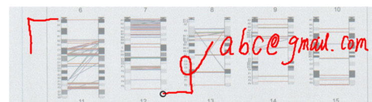
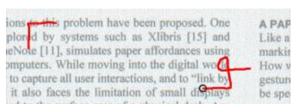
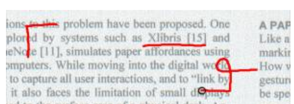
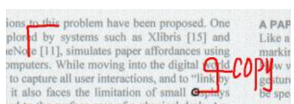
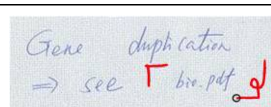
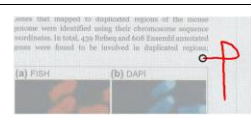
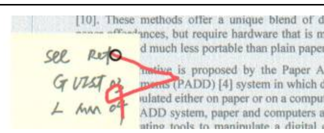
Tasks	Command or Annotations on One Page	
Freeform annotation		
Tagging with reserved keywords	 or	
Tagging with arbitrary keywords	 or	
“Google” and “Email” on paper	 and	
	Command on Page 1	**Command on Page 2**
Excerption		
Excerption with keyword		
Excerption with command name		
Hyperlink		
Stitching		

Table 2. An example PapierCraft command set for Active Reading. The strokes in blue are “Ink” and ones in red “Gesture”. The black circles indicate the starting point of strokes, and the strokes without such indicators can be drawn from either direction. For simplicity, we only use “crop marks” but other scopes are possible (see Figure 10).

4.5 Architecture of the PapierCraft Command Execution Sub-system

Behind the pen gesture command system is the infrastructure that interprets and executes the gestures in digital domain. The processing can be done in batch and real-time mode. For example, without infrastructure available, one can use the digital pen in basic model, which stores all strokes in built-in memory. Later, when infrastructure becomes accessible, the user just needs to synchronize the pen with the infrastructure like using a PDA. If the infrastructure available (via a nearby computer), the user can use the digital pen in real time mode and submit the strokes in real time.

The resulting digital documents will be available in a viewer application (CraftViewer, Figure 2 , right). At this point, users can switch to the computer to continue their work or make another printout for the next round of jobs on paper.

In designing the command execution sub-system, we have established the following goals:

1> **Support mobile users.** The pen-paper-only interface is highly portable and compatible with existing practices, so that a user may submit the strokes, in batch mode or in real time, at almost anywhere. That requires the infrastructure, including the services and data, should be also available anywhere.

2> **Support mixed-media displays.** As Sellen pointed out [Sellen and Harper, 2001], the paper-computer cohabitation is very common and will last in foreseeable future. On one hand, at a coarse granularity, paper and computers may be used at different processing stages of a digital document. For instance, one usually edits a file on computer, then prints it out for proofreading, and updates the original draft on computer later. On the other hand, at a fine granularity, people may interweave use of paper and computers in a session. For example, she may read an article and search for related information on line at the same time. PapierCraft should support all the usage modes, and make best use of both paper and screens whenever they are available.

3> **Support both real-time and batch processing of strokes.** Although we aim at ubiquitous access to the infrastructure, but it may be not available in some cases like network breaking and server shutting down. Our design should support two modes, real-time and batch processing, to gracefully accommodate the different infrastructure accessibility.

Based on the design goals, we come up with a distributed architecture as described below. The PapierCraft architecture is designed to provide an integrated view of documents and to coordinate and support interaction with them in both digital and paper versions. The *Paper Proxy* metaphor leads to the somewhat novel view of a

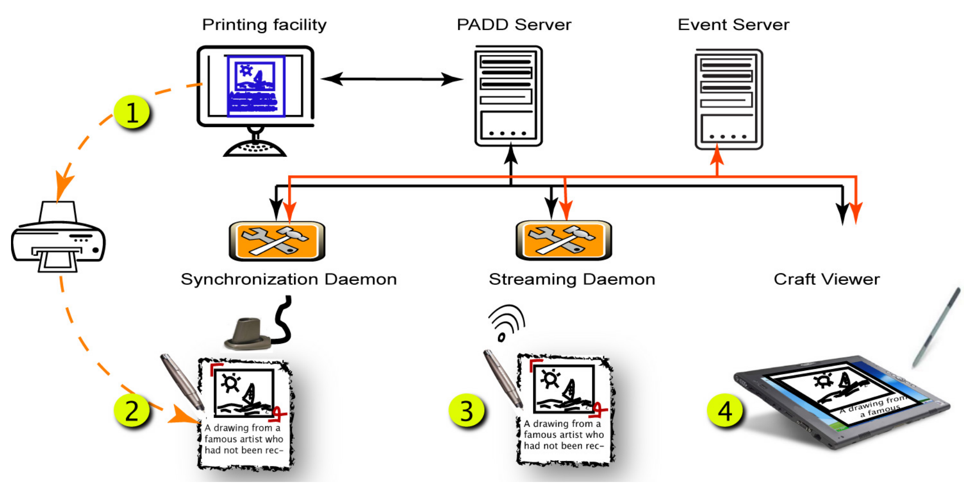


Figure 16. PapierCraft Architecture. (1) A digital document is printed via a PADD printer. The hardcopy become an alternative working media. (2) In "batch" mode, the pen synchronizes with the system via a cradle. (3) In "streaming" mode, the pen interacts with the system in real-time via Bluetooth. (4) A tablet PC can be used directly manipulate the documents through CraftViewer.

paper page as a simple display device capable of capturing pen stokes. Based on this, it was natural to adopt an architecture similar to Pick-and-Drop [Rekimoto, 1997] and Stitching [Hinckley, et al., 2004]. Similar to these systems, a central server coordinates distributed clients to accomplish users' operations across devices. For generality, our system supports interactions between paper and paper, between paper and a computer, as well as between two computers.

Figure 16 illustrates the PapierCraft architecture. There are three basic components: PADD Server, Event Server, and PapierCraft clients. The PADD server stores digital versions of all printed documents and paper notes, as well as the physical-digital-coordinate mapping information. Such information is automatically captured and submitted by the infrastructure when one prints a file through a PADD virtual printer driver. Currently, we support PDF files printed using Adobe Acrobat.

The Event server and PapierCraft clients collaborate to execute the gesture commands distributed on multiple devices. PapierCraft clients function on behalf of various display surfaces. They are responsible for submitting strokes captured either on paper or on a tablet PC in case of mixed media operations, receiving notification from the Event sever, updating the local copy of digital documents and finally uploading results to the PADD server.

Each client can reside on a different host computer. These can include the host computer on which the pen is synchronized, the computer receiving the stroke streams for real-time operation, the computer running the CraftViewer document viewer. The Event Server monitors the PapierCraft client interactions and coordinates them based on pre-defined operation patterns. The architecture is similar to network event monitoring systems like GEM [Mansouri-Samani and Sloman, 1997] and SIENA [Carzaniga, et al., 2001].

4.6 The Procedure of PapierCraft Command Execution

To balance the computational workload of involving devices in the Personal Document Interaction Space, we adopted a distributed architecture: Gesture recognition and individual commands are processed at local hosts, and global cross-display operations are coordinated at the Event Server.

Gesture commands can be processed in real time or in batch mode. Here we focus on a description of batch mode processing. The procedure for real-time execution is similar except that the strokes are sent without delay. Processing consists of three phases: (1) a stroke-processing phase during which pen strokes are uploaded from the pen and interpreted by a PapierCraft client, (2) an execution phase during which the clients are synchronized together by the Event Server for cross-page operations, and (3) a display phase during which the clients are notified of

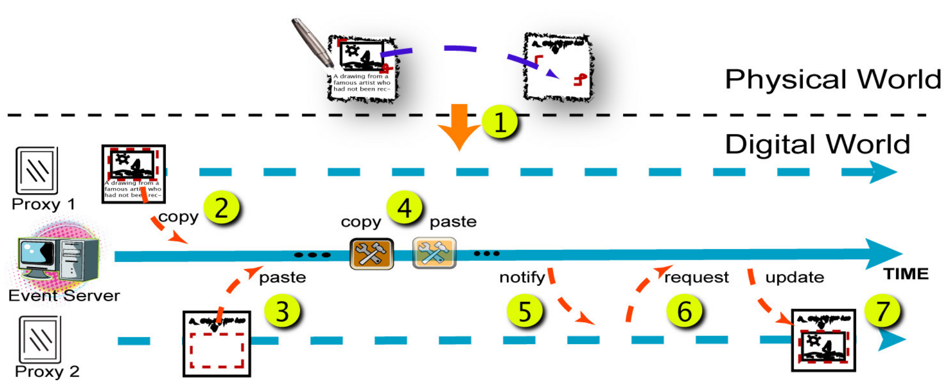


Figure 17. The Time-Space diagram for PapierCraft command execution exemplified with an excerpt operation. (1) pen synchronization starts, (2) proxy 1 sends a local event "copy" to the server, (3) proxy 2 sends event "paste", (4) the event server checks the received events stream, (5) a distributed "copy"/"paste" operation is detected and a "notify" event is sent back to the "pasting" target, proxy 2. (6) (7) after verification, proxy 2 requests data and updates the digital notes

modifications to the documents they are managing and show the results. Figure 17 illustrates the phases of execution, and the sections below detail the process.

4.6.1 Local Stroke Processing

Once a pen is plugged in, a PapierCraft client is invoked on the host computer and receives all the strokes captured by the pen (step 1 in Figure 17). After importing the strokes, the client downloads the latest versions of the corresponding digital documents from a central PADD database server, and then creates a Page Proxy for each of the document pages. These proxies act as if they were independent devices interacting with the central Event Server. The client processes strokes in temporal order, labeling each stroke as a command or an annotation stroke based on the mode-switch button's click records. Annotation strokes are simply merged into the digital file. Gesture strokes are passed to a gesture recognition engine that recognizes commands from the stroke stream. Once a command is detected, a corresponding "Local Event" is sent to the Event Server for cross-page operations (step 2, 3 in Figure 17). For example, in the case of copy, the local event includes a client ID, a timestamp, the command type, and the following command-specific parameters: the selected image, text extracted from the digital file, and surrounding annotation strokes, if any, available at that time.

4.6.2 Event Synchronization and Command Execution

Event synchronization is accomplished by the event server. It maintains a central Event Cache for Local Events coming from various proxies during a session (step 4 in Figure 17). Such a cache is necessary because events may be submitted by the clients out of order of their actual occurrences. Currently, we do not distinguish different pens. Instead, we temporally align all events in the cache and handle them as a single thread. This enables interaction across different pens which might be convenient for a single user. It could be a source of race conditions if a group of users were interacting with a given document. This single thread approach is a policy decision and other policies are possible. For example, each pen could have a private thread, allowing a separate “clipboard” for each pen.

It is important to note that associated events can be interspersed with events of other types. For instance, as in the case of a digital copy and paste sequence, one can first “Copy”, then create a hyperlink, and finally ”Paste”. This is equivalent to copy/paste followed by linking. This feature reflects the common “clipboard” semantics familiar to users [Miller and Myers, 1999].

4.6.3 Client Notification

Upon execution of a command, the event server sends a “Global Event” (called “Global” as it involves more than one client) notification to the client handling the corresponding page (step 5 in Figure 17). For instance, the client proxy might receive a “Paste data ready” event indicating that some data should be inserted into a region of a given page. If the notification is valid, the client will then send a request to the server and retrieve the pasted data (step 6 in Figure 17). Finally, it updates the opened digital file and uploads it to the PADD server (step 7 in Figure 17). If the client proxy is not responsive, the Global Event will be held until another client opens the digital file, which will receive this notification and update as described above. Currently, we assume, at any given time, there is only one such client opening a digital file, so there is no issue of version control.

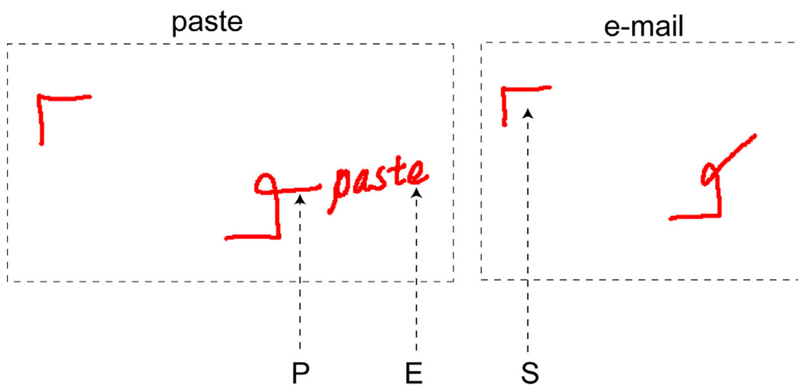


Figure 18 An example for stroke streaming parsing. The user drew two commands, "paste" immediately followed by "e-mail". After the pigtail stroke "P", if a stroke "E" is far from its following stroke, say "S" in time or space, or the user switched pen mode and flipped pages immediately after E, then E is believed the ending stroke of the command "paste".

After processing all strokes, the daemon opens the latest digital document in the viewer application, so the user can review their previous paper-based work, and continue the task with the digital version.

4.7 Gesture Recognition

The command gesture recognition is performed with two steps, stroke stream parsing and gesture recognition.

4.7.1 Stroke Stream Parsing

Parsing gesture strokes is a crucial issue. Gestures before the pigtail crossing are taken as command scopes, and all strokes after the pigtail, if any, as written text commands, of which the number of strokes can vary. As Figure 18 illustrates, we use four rules to determine if a stroke E after the pigtail P is the last stroke of the current command: (1) the following stroke ("S") is spatially further than a threshold away from E, (2) there is a gap longer than a threshold between their timestamps, (3) the user exists "gesture" mode after E, (4) E is the last stroke drawn on this page. As long as any of the four criteria is satisfied, E is taken as the ending stroke, and all strokes between P and E (including E) are submitted to the handwriting recognizer. These heuristic rules have worked fine in our preliminary tests, but formal evaluation is planned as part of future work.

4.7.2 Gesture Recognition

The PapierCraft gesture recognition engine takes a hierarchical bottom-to-top approach, which well matches the composition of PapierCraft operation gestures. The most basic gesture component are individual strokes, like a horizontal straight line for "underline" command scope, and a close circle for "lasso" scope. The component is analogous to individual symbols in human languages. Similarly, like a word made of multiple symbols, a PapierCraft command, like "cropping mark" scope includes two right-angle marks at certain relative positions. Finally, multiple commands, like "copy" and "paste", can be put together to complete a document operation. As the multiple-command has been discussed, here we focus on the two lower layers.

Corresponding to the inherent hierarch in PapierCraft gestures, we built a two-layer recognition engine with inspiration obtained from computer gesture recognition engines like SimuSketch [Kara Burak and Stahovich, 2004] and SketchREAD [Alvarado and Davis, 2004]. At the lower layer, we employed a template-based approach proposed by Wobbrock [Wobbrock, et al., 2007] to recognize individual strokes[4]. It is simple to implement, efficient and robust. Also it is trainable, so we can use the same recognition engine to train and use new gestures in the future. At the

---

[4] For simplicity of implementation, one individual stroke is defined as a series of pen tip coordinates sampled between a pen-down event and the immediately following pen-up event.

higher layer, we adopted a rule-based method to recognize multiple-stroke gestures like the cropping mark. It combines the results from the lower layer and compares them against pre-defined rules, such as “a cropping mark is composed of two right angles that are at the top-left and bottom-right positions and the distance between them are within the pre-set thresholds”. For now, we simply hard coded the rule in the implementation. In the future, a Bayesian Network [Kara Burak and Stahovich, 2004] could be applied to rule description for more flexibility.

4.8 An Early Stage User Testing

To evaluate our gesture design, we conducted a small-scale (four participants) informal test on the command system. Participants were demonstrated excerpt/paste commands and asked to perform the operations using different scope selection mechanisms. We also compared two ink/gesture mode switch methods: 1) a pen and a pedal as “gesture button”; 2) A blue pen for ink strokes and a red pen for gesture strokes.

The overall participant reactions were positive. The participants thought that our gestures would be simple to remember and the option of writing down the command name was also popular due to its ease of use. The evaluation also revealed the profound impact of feedback on the interface design. Firstly, participants generally thought that although one-pen mode switching would be preferred, the direct feedback given the ink color is important. Secondly, they agreed that, if the system can guarantee high gesture recognition rate, the interface is still acceptable even with weak feedback. However, additional feedback would be helpful for even better user experiences.

With the increasing number of digital functions available on paper, we can expect increasingly severe tension between weak paper feedback and complex digital operations. This motivated us to explore the stronger feedback mechanism through the pen.

Chapter 5: Pen-top Feedback for the Paper Interface[5]

Ink can provide immediate feedback to a degree, but it is just a simple "echo" of user input and impossible to reflect status of computer processing. For example, novice users have no means to learn the available command types except reading a manual or wildly trying; they can not know if a gesture is correctly recognized or rejected, let alone perform an interactive task like full-text search. Thus, stronger feedback is necessary for a more usable PapierCraft interface.

For such an interface with richer feedback, we first identify three feedback categories to be required, namely Interface Discover, System Status Indication and Application–specific Feedback. Then we explore how to provide the feedback without harm to the inherent paper affordances. To this end, we avoid using special electronic paper or paper-augmenting devices (e.g. a projector), and resort to light-weight pen-top feedback mechanism, which has been explored in systems like Leapfrog FLY Pen [LeapFrog, 2005] with an auditory interface and Haptic Pen [Lee, et al., 2004] with a tactile interface.

For a systematic understanding of the pen-top feedback, we have designed and implemented a multimodal feedback pen, which can present visual, tactile and auditory feedback via built-in components (e.g. LEDs and vibration motors). Using the feedback pen as an experiment platform, we explored the characteristics of individual modalities and their combinations. As a result, we have proposed a set of

[5] Portions of this chapter were originally published by the author, François Guimbretière and Corinna Loeckenhoff in [Liao, et al., 2006]

design principles for multimodal feedback, which are applicable not only to paper interfaces but also to other general computer interfaces.

By matching these design principles and the identified feedback requirements, we designed a set of pen-top feedback schemes for PapierCraft. A controlled lab experiment has proven the design's effectiveness in helping novice user learning, reducing experienced user error rate, and encouraging error corrections.

5.1 Feedback Required by A Paper Interface

To systematically examine the pen-top feedback, we group the feedback required by a paper interface into three categories.

5.1.1 Interface Discovery

As the complexity of systems like PapierCraft increases, it becomes more difficult for users to learn and remember all the available commands. For such systems to be practical, a discovery interface becomes necessary. Low technology solutions (such as a simple printed card) may help during early use of the system. However, as users become more confident, they may not carry such a card around and will need additional support to remember the location of an occasionally used command. For instance, like in the standard marking menu system [Kurtenbach, 1993], if a user does not remember a command, she should be able to explore possible commands by navigating around the menu center (in our system, the crossing point of the pigtail).

5.1.2 System Status Indication

In this category we include feedback that helps users to ascertain the current status of the system. Examples of feedback in this category include: indication of the current mode of the pen (e.g., stroke color, command vs. writing mode); indication that a given scope (e.g., a crop mark) has been recognized properly; and indication that the current command selection was recognized properly. Such feedback needs to be easy to identify, yet as unobtrusive as possible to avoid limiting the performance of expert users. For example, it should be salient if a command may not be recognized, but there should be no distracting feedback if the same command was recognized correctly.

5.1.3 Application-specific Feedback

The types of feedback in this category are application-specific and include interactions such as searching a given word in the current document, searching the definition of a word, or gathering additional information about the figures in a paper. It would seem an obvious solution to accomplish these tasks through the use of a nearby display such as in the Paper++ system [Norrie and Signer, 2003]. However, we believe that it is useful to offer at least some of the simpler tasks in paper only environment to increase flexibility of use. Timing is less critical for such feedback since it corresponds to a task level time frame.

5.2 A Multimodal Feedback Pen as an Experiment Platform

To provide the required feedback for PapierCraft, we first set a set of goals to guide our designs.

5.2.1 Design Goals

1. **High portability**. This is the primary goal of our feedback pen design, because, like the requirements on the gesture command system, the feedback

devices should never cost the original paper-pen affordances. Although some mobile devices, like PDAs in Books with voices [Klemmer, et al., 2003] and Paper++ [Norrie and Signer, 2003], could be used for the paper interface for additional information, they should not be a *necessary* part of the interface.

2. **Easy setup**. It aims at the similar high accessibility of paper, which is always "on", to support mobile users, who may not bother to spend significant time on setting up the system at every work place.
3. **Compatibility with exiting pen practices**. The design should be seamlessly integrated with the exiting pen-paper use, without forcing users to change their familiar practices.

Keeping these goals in mind, we examined various feedback mechanisms, and finally focused on a pen-top feedback approach, since it is naturally compatible to existing practices and could be highly portable and easy to setup with appropriate designs. The key is how to render the feedback information via a digital pen of normal pen's form factor.

Obviously, the conventional screen-based high fidelity visual feedback is hard to support our design goals, so we turn to other approaches, using hardware that can be built into the form factor of a pen, such as LEDs, micro-motors and wireless earphones. Specifically, we studied low-fidelity visual feedback (e.g. color or brightness of LEDs) and non-visual feedback (e.g. tactile and auditory information) in the context of pen-computing.

Some researchers have been exploring such pen-top multimodal feedback, exemplified by FLY Pen [LeapFrog, 2005], LiveSribe Pen [LiveScribe, 2007] and Haptic Pen [Lee, et al., 2004]. However, there is lack of a systematic exploration about the characteristics of the individual modalities and their combination. To this end, we decided to build a multimodal feedback pen as an experiment platform.

5.2.2 Design of the Multimodal Feedback Pen

We have designed and implemented two version of the multimodal feedback pen (Figure 19), which can provide visual, tactile and auditory feedback through built-in LEDs, vibration motors and voice/sound (currently simulated by a nearby computer).

As Figure 19 illustrates, the pen is based on an off-the-shelf Logitech io$_2$ Bluetooth pen. Two LEDs around the pen tip provide visual status-indication feedback. One vibration motor at the eraser end provides tactile status-indication feedback to alert users of potential errors and ambiguities. Voice feedback (simulated by a base station PC) provided higher-level information for the purposes of discovery

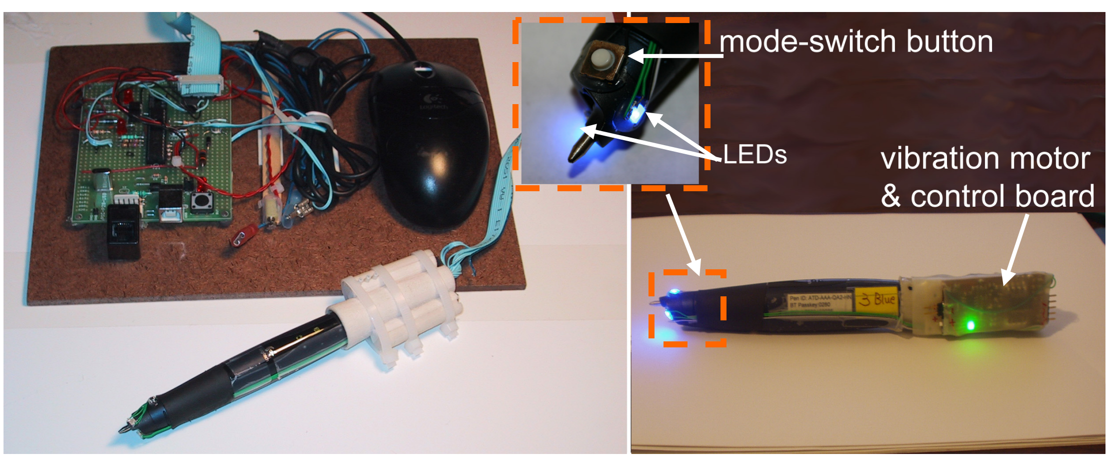


Figure 19: The two versions of the Feedback pen hardware implementations. (Left) Version 1 uses a ribbon cable to connect the pen to the control board, which then talks with the base station PC via USB cables. (Right) Version 2 miniaturizes the control board with a printed circuit board and communicates with the base station via Bluetooth. (Inset) the close-up view of the button and LEDs

feedback and task feedback. A mode-switch button is installed around the pen tip. And a feedback control board, based on a PIC Microcontroller, is adopted to control the LED's and the motor. Note we used the version one for the pen-top feedback evaluation (Section 6.1), and the version two for the subsequent gesture and application evaluation (Section 6.2 and 6.3 respectively). The two versions only differ in terms of hardware implementation, and render the same feedback for PapeirCraft commands.

Figure 20 illustrates the architecture of the feedback pen subsystem. Because we are not allowed to program the digital pen's firmware, we currently process all pen strokes at a separate base state computer, to which the feedback pen connects via USB cables (version 1) or Bluetooth (version 2). The captured strokes and mode-switching button clicks are transmitted to the base station in real time (thus the pen-top feedback is not available for batch-mode stroke processing). The station processes

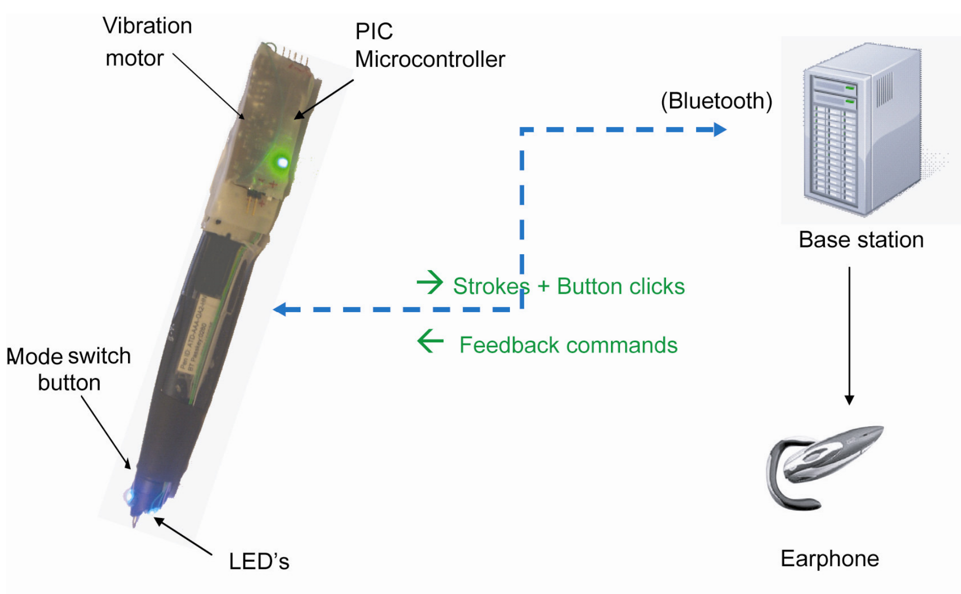


Figure 20: The architecture of the multimodal feedback pen subsystem. The architecture is the same for the two feedback pen generations except the placement of the microcontroller and pen-base station communication media (see Figure 19 for detailed differences).

the strokes with the help of PapierCraft infrastructure, and then sends back instructions to the feedback control module, which then turns on and off the LED's and the motor accordingly.

Although the current implementation relies on a separate base station for background data processing, the interface satisfies our design goals of portability and compatibility of existing practices. In the future, with the available pen-computer platforms like LiveScribe pen [LiveScribe, 2007], we will be able to finally merge the base station into the pen itself.

5.3 Characteristics and Design Principles of Individual Modal Feedback

With the hardware platform, we conducted a serial of pilot user study with 2-3 participants in each round (total N = 12). For example, in one round, we studied different approaches for positive feedback using LEDs, sounds, and vibration. These pilot tests helped us to establish the following general design guidelines for pen-top feedback.

5.3.1 Tactile feedback

Tactile sense refers to sensations evoked by skin stimulation [Poupyrev, et al., 2002]. Tactile feedback provides an important and interesting information channel for handheld devices. It allows precise and fast motor control. For example, it is about five times faster than vision for users to resolve successive data [Geldard, 1960]; It generates low cognitive load of users, so can be performed in parallel with other operations [Poupyrev, et al., 2002]; Further, it supports information encoding. For example, people can accurately sense the variants of textures and surfaces [Poupyrev, et al., 2002]. Thus, our design is trying to take advantage of this modality.

The current Logitech pens already use a small vibration motor to indicate error conditions. Inspired by this approach, we selected an implementation similar to Haptic Pen [Lee, et al., 2004] to allow for better control of timing as well as a wider range of tactile sensations.

Our first finding with regard to tactile feedback was that it should be used *parsimoniously*. While powerful, such feedback can be a source of annoyance if it is used for any long period of time. This explains why we reserved tactile feedback for status-indication and discovery feedback (see Table 3). Our second finding was that providing tactile feedback as positive feedback can actually *slow down* execution. For example, during pilot testing of a marking menu implementation, we found that when tactile feedback provides stronger vibrations as the pen gets closer to the optimal

		Feedback type		
		Discovery	Status	Task
Modality	Visual	Command direction	Mode, Recognition	Page-level location
	Tactile	Boundary warning	Ambiguity detection	
	Sound	Boundary crossing		
	Voice	Command name		Document-level location

Table 3. Modality by feedback type matrix. The gray cells indicate unadvisable combinations. For example, voice feedback does not provide the speed and simplicity required for status-indication feedback. To limit mapping complexity, sounds are only used for discovery feedback at this point.

path, subject performance decreases. The same phenomenon holds for auditory or color coding positive feedback.

At first, this result may seem to contradict the work of Zhai et al. on Trackpoint [Campbell, et al., 1999]. However, the two tasks represent very different usage conditions. Zhai et al.'s experiment was focusing on a tracking task where positive feedback is very important. In contrast, optimal performance with marking menu is reached in "open loop" interactions where muscle memory plays a major role. In such contexts, adding feedback might be distracting as it may induce users to revert to a tracking strategy instead of an "open loop" interaction. Thus, we used tactile feedback exclusively to indicate erroneous or ambiguous areas. For example, our pen vibrates when the users are too close to the border between two marking menu octants thus creating the potential for ambiguity.

5.3.2 Low fidelity visual feedback

New multi-color LEDs are small, power-efficient, and provide a wide range of possible feedback. LEDs can be placed to shine directly on the paper (to show the currently selected color) or to be visible on top of the pen tip to show the status of the pen even when the pen is not near a piece of paper. For example, our system uses the top LED to provide feedback for command selection, since at the end of command selection, the pen is often already lifted into the air.

Our pilot studies showed that LEDs worked very well for modal feedback (e.g., current stroke color, confirmation of command selection). Not surprisingly, we also found that it is important to avoid blinking light as much as possible since it is very distracting for users. Further, for abstract mapping (e.g., the name of the currently selected command), it is important to limit the number of colors to a minimum. Otherwise, the mapping between color and meaning increases mental load. Another issue regarding color mapping are ambiguities encountered by color-blind users. To address this latter problem, it may be possible to use colors with different luminance

Unlike tactile feedback, visual feedback can be used for longer periods of time. However, like tactile feedback, it may slow down performance, especially if it is used as a visual guide. In some cases, this effect could be used to intentionally slow down users who are about to carry out a potentially problematic operation (e.g., “Delete”).

5.3.3 High fidelity visual feedback

Some pen systems, such as the WIZCOM translator pen [WIZCOM, 1995], integrate an LCD display into the pen. It may even be possible to create small projection displays by installing a small low power laser raster [2005] at the eraser end of the pen. Such displays would offer a high bandwidth channel. However, they will add to the bulk of the pen and might significantly impact power consumption. Therefore, we did not consider these options in our current design.

5.3.4 Auditory feedback

As shown by the Fly pen system [LeapFrog, 2005], voice (and of course sound) can be used for pen-top interfaces. Like haptic feedback, auditory feedback has access to pre-attentive channels that can easily attract users’ attention.

Because the presentation of information through spoken language is essentially serial, it may take up a lot of time. Therefore, voice feedback should be reserved for feedback which operates under more extended time frames, such as discovery and task level feedback. Nevertheless, short sounds can be used for status-indication feedback like status changes or action confirmations. The latter approach has been extensively implemented in many existing systems such as ARKOLA [Gaver, et al., 1991] and Mercator [Mynatt and Weber, 1994]. One potential problem is that auditory feedback may raise privacy issues. However, these could be easily alleviated by using headphones or a Bluetooth earpiece.

We summarize the design principles in a cross-matrix of feedback mechanisms and feedback types in Table 3. These principles are then applied to PapierCraft command system as presented below.

5.4 Multimodal Feedback for PapierCraft

Figure 21 illustrates our pen-top feedback design for each of the types of feedback we explored.

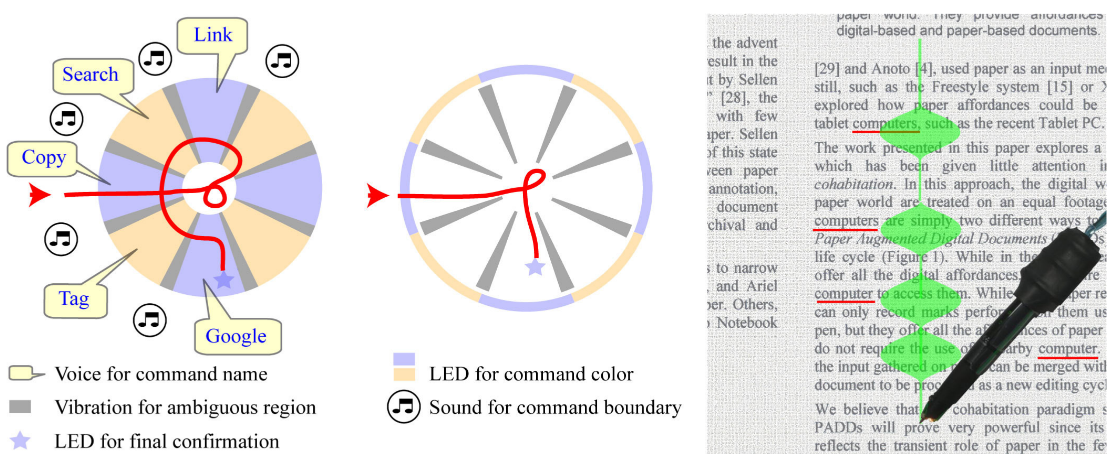


Figure 21: (Left) An illustration of a novice user receiving discovery feedback. The gesture stroke (red line) leads from left to right and the user receives feedback through voice, sound, vibration, and LEDs. The center blank region is a “silence” zone with no feedback. (Middle) An expert selects the same command, receiving feedback for final confirmation. (Right) Task level feedback during search. After a voice informs users which page contains the target word, they may scan this page from top to bottom. When lines containing a search hit are close by, the LED on the pen changes to high brightness (indicated by the thickness of the green line). For clarity, the target word “computer(s)” is underlined in this illustration.

5.4.1 Interface Discovery

Interface discovery feedback is intended to help novice users to discover the interface and intermediary users to remember commands that are not used very often. In pilot testing, we examined different mechanisms to convey command names including color coding, non-speech auditory coding, and vibration pattern coding. We found that voice feedback is the most natural way to provide information about command names. None of the other approaches worked well for a marking menu with eight or more items.

Figure 21 (left) illustrates our discovery feedback mechanism. Upon drawing the pigtail, the discovery mechanism is triggered after a timeout of 500ms to avoid distracting expert users. This delay is slightly longer than the typical 330 ms delay [Hinckley, et al., 2005] because we discovered that users take slightly longer to mark a menu on paper. After the delay, the system speaks the name of the command triggered by the current octant. The top LED also indicates the current color of the octant. We first experimented with assigning one color for each possible direction, but discovered that this was quite confusing. Noting that what matters for users is to distinguish between two adjacent octants, we reduced our color coding to only two colors: blue for the primary direction (e.g., North vs. South, East vs. West) and yellow for the secondary direction (e.g., North-East vs. South-West). These two colors form a strong contrast (even for users with the common red-green color blindness) which makes them easy to distinguish.

As users start exploring available commands by circling around the center of the menu, tactile feedback is used to indicate menu boundaries and, more specifically, the areas for which command recognition might be ambiguous. To allow for quick exploration, the system speaks the name of a new octant as soon as the pen enters it (even if the previous name is not yet completed). This feature initially created some confusion since during rapid movements, command names were sometimes skipped altogether. For example, users would feel three vibrations but hear only two different spoken octant names. To better convey navigation status, a short “popping water bubble” sound was added whenever a boundary was crossed.

The desired command is selected upon pen lift. Simultaneously, the top LED shows a single pulse in the color of the selected octant and slowly decays. Note that to abort the selection, users can return the pen tip to the center of the menu (i.e., the crossing point of the pigtail) and lift the pen.

5.4.2 System Status Indication Feedback

Our system uses two LEDs to indicate the current pen status. The bottom LED indicates the current stroke color and the top LED indicates if the pen is inking or used in command mode.

Our design for experts focuses on alerting users about possibly ambiguous situations. To encourage skill transfer, the expert interface uses the same color coding and tactile feedback as the discovery interface, but does not use voice or color feedback during marking. If a mark is far away from any menu boundaries, we do not provide any feedback until the mark is finished. Then we provide a single, slowly decaying pulse of the color corresponding to the selected direction. If the mark enters one of the ambiguous areas between two menu octants, we use tactile feedback to warn users, and show the color of the recognized direction upon pen lift. This makes it easy for users to check if the system recognized the mark correctly.

When called up through a pigtail gesture [Hinckley, et al., 2005], marking menu is often associated with an initially curly stroke that could trigger a transient vibration. To reinforce the mapping between the lack of tactile feedback and a successfully issued command, we added a "*silence*" zone in the center of the menu where no feedback is provided.

5.4.3 Application-specific Feedback

To explore an example of more complex feedback, we allowed users to search a given word in the printout of a document. For this feature, the pen needs to be uploaded with search information about the current text (e.g., during printing, through the PapierCraft infrastructure [Liao, et al., 2005]). In the future, users will be able to provide their own written keywords, but in our present prototype, users select the keyword from printed text.

For this task, we identified two kinds of necessary feedback. First, users need to find the pages which contain the target word. Since it would be tedious to scan the whole document, we used voice feedback to provide the list of relevant pages. When a target page is reached, the user needs to identify the exact location of the word. For that sub-task, voice feedback would be time consuming and difficult to process (e.g., "left column, 3rd paragraph line 35"). Instead, we used visual feedback. Users simply swipe the pen along a page margin and observe the top LED on the pen which lights up when the pen passes a line that contains the word. If there is no word selected for the “search” command, the previous keyword, if any, will be used. Figure 21 (right) illustrates the process.

We considered using tactile feedback for the within-page location, but we decided against it because of the following concerns: first, narrow tactile “bumps” are difficult to reliably identify, especially if the user moves rapidly; second, wider bumps with a ramp are annoying for users since they create vibrations of long duration. Instead, we used tactile feedback to indicate errors (e.g., when searching on a page which does not contain the target word).

Chapter 6: Evaluation on PapierCraft[6]

We evaluated PapierCraft to answer two questions. The first one is about the usability, *Can people use this system?* The second one is about the potential applications in real life, *Will people use the system?* To answer these questions, we examined PapierCraft at three interaction levels from low to high, known as the *command-component* level, the *whole-command* level and the *application* level. For simplicity, the terms *command* and *gesture* are exchangeable in the following presentation.

The first two levels address the usability issues. The command-component level evaluation tested how well a user draw PapierCraft command *components*, which include the command scope, the pigtail delimiter and the command type (see Chapter 4). We first focused on the command types, and studied how it can be enhanced with pen-top feedback. Afterwards, at the whole-command level, we tested all the three components, measuring the learnability and recognition rate of the PapierCraft commands with various scopes and types. Finally to evaluate the application level interaction, we investigated a PapierCraft application in a real-world-like Active Reading scenario. This high-level evaluation helps us test the main hypothesis of this dissertation that PapierCraft bridges the paper-computer gap by combining the affordances of the two media (paper and digital media). This systematic approach enables us to concentrate, at a time, on a relatively small part of PapierCraft, and to understand it at both micro- and macro- scales.

---

[6] Portions of section 6.1 were originally published by the author, Guimbretière and Corinna Loeckenhoff in [Liao, et al., 2006]

We adopted an experimental approach, comparing PapierCraft against the existing Tablet PC interface at all the three levels. As these two interfaces are very representative in the spectrum of interactive displays, this approach may highlight their pros & cons, and shed light on the design of new interfaces that combines the merits of the two media for digital document interaction.

6.1 Command-Component Level Evaluation: Pen-top Feedback

We began with pen-top feedback for the command type selection. As we discussed in Chapter 5 Section 1, PapierCraft supports three types of pen-top feedback for command issuing, namely *interface discovery*, *system status* and *application-specific feedback*. The first two are common to all PapierCraft commands and tightly tied to the user experience of paper-based interface, hence the focus of our evaluation.

We evaluated two important features of the pen-top feedback design. First, we examined if the interface discovery feedback would help novel users explore the available command types of an unfamiliar PapierCraft interface and improve their performance quickly. Second, we tested if the system status feedback would help expert users reduce errors in the command type selection without sacrificing their performance too much.

To highlight the possible effects of the pen-top feedback, we conducted a controlled experiment, comparing three different techniques representing the range of currently available pen interfaces:

1 A simple PapierCraft interface in which all interactions with the marking menu are performed on paper and the only immediate feedback is the ink itself. This technique represents the lower end of the spectrum of feedback fidelity. In accord with existing pen systems we also provided a quick reference card printed with the currently used marking menu commands. While users may not always carry such a card in real-world settings, we felt that not providing a reference card would be very frustrating for users and not tell us much about the value of our system.

2 A multimodal pen-top feedback system. In this condition, users were only allowed to see the quick reference card during training. During experimental trials, they had to rely exclusively on our system to discover the menu or detect their errors. In this configuration, all interactions were performed on paper.

3 A tablet PC with an implementation of the same marking menu task. This configuration represents the higher end of the feedback fidelity spectrum. The pigtail-enabled marking menu was implemented in a manner similar to Scriboli [Hinckley, et al., 2005] with a 500 ms delay before the pie menu layout appeared. Upon selection, the selected octant was highlighted and appeared for 75 ms (without showing any other octants) for confirmation purposes.

6.1.1Experimental task

To compare the three techniques, we picked a typical task in PapierCraft: use the "underline" scope selection to select a word, and then issue a given command. This task is easily tractable and forces users to always start their pigtail in the same direction. This is important since the performance of pigtail-based marking menus is affected by the starting direction.

To avoid the variance introduced by mode-switching actions and to focus more on feedback impact, we set the pen to gesture mode for all three techniques. Thus, participants did not need to press the gesture button. Accordingly, the top LED of the multimodal pen was not used for mode indication but for other types of feedback.

Figure 22-Right shows an example of the experimental interface which was either printed on paper or presented on the tablet PC screen. First, the users had to tick on the “start” button, then underline a dotted line in the central panel, then select the menu command presented on a screen in front of them (one out of eight possible choices), and finally tick the “done” button when they thought that their command selection was correct. Thus, users needed to first commit to their current selection before receiving feedback about its accuracy. Users could make as many corrections as they wished before clicking on the “done” button. After clicking this button, the computer played a sound reflecting success or failure. We provided error feedback to ensure that participants’ error rate would stay below 12%. We chose a comparatively high threshold because one goal of the experiment was to examine how error rates differed across techniques. Thus, it was important not to impose too strict limitations on error rate. At the same time we needed to ensure that subjects did not rush through

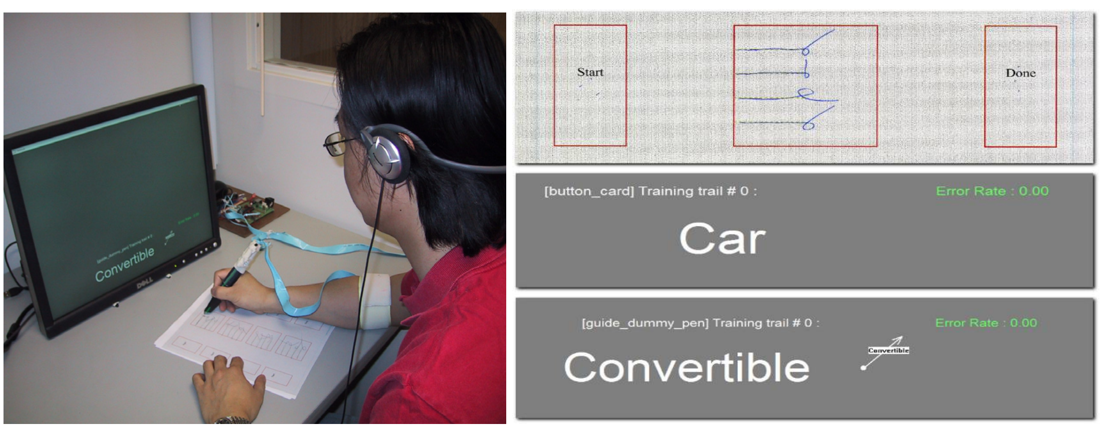


Figure 22: (Left) the experiment hardware setting for the feedback pen condition. (Right-Top) the experimental interface on paper. (Right-Middle) A sample stimulus for the discovery setting with current average error rate at the top right corner (for the latest 20 trials). (Right-Bottom) A sample stimulus for the expert setting. A labeled arrow in the middle illustrates the correct direction of the marking menu item (e.g., “convertible”) for expert simulation.

the experiment at the expense of data quality. We believe that the 12% level offers a good compromise between these two objectives.

To evaluate both novice and expert performance, the task was run in two different configurations. In the discovery configuration, the stimulus screen provided only the name of the correct menu selection. Users could use any feedback available in the current setting to select the appropriate menu item. This configuration was intended to evaluate how interface discovery feedback could help users explore a new menu system. The discovery condition was always run first. In the expert setting, the stimulus screen provided both the name and the direction of the correct selection as suggested in [Balakrishnan and Patel, 1998]. The goal for this configuration was to simulate expert performance and evaluate if status-indication feedback would help expert users to catch errors early.

6.1.2 Performance Measures

Task Completion Time and *Accuracy* were the two main dependent variables. Completion time is the interval between ticking the "start" and the "done" buttons. Accuracy refers to the rate of correctly submitted command selections. To examine error correction behavior, we also examined the *Correction Rate*, the proportion of trials in which an initially wrong menu selection was later corrected.

6.1.3 Procedure

We used a within-subject design for this experiment. Each participant completed the task using all three techniques in a fully counterbalanced order. For each technique, participants first completed the discovery setting and then the expert setting. For the discovery configuration, users performed 4 training blocks followed by a 12-block measurement phase. For the expert configuration, there were 2 training blocks and 10 measurement blocks (fewer blocks were used for this setting, since the task was simpler and showed less variance). There was a mandatory 4-second break after every 2 blocks. Each block corresponded to 8 selections (one for each octant of the menu) presented at random. To avoid learning effects across techniques, we used a different set of command names for each technique (e.g., names of vehicle types or fruit names). The association between sets of command names and techniques was counter-balanced as well. After each technique, participants completed a questionnaire about the technique. A general questionnaire was completed at the end of the experiment.

6.1.4 Experimental Setup

The experimental settings are illustrated in Figure 22. Visual stimuli were presented on a flat LCD display in front of the subjects. A pile of printed documents (with Anoto pattern) or a tablet PC was put in front of the display without fixed orientation or position, simulating the real-life scenario of reading and writing. Participants used a stylus on the tablet PC or our augmented digital pen on Anoto paper. The augmented pen is the version 1 of our feedback pen (see Chapter 5 for details), which connects to the control board via a ribbon cable. The same pen was used for the simple pen and the multimodal pen settings but the feedback features were only enabled for the latter.

The experiment was controlled and data were logged by the same tablet PC for all techniques. Depending on the technique, the PC received stroke information from its own stylus or from the augmented pen (via Bluetooth). When feedback was enabled, it controlled the LED and the solenoid through a ribbon cable. Auditory feedback was rendered through a stereo headphone.

6.1.5 Participants

We recruited 12 participants, 3 female and 9 male. All of them were college students or had at least a college degree, and ranged in age from 18 to 35. All had used a desktop computer for 7-18 years and 3-12 hours per day. Three participants had 1.5-5 years of experience with a PDA, the others had not used pen computing at all. None of them had ever used a digital pen. It took participants about 90 minutes to finish the experiment, including the training phases, experimental phases, and questionnaires. They received $20 for their participation.

6.1.6 Results of Discovery Setting

In the results presented below, Greenhouse-Geisser correction was used to account for deviations from sphericity. All post-hoc tests used Bonferroni corrections.

To control for outliers, we removed trials with completion times more than 3 SD above the mean within a given block and technique. This amounted to 1.59% of the data points.

Task completion time

We first studied how completion times for each of the techniques developed across subsequent blocks. A technique by block repeated measure ANOVA found a main effect of technique, $F(1.37, 15.1) = 5.35$, $p < .05$, partial $\eta^2 = 0.33$, suggesting that completion times (in milliseconds) in the multimodal pen condition (M = 3840, SD = 2330) were marginally higher than in simple pen condition (M = 2830, SD = 771, p = .06), but not significantly different from the tablet PC condition (M = 3070, SD =

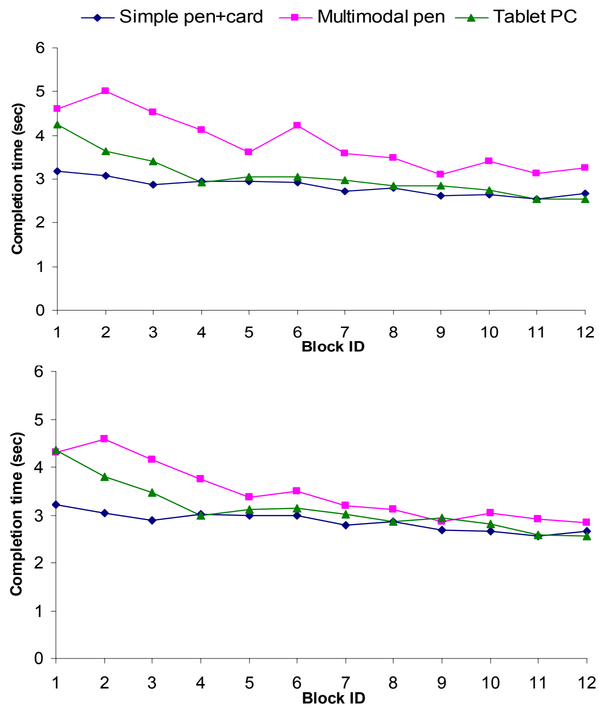


Figure 23: Mean completion time for the discovery setting. The top graph includes all participants while. The bottom graph excludes participants who did not follow instructions (see text).

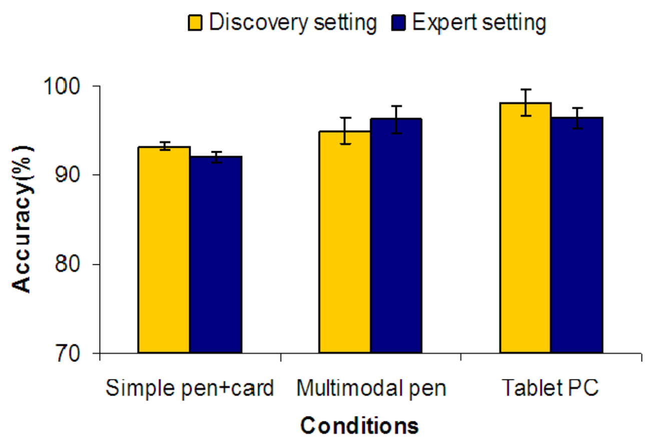
1280, $p = .20$). We also found a main effect of block, $F(3.48, 38.2) = 20.0$, $p < .01$, partial $\eta^2 = 0.65$, suggesting that completion time decreased across blocks. However, these effects were qualified by a significant interaction suggesting that the gap between techniques diminished across blocks, $F(22, 242) = 3.58$, $p < .01$, partial $\eta^2 = 0.25$, as shown in Figure 23 (top).

Because the variance in the multimodal pen condition was higher (SD = 2330 ms) than in the other two conditions (SD = 771 ms and 1280 ms, for simple pen and tablet PC respectively) and because the learning curve for the multimodal condition showed discontinuities (e.g., in Block 6, see Figure 23, top) we examined the log data and experiment records to identify any participants who might have had problems following instructions. We found that Participant 6 used the voice feedback instead of the LED for command type confirmation which created an artificial delay. Participant 8 focused on trying to recall the correct items instead of using the discovery interface, as indicated by an unusually long thinking time before starting to draw. To better understand the learning curves without this bias, we repeated our analyses excluding these two participants (Figure 23, bottom). The pattern of results was comparable showing a main effect of block, $F(11, 99) = 16.5$, $p < .01$, partial $\eta^2 = 0.65$ and a strong technique by block interaction, $F(22, 198) = 3.39$, $p < .01$, partial $\eta^2 = .27$. The effect of technique was only marginally significant, $F(2, 18) = 2.61$, $p = .10$, partial $\eta^2 = 0.23$. However, note that the removal of two participants might invalidate the original counter-balancing among the techniques. Thus, a larger study will be needed to confirm these results.

Together, these results indicate that although participants' initially experienced a higher task completion time in the multimodal pen condition, they were able to master the interface after 12 blocks. The initially higher task completion time is not surprising since users needed to perform a sequential search to familiarize themselves with the menu items while in the other conditions, a simple glance at the reference card (in the simple pen condition) or the screen feedback (in the tablet PC condition) was sufficient. Also, as illustrated by the poor performance of participants 6 and 8, successful use of the multimodal system requires that users are thoroughly trained in the optimal strategies for this technique.

Accuracy and Error correction behavior

For accuracy, a block by technique ANOVA found a main effect of technique, $F(2, 22) = 9.17$, $p < .01$, partial $\eta^2 = 0.45$, suggesting that tablet PC ($M = .98$, $SD = .14$) showed significantly higher accuracy than simple pen ($M = .93$, $SD = .25$, $p < .01$)



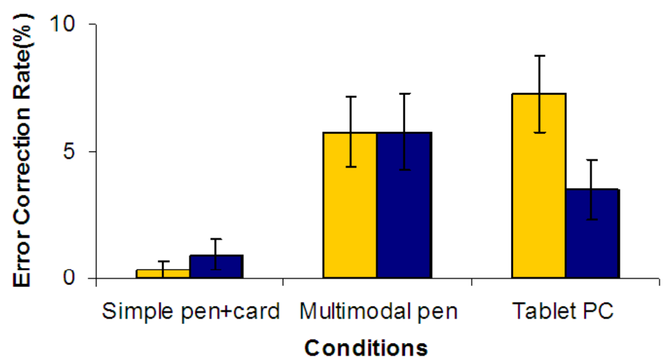


Figure 24: Mean accuracy (top) and correction rate (bottom), for both discovery and expert setting (error bars show 95% confidence interval).

and multimodal pen ($M = .95$, $SD = .22$, $p < .01$, see Figure 24, top, yellow bars). There was no main effect of block and no technique by block interaction.

Since it was one of our goals to help users detect their mistakes early, we also examined the correction rates. A block by technique ANOVA found a main effect of technique, $F(1.29, 14.2) = 18.0$, $p < .01$, partial $\eta^2 = 0.62$, suggesting that the simple pen ($M = .004$, $SD = .06$) had significantly lower correction rates than the multimodal pen ($M = .06$, $SD = .24$, $p < .01$) and the tablet PC ($M = .07$, $SD = .26$, $p < .01$, see Figure 24, bottom, yellow bars). There also was a main effect of block, $F(11, 121) = 2.29$, $p < .01$, partial $\eta^2 = 0.17$. Further examination revealed that correction rates increased across blocks, most likely because users became more familiar with the error correction mechanisms for each technique. There was no block by technique interaction.

These results suggest that while accuracy rates are comparable in the two paper-based interfaces, the multimodal pen is better than the simple pen and as good as the tablet PC in encouraging users to correct their mistakes.

6.1.7 Result for Expert Setting

As in the discovery setting, we removed trials with completion times more than 3 SD above the mean within a given block and technique. This amounted to 2.05% of the data points.

Task completion time

A block by technique ANOVA found a main effect of technique, $F(2, 22) = 9.57$, $p < .01$, partial $\eta^2 = 0.47$, suggesting that the tablet PC (M = 1920, SD = 454) was significantly faster than the multimodal pen condition (M = 2270 , SD = 620, $p < .01$), while the difference between multimodal and simple pen (M = 2060, SD = 473) was not significant ($p = .17$). There also was a main effect of block, $F(9, 99) = 3.55$, $p < .01$, partial $\eta^2 = 0.24$ reflecting a learning effect across blocks, but no block by technique interaction.

Accuracy and Error correction behavior

A block by technique ANOVA with accuracy rates as the dependent variable found a main effect of technique, $F(2, 22) = 16.8$, $p < .01$, partial $\eta^2 = 0.61$, suggesting that both multimodal pen (M = .96, SD = .19) and tablet PC (M = .96, SD = .19) had higher accuracy rates than the simple pen condition (M = .92, SD = .27 , $p < .01$ for both, see Figure 24, top, blue bars). There was no main effect of block and no significant block by technique interaction. This result reflects the effectiveness of the multimodal feedback for expert users.

For correction rates, a block by technique ANOVA found a significant main effect of technique, $F(2, 22) = 10.5$, $p < .01$, partial $\eta^2 = 0.49$, suggesting that the simple pen ($M = .01$, $SD = .10$) had significantly lower correction rates than the multimodal pen ($M = .06$, $SD = .23$, $p < .01$) and the tablet PC ($M = .04$, $SD = .18$, $p < .05$, see Figure 24, bottom, blue bars). There was no main effect of block and no block by technique interaction. This finding suggests that the stronger feedback in the multimodal pen as compared to the simple pen condition encourages error corrections.

6.1.8 Subjective Evaluation

We included the NASA TLX using a 1-7 scale to evaluate user experience in each session. The results confirmed that the expert phase of the experiment had a lower task load. The questionnaire also reflected objective performance characteristics. A 3 (technique) by 2 (Discovery vs. Expert setting) ANOVA on TLX "Performance" scores, found a main effect of technique, $F(2, 22) = 4.28$, $p < .05$, partial $\eta^2 = 0.28$. Post-hoc tests showed that compared to the tablet PC condition ($M = 5.71$, $SD = 1.23$), user-perceived performance was significantly lower in the multimodal pen condition ($M = 4.79$, $SD = 1.74$, $p < .05$) and marginally lower in the simple pen condition ($M = 4.79$, $SD = 1.41$, $p = .06$). There was no difference between the discovery and expert setting and no setting by technique interaction.

Our questionnaire also asked participants to rate the usefulness of individual characteristics of the interface on a scale from 1-7. Users rated the LED color coding in the discovery setting (M = 6.17, SD = 1.59) and the opportunity to correct errors in general (M = 6.08, SD = 1.00) as the most important features of the multimodal pen interface. This suggests that our design was successful not only on the objective level (see above) but also on the subjective level. Another interesting finding was that the vibration feedback in the expert setting did not receive good scores (M = 2.67, SD = 1.56). A possible cause is that during rapid movement, the vibration may have been too short to be perceived reliably. Increasing the minimum vibration time may address this problem. The sound-based indicator for boundary crossing during discovery did not fare much better (M = 3.58, SD = 1.93). Future interfaces should fine-tune these features.

By comparing the PapierCraft feedback pen to a normal pen and a Tablet PC, we have demonstrated the effectiveness and efficiency of the pen-top feedback in helping users select command types. Next, we will look into the PapierCraft gestures at a larger scale, evaluating them at the whole command level.

6.2 Whole- Command Level Evaluation: Performance of Drawing Gestures

At the whole-command level, we dealt with a broader usability question: "How well does an average user draw the PapierCraft gestures?" To answer this question, we needed to examine how users draw different command scopes and types, specifically the user input speed and accuracy. And to emulate the realistic use of PapierCraft, we wanted to test it in a typical application scenario, say Active Reading.

Since it is hard to use absolute quantitative measures to qualitatively judge whether or not a user performs well, we compared PapierCraft with a Tablet PC interface. Our hypothesis was that, after some training, *PapierCraft users can achieve* *a performance comparable to that of Tablet PC users*. Unlike the last pen-top feedback experiment, we did not use the "non-feedback pen" setting, because this experiment focused on the gesture learnability and recognition rate, and not on the effect of pen-top feedback.

6.2.1 Experiment Task

The experiment task emulated a typical Active Reading scenario: an individual interweaving reading, annotating, and digital operations while working on a document. With PapierCraft integrated, such an Active Reading scenario consisted of repeated interaction cycles involving PapierCraft gestures. Each cycle usually included 5 steps, namely: 1) *annotation*, 2) *switching the pen to "command" mode*, 3) *drawing a command gesture*, 4) *switching the pen back to "annotation" mode*, and 5) *continued annotation*.

For the purposes of emulation, we used a real Computer Science research document as the working context for participants' input (Figure 25-left), and not the mostly blank sheets in the pen-top feedback experiment. Figure 25 illustrates an example: Within the document, a participant used a digital pen or stylus to tap a

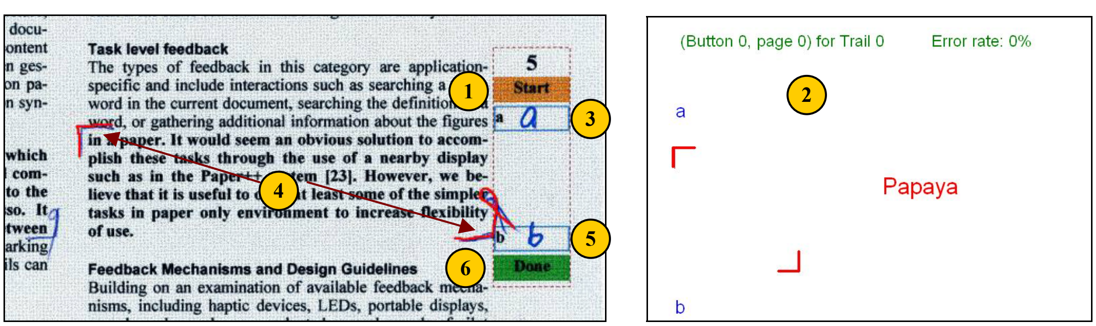


Figure 25. A paper version of the input interface (left) and a stimulus (right). The interaction steps are indicated by the numbers: (1) tap the "start" button, (2) read the stimulus that shows in response to step 1, (3) following the stimulus, write "a" in the annotation mode, (4) draw a cropping mark scope and a marking menu for "Papaya" in the gesture mode (highlighted in red for clarity), (5) write "b" in the annotation mode, and (6) tap the "done" button to submit the input.

“start” button to begin the trial (step 1). In response, instructions, i.e. an experiment stimulus, were shown on a screen (step 2). Following the instruction, the participant used the pen in “annotation” mode and filled out the blue annotation input box with the designated letter (e.g. “a” at step 3). Then, she switched the pen mode to “command” mode, and drew a PapierCraft gesture with the requested command scope and type (e.g. the cropping mark scope and marking menu for “Papaya” at step 4). The command selected the specified document content, which was the bold text or the figure next to the annotation input boxes. She then drew another letter in “annotation” mode (e.g. “d” at step 5).

The participant could re-draw the input as many times as she wanted. Once she felt that the input was good enough, she tapped the “done” button to submit the input (step 6). If there was no error, a brief “happy” sound was played, otherwise, a “sad” sound followed along with a detailed error description. In this way, the participants could learn from errors and improve their technique during the experiment.

6.2.1.1 Two tasks to select keywords and blocks

Different PapierCraft command scopes aim at different document contents and support different tasks. These scopes can be grouped into to two categories based on their targeted document content. The first one, *keyword selectors* (the *underline* and *lasso* scopes), are designed for a section of a text line; the second one, *block selectors* (the *cropping* mark and *margin bar* scopes), are used for a portion of a figure, a table, or a paragraph.

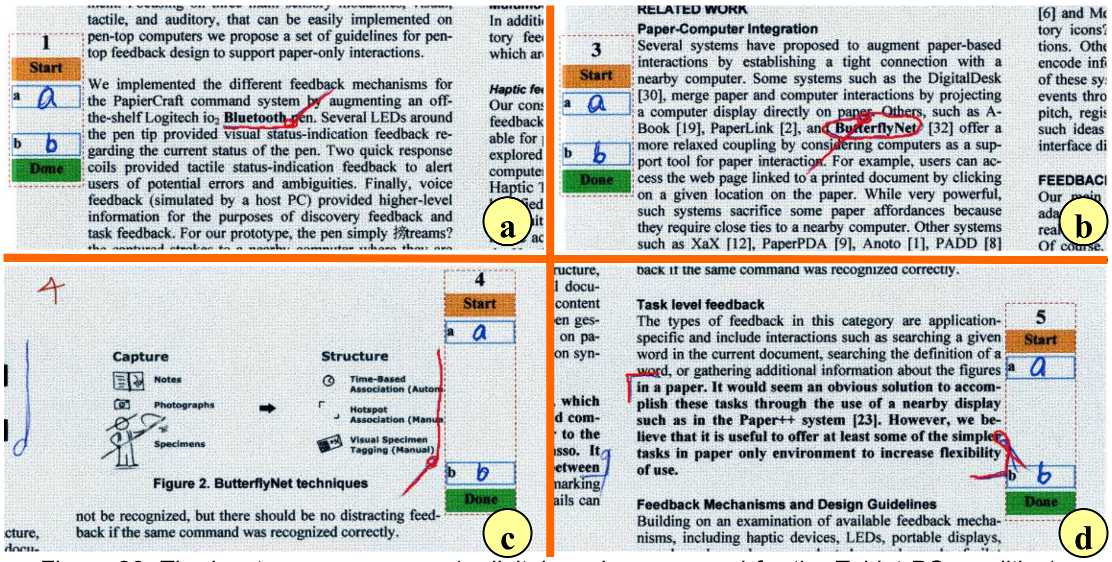


Figure 26. The input pages on paper (a digital version was used for the Tablet PC condition) with 4 scope types. (a) and (b) keyword pages with the underline and the lasso to select keywords. (c) and (d) bock pages with the margin-bar and the cropping-mark to select a paragraph and a figure, respectively. The gestures are highlighted in red for clarity.

To separately examine the two groups of scope selectors, we designed two kinds of user input pages: the *keyword* page and the *block* page. In a keyword page (Figure 26(a) and (b)), participants were asked to use *underline* and *lasso* gestures to exactly select the designated keywords in bold. For generality, we alternately used one-word and two-word targets and roughly evenly distributed them within a page. In block pages (Figure 26 (c) and (d)), participants had to use *cropping-mark* and *margin-bar* gestures to select several lines of text or a figure. Again, we also arranged the target blocks evenly on the pages.

6.2.2 Experiment Setting

The experiment was conducted in our lab. All stimuli were rendered on a vertical monitor in front of participants, who in response drew the required command scopes and types on either PapierCraft paper sheets or on a Tablet PC (Figure 27).

The PapierCraft paper was letter-sized with an Anoto pattern in the background. The multimodal feedback pen implantation used was version 2, which

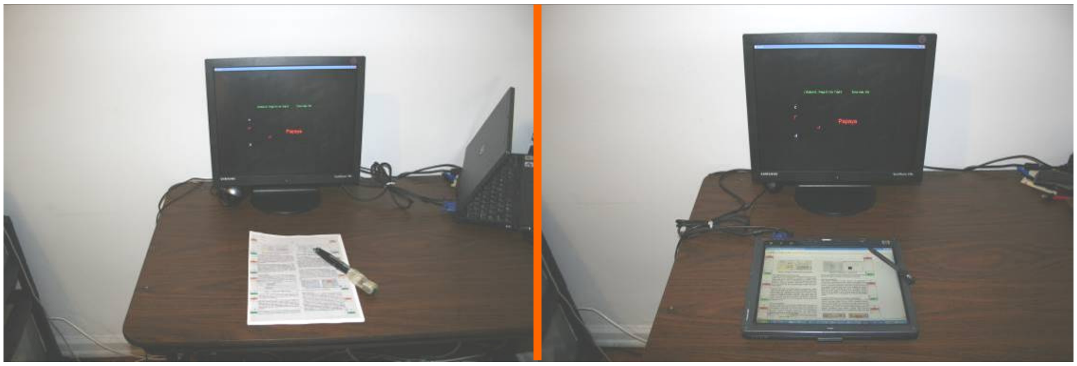


Figure 27. The experiment setting. (Left) The PapierCraft condition with the base station nearby. (Right) The Tablet PC condition. The Tablet PC was used with dual-display configuration.

uses a miniaturized control board (see Chapter 5 for details). The pen was connected to a Tablet PC as a base station, via a Bluetooth gateway. The base station received streaming strokes from the pen, processed them in real time, and presented stimuli and results on the vertical monitor. It also simulated auditory feedback through a speaker for the feedback pen. In PapierCraft condition, the screen of the Tablet PC was hidden from the participants, who consequently had only the pen-top feedback.

In the Tablet PC condition, the same Tablet PC was used for the input interface. Therefore, the two conditions shared the same recognition algorithm and computation power, thus avoiding the confounding variances for these aspects. The size of the documents shown on screen was adjusted to be roughly the same size as a paper copy (through manual measurement). The main differences were that Tablet PC condition participants used a stylus on, and received visual feedback (e.g. a pie menu) directly from, the screen. In both conditions, the Tablet PC logged all user input for later quantitative analysis.

Without losing generality, we adopted the ACM conference article format with two columns and 10pt font in both conditions. Because the experiment focused on the gestures, and not on the underlying document content, we only adopted two different document pages, each of which was duplicated for the keyword pages or block pages.

6.2.3 Experiment Procedure

For each condition, we employed four blocks, each with 4 pages for 4 different command scopes, respectively. Each page contained 8 trials for 8 different command types. Thus, there were 4 blocks, 4 command scopes, 8 command types, totaling 128 trials on 16 pages. Both the order of the command scopes in one block and the order of the command types on one page were randomized. Further we adopted 2 different sets of background documents and command names for the 2 conditions in counterbalanced order.

At the beginning of a condition, we had a training block of 2 pages with 16 trials, followed by 4 testing blocks. The training and testing blocks used the same menu for a long enough learning procedure. For each testing page, participants were asked to perform the trials 0-7 as indicated in the document. At the end of each page, there was a 5 second break enforced by the experiment program.

To help users basically memorize the menu and to help them achieve a semi-expert skill level, we gave participants a "cheating" card showing the current menu during the first block. Afterwards, the card was removed, and participants needed to refer to the pen-top or the on-screen feedback for unfamiliar menu items.

For error control, we showed the current error rate of the last 16 trials on the stimulus screen. Once the rate was above 12.5% (i.e. more than one out of 8 trials were wrong), the error rate number would turn red and the participants were reminded to slow down a little. This design was similar to that in the pen-top feedback experiment, aiming to study the user performance within a reasonable range of error rates.

At the end of each condition, participants filled out a questionnaire for the perceived word load at 2 check-points (immediately after card removal and at end of the test), which examined the effect of the cheating card. Finally, participants finished an overall evaluation form at the end of the whole experiment (see Appendix 2 for details).

6.2.4 Performance Measures

We wanted to test the user performance (speed and accuracy) in drawing whole PapierCraft gestures, so we focused on the following 2 measurements:

1. **Task Completion Time**: the duration (in milliseconds) between tapping the "start" button and the "done" button

2. **Block Error Rate**: the percentage of trials that had at least 1 error in a block (32 trials). The major error types included: "wrong command scope or type," "wrong pen mode," and "inaccurate selection." The *inaccurate selection* error meant that the selected document content was not the requested one, even though the shape of the command scope and type may have been correct. Note that this measurement was dependant upon the input page types. For keyword pages, participants were required to select the exact target words. In contrast, for block pages, it was acceptable if at least 80% of the requested block was selected.

We also used questionnaires to measure the self-reported user experience in terms of the **understandability**, the **memorability,** and the **perceived success rate** of the pen gestures.

6.2.5 Results

We recruited 12 participants (8 male and 4 female) from the university campus. We compensated each 20 dollars for about 90 minutes of their time. 10 of them were 21 - 30 years old, 1 was between the ages of 31 - 40, and 1 was in the range of 15 - 20. Among them were 3 college students, 8 graduate students, and 1 visiting scholar with a Ph.D. In addition, 7 of them had 0.5 - 7 years of stylus experience. And 3 participants had used Nokia or Logitech digital pens in the past 1 - 3 years, but were not regular users. None of them were familiar with the PapierCraft gesture command system.

We collected 12 participants who each participated in 2 conditions, 4 blocks, 4 scopes, and 8 trials, totaling 3072 trial-wise samples. To control outliers, we removed trials with a completion time of more than 3 standard deviations (SD) above the mean within a set (condition * block * scope type). We considered the scope type in outlier removal, as different scope shapes inherently require different drawing time. In total, 1.82% (56 out of 3072) of the data points were removed. In the results below, we used Greenhouse-Geisser correction to account for deviations from sphericity, and Bonferroni corrections for all post-hoc tests.

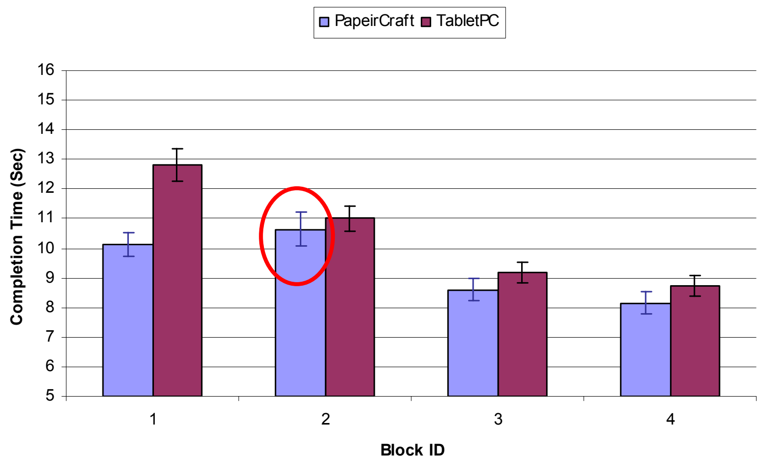


Figure 28. Condition-specific mean task completion time over blocks (95% confidence interval). Red circle indicates a slight increase of completion time in the PapierCraft condition.

6.2.5.1 The Speed of Drawing PapierCraft Gestures

We first examined user learning behavior in terms of task completion time. Repeated measures condition * block * scope type 3-way ANOVA shows that block is a main effect, $F(3, 33) = 44.54$, $P < .01$, partial $\eta^2 = .80$. It indicates the improvement of users' speed along the blocks. But this learning effect is qualified by a strong condition by block interaction, $F(3, 33) = 6.16$, $P<.01$, partial $\eta^2 = .36$. Indeed, although post-hoc pair-wise comparison suggests participants were significantly slower in blocks 1 (M = 11490[7], SD = 4892, P<.01) and 2 (M = 10824, SD = 4927, P<.01) than in block 3 (M = 8900, SD = 3621) and block 4(M = 8447, SD = 3505), a close look at the average user speed at different conditions and blocks (Figure 28) suggests that the PapierCraft condition has a different learning trend. The task completion time increased a little at block 2 and then declined. Based on our observations, we believe this trend was mainly caused by the removal of the cheating

[7] The time unit is millisecond in the following sections, except if otherwise noted.

card at the beginning of block 2. Due to paper's weak visual feedback, participants tended to use the card much more than in the Tablet PC condition, thus suffered more from the card removal.

We did not find a statistically significant difference between the two conditions over the 4 blocks. To examine the resulting expert-level performance, we further analyzed the task completion time of the last block. A paired-samples T test showed no significant difference between PapierCraft (M = 8155, SD = 3543) and Tablet PC (M = 8734, SD = 3449), with $T(11) = -.86$, $P = .41$. Similarly, we did not find a significant condition by scope type interaction, neither (condition * block * scope type) interaction.

However, scope type alone was found to be a main effect, $F(3, 33) = 21.97$, $P < .01$, partial $\eta^2 = .67$. A post-hoc pair-wise comparison suggests that the cropping mark (M = 11161, SD = 4414) takes significantly more time than the underline (M = 8912, SD=3862, P<.01) and the margin bar (M = 9567, SD=4690, P<.01), and marginally more than the lasso (M = 10026, SD=4587, P=.057). Figure 29 shows this trend. This is not surprising since the cropping mark usually requires more hand

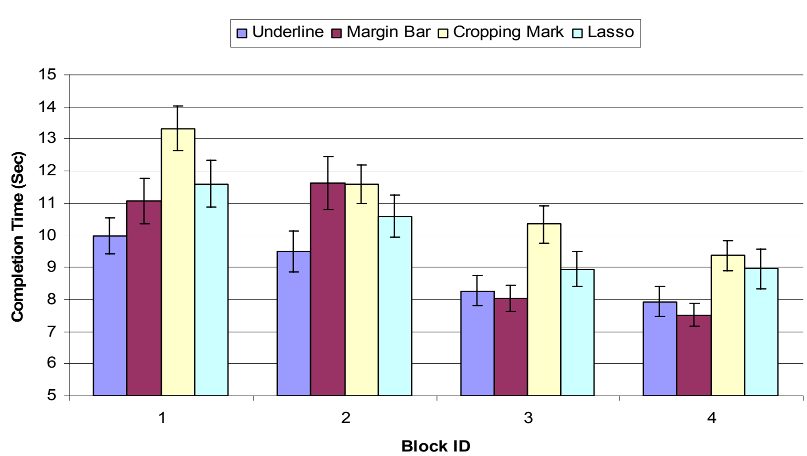


Figure 29. Scope-specific Mean Task Completion Time over blocks (95% confidence interval)

movement.

The above result is qualified by a strong block by scope type interaction, $F(9, 99) = 5.57$, $P < .01$, partial $\eta^2 = .34$. It suggests the difference among scopes changes depending on specific blocks. Thus, we focused on the last block to examine the expert-level performance. Repeated measures one way ANOVA suggests that scope type is a main effect, $F(3,33) = 8.93$, $P<.01$, partial $\eta^2 = .45$. A post-hoc pair-wise comparison indicates that there is no significant difference between the cropping mark (M = 9366, SD = 3361) and the lasso (M = 8960, SD = 4253), or between the underline (M = 7937, SD = 3299) and the margin bar (M = 7528, SD = 2618). More precisely, the margin bar takes significantly less time than the cropping mark ($P<.01$) and the lasso ($P<.05$), and the underline is faster than the cropping mark (<.05). This result correlates with the amount of hand movements needed to draw the gestures.

6.2.5.3 Error Rate

We first examined the overall error rate for each block, which encapsulated all types of errors. Repeated measures condition * block * scope type 3-way ANONA

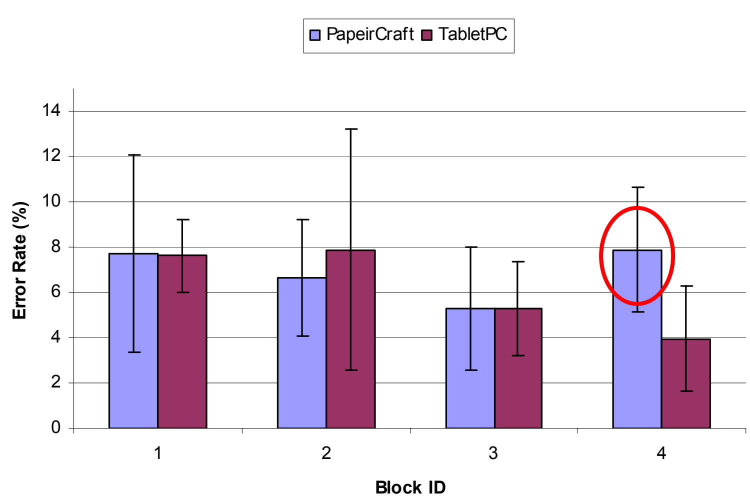


Figure 30. Mean error rate over blocks. Red circle indicates a small increase of error rate in the PapierCraft condition

found no main effects. And there was no interaction found, either. Moreover, as Figure 30 shows, the average error rate over blocks remained below 8% in both conditions. This result indicates the generally low error rate of PapierCraft gestures.

A close look at Figure 30 shows an interesting phenomena in block 4, in which the error rate with PapierCraft slightly increases from 5.29% in block 3, i.e. 20 error trials out of 376 valid trials (after excluding some outliers from the original 384 points), to 7.89%, or 29 out of 372. Further review of the log indicates that 7 participants increased their errors between 1 - 3 from those in the previous block. One possible explanation for this change comes from the experimental procedure: Since the error rate remained low, we wanted to test the upper limit of the user performance, so reminded the participants to increase speed as long as the error rate was below or equal to 12.5%, which actually increased the time pressure put upon participants.

Pen mode switching is an important user action in PapierCraft, so we specifically examined the pen-mode switch error (i.e. drawing distracting letters in "command" mode or gestures in "annotation" mode). The results showed the average of this type of error was less than 2% in all conditions and all blocks, which suggests that the pen-mode switching is not an issue in user performance.

6.2.5.4 Subjective Evaluation

We first checked the understandability of the scope gestures based on the participants' responses to our questionnaire. We examined the four scope gestures, namely the underline, the lasso, the margin bar, and the cropping mark. We ignored the interface types, as participants drew the same gestures for both conditions. Figure 31 suggests that all scope types are easy to understand. This is consistent with the

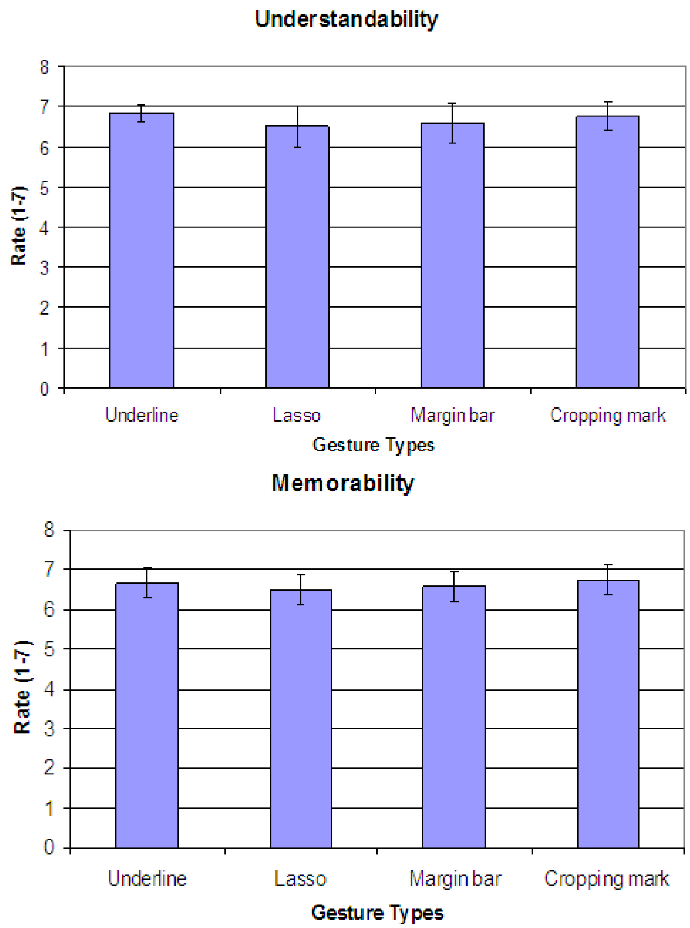


Figure 31. Mean user responses to understandability and memorability of various scope types

result of a one way repeated measure ANOVA on understandability, which found no main effect, $F\ (1.60, 17.56) = .65$, $P = .50$, and partial $\eta^2 = .06$. Similar results were also discovered for memorability, with no main effect found, $F(3,33) = 1.77$, $P = .17$, partial $\eta^2 = .14$.

Perceived Success Rate

We then tested how the different gestures and interfaces affect user perceived performance. We ran a repeated measure two-way (condition by gesture type) ANOVA on user responses for perceived success rate (Figure 32). We found gesture type to be a main effect, $F(3, 33) = 6.02$, $P < .01$, partial $\eta^2 = .35$, suggesting the lasso

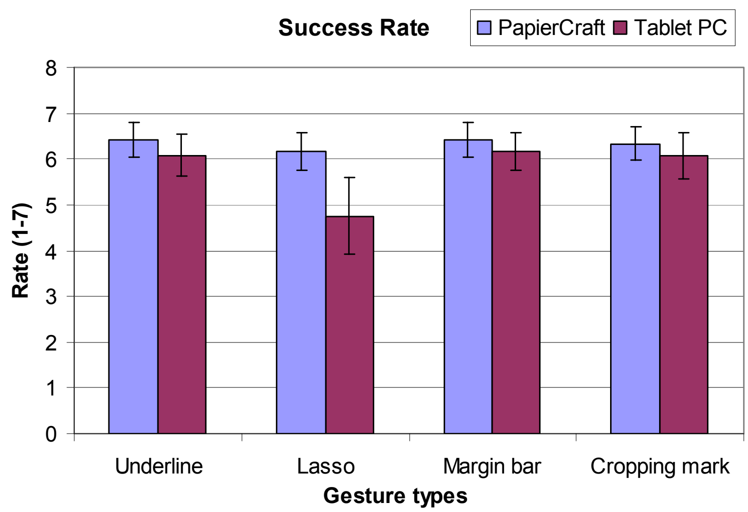


Figure 32. Perceived success rate for various gesture types

(M=5.46, SD=1.35) had significantly lower success rate than the cropping mark (M=6.21, SD=.78, P<.05). So is condition, $F(1,11) = 6.80$, $P < .05$, partial $\eta^2 = .38$, suggesting that PapierCraft (M = 6.33, SD=.66) was thought to have a significantly higher success rate than Tablet PC (M=5.77, SD=1.15, P < .05).

But these results are qualified by a strong condition by gesture type interaction: $F(3, 33) = 7.36$, $P < .01$, partial $\eta^2 = .40$. As Figure 32 illustrates, in the Tablet PC conditions, there was a larger difference between the lasso and other scopes, which does not appear in the PapierCraft condition.

This may be attributed to the difficulty in drawing the lasso gesture within a relatively small region on the Tablet PC screen. Participant 9 complained that it was "difficult to know where to put the pigtail on the lasso," and participant 12 stated, "Lasso drawing was more difficult." Moreover, Tablet PCs suffer from their relatively low display quality compared to paper, which may exacerbate the difficulty in drawing the lassos. For example, participant 14 said "Because of parallax, lasso is not accurate on PC," and participant 19 claimed that the "Computer surface is a bit too smooth for the pen to travel on." It would be interesting to further explore how

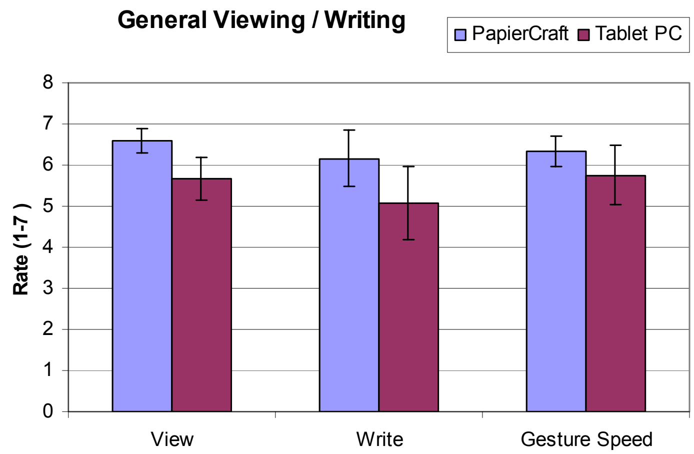


Figure 33. Subjective rate of general viewing/writing experience on paper and the Tablet PCs

the text spacing and the display surface properties affect the precise selection of document details with pen gestures.

General Viewing/Writing Experience

We also tested the participants' viewing and wring experience with regard to the different display surfaces (Figure 33), regardless of the pen modes and gesture types.

For general viewing experience, a paired-samples t-Test on the user responses showed that PapierCraft (M = 6.58, SD = .51) was rated significantly higher than the Tablet PC (M = 5.67, SD = .89), with $T(11) = 4.75$, $P < .01$. The same significant difference was also found for general writing experience, $T(11) = 2.49$, $P < .05$. Participants significantly preferred PapierCraft (M = 6.17, SD = 1.19) to Tablet PC (M = 5.08, SD = 1.56). The user comments suggest reasons for this trend. For example, participant 8 said "Paper interface: faster to perform operations (due to tangibility)," and participants 9 and 13 complained that "The PC pen is difficult to press the button" and "Doesn't feel very natural on tablet PC," respectively.

Usefulness of Pen-top Feedback

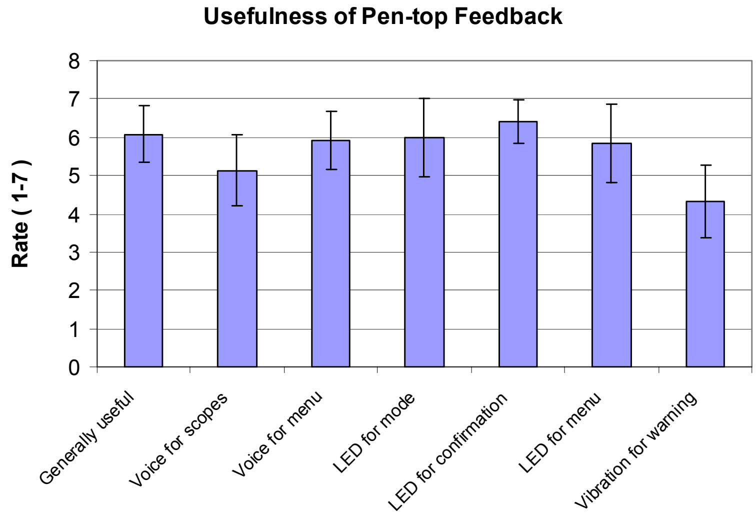


Figure 34. User rating on pen-top feedback.

Finally, we asked participants to rate the usefulness of the pen-top feedback (Figure 34). Participants believed the pen-top feedback was generally useful (M = 6.08, SD = 1.31). The scores for specific pen-top feedback features are comparable to our previous experiment. For example, "LED for confirmation," "LED for mode," and "voice for menu" are the top 3 most useful features, and "vibration for warning" was rarely used and received the lowest rating.

6.2.6 Design Implication

The experiment has successfully confirmed the learnability of the PapierCraft command system. In a relatively short time period (20~30 minutes), average people can learn a completely new PapierCraft interface and reach a skill level comparable to that on Tablet PCs. Our evaluation and post-test briefing also revealed some design concerns for both paper and Tablet PC interfaces:

1. Slippery screen, pen-cursor parallax, thickness, and weight are problems for Tablet PC. This suggests that the text-rich document interaction may have higher requirements for these factors.

2. Physical properties of pens, including the button position, size, weight, and weight balance, are important to user experience.
3. The system should be more robust to input variance (e.g. a broader range of acceptable lasso gestures), since users may feel that this system is more difficult to use if more restriction is applied.

6.3 Application Level Evaluation: Paper-Computer Combination

Based on the above lower level evaluations, we then examined the main hypothesis of this dissertation: *PapierCraft can bridge the paper-computer gap by combining the affordances of paper and computers*. To test this hypothesis, we focused on a typical PapierCraft application, active reading, which is the combination of reading with deep thinking and understanding [Adler and Van Doren, 1972]. We reviewed the characteristics of typical paper and computer interfaces for active reading, identified their key interface properties, and tested how PapierCraft combines these properties to achieve a paper-computer bridging for better user experiences.

As we discussed in Chapter 3, active reading involves a lot of sub-tasks,

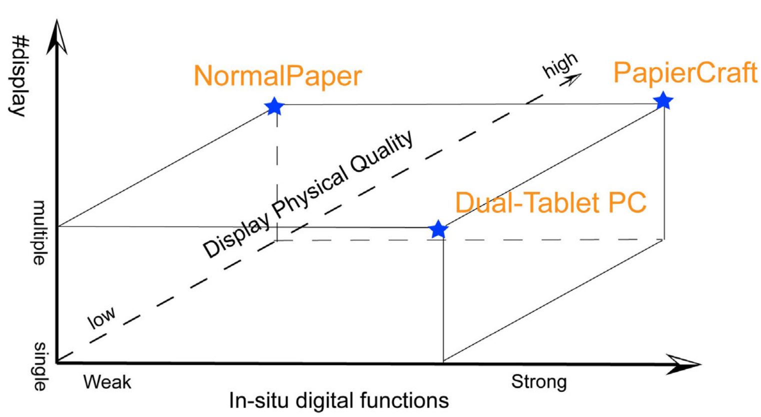


Figure 35. The design space of active reading interfaces

including reading, noting, organizing, navigating, and searching. For these sub-tasks, paper and computer interfaces offer different levels of support in terms of three key design factors, namely the display physical quality, the in-situ digital functions, and the number of displays, which can all be illustrated in the active reading interface design space as shown in Figure 35.

We investigated whether PapierCraft can provide good support for these three key design factors. To this end, we picked two extremes, *Normal paper* and *Dual Tablet PCs* (for simplicity, we use the *Tablet PC* in the following presentation), in the design space to identify how PapierCraft might bridge the gap between them. By comparing PapierCraft with normal paper, which has no in-situ digital function, we were able to study the effect of the digital capability of PapierCraft; by contrasting PapierCraft to the Tablet PC, which has no paper-like display physical quality, we were able to examine the impact of paper affordances on active reading interactions.

We did not compare PapierCraft with single display-based interfaces, as it is well-accepted that multiple display settings can provide users with more flexibility in information organization, navigation, and simultaneous read-write tasks [O'Hara and Sellen, 1997].

6.3.1 Experiment Task

We examined the above-named three interface types in an active reading scenario: Participants were asked to use an interface to read a reasonably long article, write a summary, and then answer detailed questions about the article.

Our design was inspired by research in the literature. For example [O'Hara and Sellen, 1997] and [Morris, et al., 2007] both used the summarization task to test the user experience of computer and paper interfaces. This task is believed to be a good representation of knowledge-related activities, because it requires intensive and deep reading, thinking and writing, as well as a variety display-related interactions, such as annotating, noting, navigating, browsing, copy/pasting, and so on [Morris, et al., 2007, O'Hara and Sellen, 1997].

However, the summarization of a text is a free format task, so there is no guarantee that the participants would perform specific interactions, such as copy/pasting and web searches, which are very important aspects to be examined. In response, we extended O'Hara and Morris' design by appending the original summary-only task with an additional quiz section, in which participants were asked to Google specific keywords, open URLs, illustrate and compare figures, and find words within documents. In this way, the experiment task reflected more typical activities, and it was easier for us to study more details of user interaction. As a result, we incorporated two task sections: a summary and a quiz section.

6.3.1.1 Design of the Summary Section

In this experiment section, we aimed to examine if paper affordances can boost user experiences in reading, annotating, navigating, browsing, and spatially arranging documents. We hypothesized that, with better display qualities for these subtasks, PapierCraft and normal paper would provide better user experience than the Table PC.

Under each of the three conditions (normal paper, PapierCraft and theTablet PC), the participant was asked to read one 4-page article of about 1100 English words in length. The articles were selected from New York Times to ensure that average people could understand them and finish reading within 10-15 minutes. The articles' difficulty levels were roughly equal, judged from our pilot test. The design was in line with previous works in the literature [O'Hara and Sellen, 1997] [Morris, et al., 2007].

The experiment time was an issue. To ensure that participants could finish all of the tasks in 2.5 hours, we simplified the summarization procedure by asking participants to first write a thesis sentence for the whole article and then one summary sentence for each paragraph. Although no final, formal summary was generated, all of the important sub-tasks, like reading and annotating, still occurred and so were subject to observation. Our pilot test showed that, no matter if participants wrote the final summary or not, they had similar reading, annotation, and navigation interaction. This confirmed the validity of our design.

Specifically, we used the following instructions for this section (for more details, please see Appendix 3):

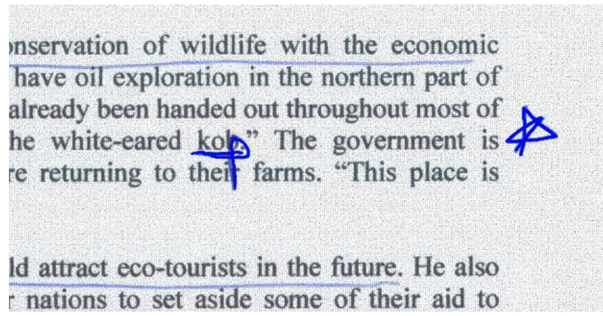
1. *Skim the article, annotate or take notes just as you usually do. Especially, you may underline* ***topic sentences*** *and circle* ***keywords****.*
2. *Write a* ***thesis statement*** *(1-2 sentences) for the main idea of this article.*
3. *Write short and simple* ***summary sentences (1*** *for each original paragraph), using your topic sentences, annotations, and notes. Keep the summary in the* ***same logical order*** *as the original article.*

6.3.1.2 Design of the Quiz Section

We tested if in-situ digital functions could improve the active reading user experience for four representative tasks, including web search, web page reviewing, document comparison, and keyword finding within a document.

Subtask 1: Web search for keywords

This task was to simulate web search for the explanation of an unfamiliar word. Participants first located a given word in the article, and then drew a star mark in the margin next to the word, underlined the word, Googled it, and then copied a one sentence explanation of the word from Wikipedia (see Figure 36 for an example).


nservation of wildlife with the economic
have oil exploration in the northern part of
already been handed out throughout most of
he white-eared kob." The government is
re returning to their farms. "This place is

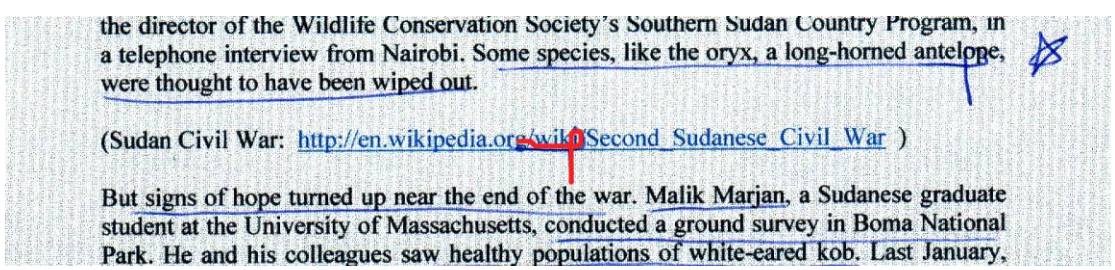
ld attract eco-tourists in the future. He also
r nations to set aside some of their aid to

Figure 36. An example of web search for a keyword "kob". The participant first drew a star, then underlined the keyword, followed by the "web" command. Marks are highlighted for clarity.

There were 3 keywords spread over 3 pages for this subtask. The star mark and underline aimed to emulate the interweaving of reading and searching: A web search is usually initiated in the middle of on-going reading or annotating, and so the reader needs to switch focus from the document segment to the web browser.

Subtask 2: Opening a web page for related information

Participants opened a web URL in the article (Figure 37), and copied one picture from the web page to their document. The web pages were randomly selected, but relevant to the article. Participants could select any picture on that page, because we cared more about the interaction than the picture content.


the director of the Wildlife Conservation Society's Southern Sudan Country Program, in a telephone interview from Nairobi. Some species, like the oryx, a long-horned antelope, were thought to have been wiped out.

(Sudan Civil War: http://en.wikipedia.org/wiki/Second_Sudanese_Civil_War)

But signs of hope turned up near the end of the war. Malik Marjan, a Sudanese graduate student at the University of Massachusetts, conducted a ground survey in Boma National Park. He and his colleagues saw healthy populations of white-eared kob. Last January,

Figure 37. An example of the web-opening subtask. Participants could use the "web search" command (highlighted in red for clarity) to select any part of the URL to open the web page.

Subtask 3: Illustrating document content

This subtask aimed to test user experiences of information transfer and multiple-display operations. Participants first used text, sketches, and/or pictures (whichever they thought most effective and efficient) to describe the picture.

For example, questions included: "*In Figure 1, find the following objects: **mountain**, **river**, and the **dam***" (Figure 38), or "*In Figure 2 find the **solar array joints** of the international space station.*" Participants were asked to briefly describe the targets' relative locations in the pictures.

Further, participants were also asked to compare 2 figures to find and describe their similarities and/or differences. For example (Figure 39): "*Compare the recent International Space Station (figure 2) and its previous configuration (figure 5), and find and number **three** differences, and roughly describe their location in the pictures.*"

Subtask 4: Locating details with keyword finding

Participants were asked to answer 3 questions about details by searching for

Figure 38. One figure in a testing article for illustrating document details

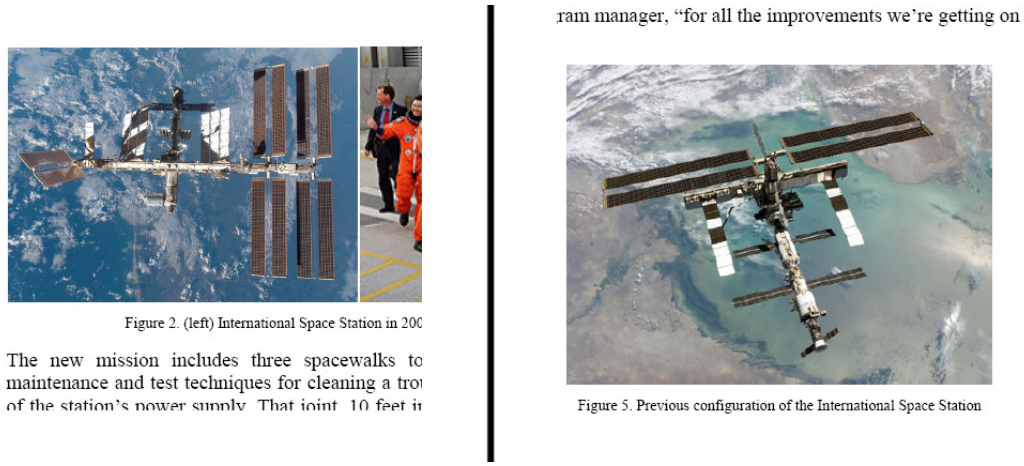


Figure 39. An example of figures for page comparison. (Left) a figure on page 2 (Right) another figure on page 4ure on page 4

keywords in a document. For example, with the question: "*What did Michael Leinbach say about the launch?*" the participant was expected to first locate a keywords, e.g. Michael Leinbach, within the article, and then find the answer to the question in the context paragraph. This finding-details-via-keyword is a very common strategy when people face an unfamiliar and long document.

One key design issue was the interference of human's short-term memory: If using the same article that the participant just read, she may still remember the location of the keywords, which is quite possible given the short length of the articles. Thus, the testing would not reflect the real user performance. To address this issue, we used a separate article on a similar topic. Choosing a relevant second article maintained a somewhat continuous thought flow and reduced the side-effects of sudden topic-switching. Our pilot and formal testing showed the effectiveness of this design. Further, to avoid too long a testing time, we set a two-minute limit on each question. Participants had to stop even if they did not find the answer.

6.3.2 Device Setting

The hardware configuration was to simulate a typical knowledge worker's setting: a laptop for document editing and separate display surfaces for reading (screens or paper). The design arose out of several concerns: the use of a laptop provides the required portability for mobile computing; using separate displays for reading and writing can avoid the distractive window switching in case of small screens [O'Hara and Sellen, 1997]; the laptop is well integrated with PapierCraft to provide a portable dynamic display for information like web pages; and as Morris's study [Morris, et al., 2007] suggested, the keyboard is good for editing formal documents and the pen good for free-form annotations. Thus, we adopted a mixed-input setting, with the pen for annotating documents and the keyboard for composing answers. The resulting experiment setting is illustrated by Figure 40, and the detailed configurations are as follows.

6.3.2.1 Detailed Settings

Paper Condition: Participants used a normal ink pen, letter-sized printouts, and several blank white sheets for scratch paper. To transfer information from one display to another, participants needed to manually type or write.

PapierCraft Condition: Participants used a multimodal feedback pen, Anoto-

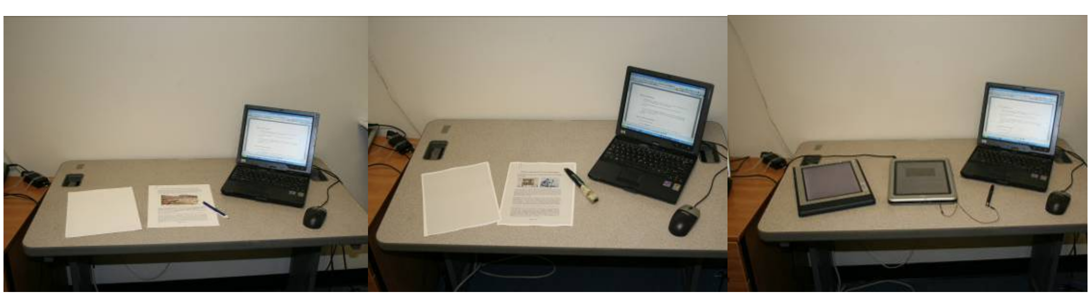


Figure 40. Hardware configurations: (Left) normal paper (Middle) PapierCraft (Right) Tablet PC

enabled printouts, and scratch paper. The pen implementation was the feedback pen version 2 (see Chapter 5 for details), which adopts a miniaturized control board and connects to the editing laptop via a Bluetooth gateway. The laptop processed the pen strokes in real time and performed pen gesture commands accordingly.

Since we wanted to focus on the user experience of specific functions, and not the general performance of the PapierCraft command system, we only used 3 commands (Figure 41): web, copy, and find. Further, we tried to simplify gesture rules and automate the command settings as much as possible. For instance, the web command only supports the underline scope. If the selected text is part of a URL, the system automatically figures out the full URL and opens the web page in a browser on the laptop (Figure 37). Otherwise, it will Google the selected words.

The copy command supports two scopes, the cropping mark and the underline,

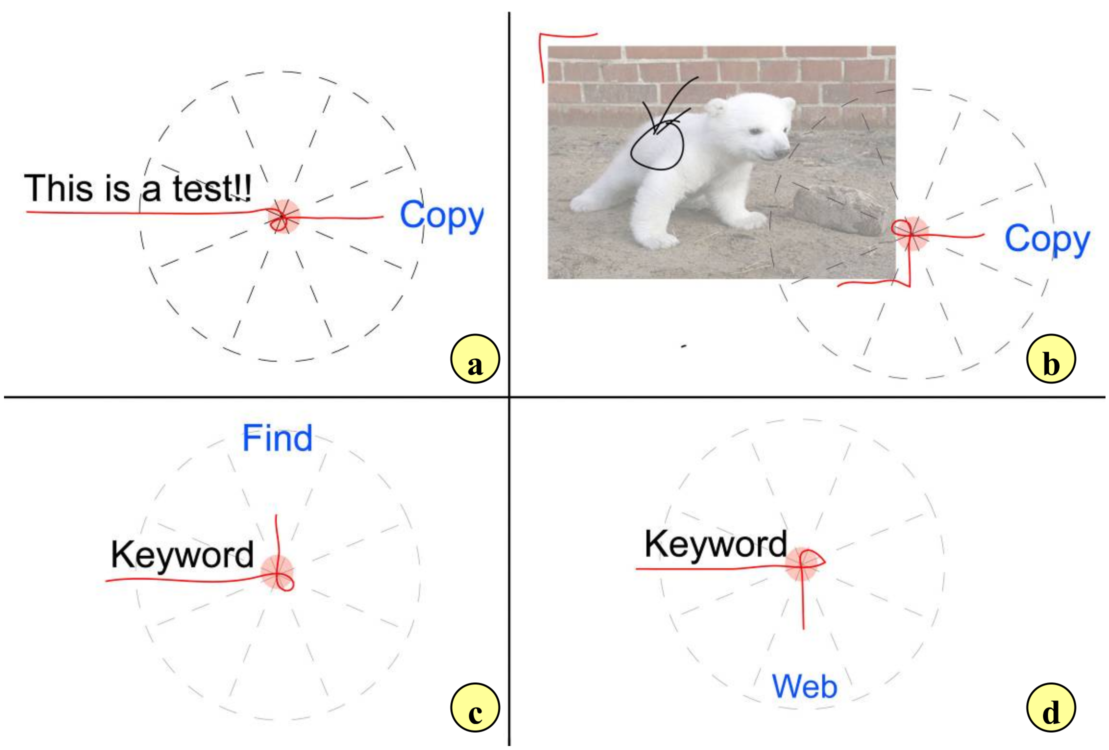


Figure 41. The gesture command set. (a) (b) “Copy” for texts and pictures. (c) “Find” for keyword search within documents. (d) “Web” for web search or opening a web page

for pictures and texts, respectively (Figure 41). We automated the copied data type selection: if the percentage of text area within the command scope is higher than a threshold, the system categorized the selection as pure text, otherwise as a bmp in the clipboard of the laptop, from which it is easily pasted into a Word document.

For the find command, we used the pen-top feedback to indicate the positions of hits: first speak out the rough position of the next hit, and then use LED color to indicate the precise line (see Chapter 5 for more details). Although the nearby laptop may offer stronger visual feedback, e.g. highlighted keywords, we excluded it from the PapierCraft condition in order to highlight the capability of the pen-top feedback.

Besides the above gesture commands, we provided an annotation management facility, Snippet Reviewer (see Figure 42), which is similar to XLibris [Schilit, et al., 1998]. After participants finished reading on paper, the program recognized

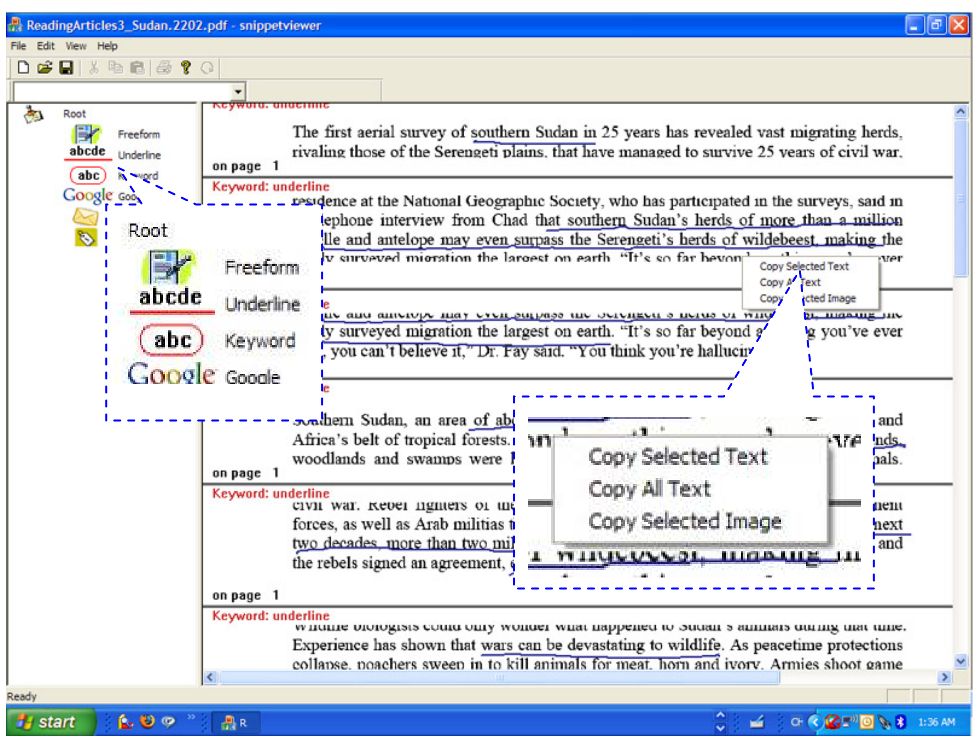


Figure 42. Snippet Reviewer, with two new snippet categories, underline and circle. Users can copy the underlined or circled text via the popup menu shown above

annotations that looked like an underline or a circle, and then generated snippets composed of the selected text and a snap-shot picture of the document segment. Later, all these snippets were grouped and reviewed in the Snippet Reviewer running on the laptop. From there, one can simply select one or all snippets or copy the text into the editing program, thus easing summarization.

Tablet PC Condition: Participants used a stylus on two tablet PCs to annotate the testing documents and take notes. Otherwise, the computer interface supported the exact same pen gestures and dynamic information rendering (e.g. open a browser or the Snippet Reviewer on the laptop) as the PapierCraft condition.

The differences lied in the feedback. For example, on the Tablet PC, a popup marking menu showed up after a 500 ms pause after a pigtail cross; on PapierCraft, there was instead a voice menu and the associated LED colors on the digital pen. And, with keyword finding, the Tablet PC interface automatically flipped to the hit page, and highlighted the target word. With this stronger visual feedback, this condition was expected to have better user experiences than the others for this subtask.

6.3.3 Procedure and Measures

Considering the cross-participant variance, we conducted a within-subject experiment with 3 counter-balanced conditions. The whole experiment was designed to be finished within 2.5 hours. For each condition, the testing began with a training session to help the participant familiarize with the available facilities in that condition. Participants were told that they had the flexibility to choose whatever tools that they thought most effective and efficient to finish the task. In this way, we could study the spontaneous user responses to the new techniques.

During the testing session, the participants first read a given article (the specific articles were counter-balanced), and then typed the summary on the laptop, probably with the help of gesture commands and other tools. Then, they proceeded to the quiz section shown on the laptop. They referred back to the reading material, performed the appropriate operations, and composed answers to the questions on the laptop.

After each condition, participants filled out a NASA work load index questionnaire [Hart and Staveland, 1988]. When all three conditions were done, participants finished a self-report questionnaire about the user experience of each sub-task for the different interfaces. The questionnaire entries were ranked according to the Likert scale, with answers ranging from 1-7 (1 for most negative experience). We also asked participants to elaborate reasons for their choices, which gave us insight about why and how participants scored a specific interface for a task. We did not examine the exact task completion time or error rate, as we focused on the high level user experience, not on the low level interaction techniques. For details, please refer to Appendix 4.

6.3.4 General Results

In the following discussion, except if otherwise noted, Greenhouse-Geisser correction was used to account for deviations from sphericity. All post-hoc tests used Bonferroni corrections.

We first considered the user responses to the questionnaire. Note that the questionnaire and the experiment tasks were structured in two categories. The first category, *Paper-friendly Tasks,* consisted of sub-tasks in which paper affordances played a key role, including tasks like read, annotate, note, navigate, spatially layout, and compare. In contrast, the second category, *Digital-friendly Tasks*, included the rest of the sub-tasks, in which in-situ digital functions make a difference. Figure 43 shows the mean and confidence intervals of the user responses (on a scale of 0-7) to the specific questions in the two categories.

We first investigated the main effects within each category. For the paper-friendly tasks, repeated measures task by technique 2 way ANOVA on the user responses found technique to be a main effect, $F(2,20) = 45.65$, $P < .01$, partial $\eta^2 = .82$. A post-hoc pair-wise comparison showed that PapierCraft ($M = 6.18, SD = 1.05$, $P < .01$) and normal paper ($M = 6.32$, $SD = 1.14$, $P < .01$) were rated significantly higher than the Tablet PC ($M = 4.31, SD = 1.58$). There was no significant difference between PapierCraft and normal paper, though. This is consistent with the task categorization, and suggests that PapierCraft supports these tasks as well as normal paper.

For the digital-friendly tasks, repeated measures task by technique 2 way ANOVA on the user responses also found technique to be a main effect, $F(2,22) = 85.72$, $P < .01$, partial $\eta^2 = .89$. A post-hoc pair-wise comparison indicated that PapierCraft ($M = 6.07$, $SD = 1.06$, $P < .01$) and Tablet PC ($M = 6.22$, $SD = 1.03$, $P < .01$) was significantly better than normal paper ($M = 2.83$, $SD = 1.61$). There was no significant difference between PapierCraft and the Tablet PC. However, this result should be taken with caution due to a significant task by technique interaction, $F(3.82, 42.00) = 6.49$, $P < .01$, partial $\eta^2 = .37$. A close look at Figure 43 suggests the task "annotation use" may affect the user experience of the techniques, which was caused

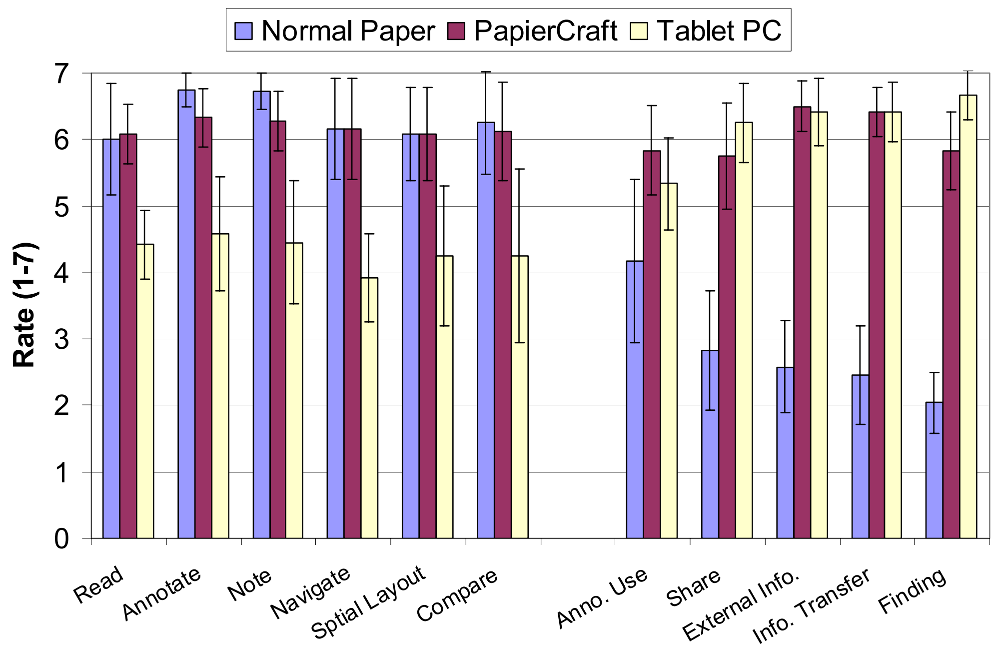


Figure 43. The mean and confidence interval of the user experience of the experiment tasks. (Left) Paper-friendly tasks (Right) Digital-friendly tasks.

by the insufficient contextual information provided by the snippet management facility, an issue that we will revisit later on. But overall the results were coherent with the task categorization, and positively indicated the digital capability of PapierCraft.

For a better overview, we averaged every participant's responses within each (technique * category) block, and ran repeated measures technique by category 2 way ANOVA on the results. We found category to be a main effect, $F(1, 11) = 9.32$, $P < .05$ and partial $\eta^2 = .46$, suggesting that participants got significantly better user experiences in paper-friendly tasks (M=5.61, SD=1.14, P<.05) versus digital-friendly tasks (M=5.03, SD=1.77). Technique was also a main effect, indicating that PapierCraft (M=6.12, SD=.49) received significantly higher ratings than the Tablet PC (M=5.27, SD=1.27, P<.01) and normal paper (M=4.57, SD=1.97, P<.01), and the Tablet PC received higher ratings than normal paper (P<.05). But this result should

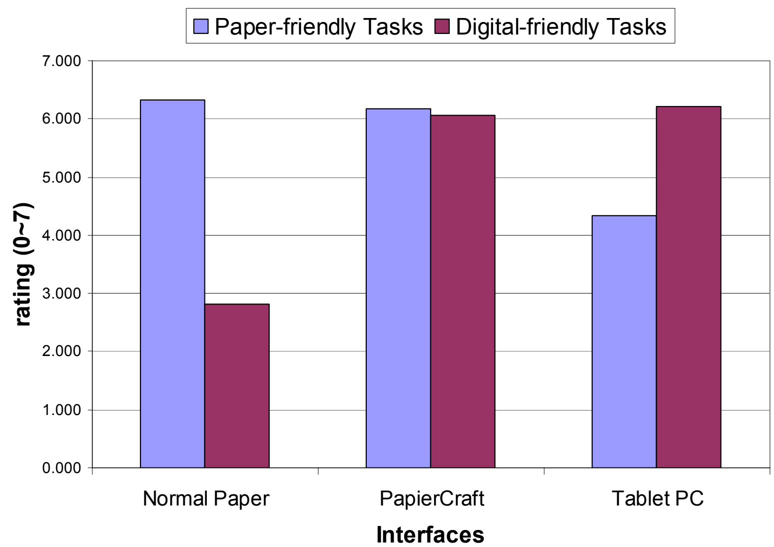


Figure 44. Averaged user ratings on the three interfaces per category.

also be interpreted carefully due to the strong category by technique interaction, $F(2,22) = 142.70$, $P<.01$, and partial $\eta^2 = .93$.

We then tested the category difference for each technique. For PapierCraft, paired-samples T test showed no significant difference between paper-friendly tasks (M=6.18, SD=.46) and digital-friendly tasks (M=6.07, SD=.54), $T(11) = .47$, $P=.65$. This suggests that PapierCraft can provide very good user experience in both task categories. In contrast, for normal paper, the paired-samples T test found that participants rated it significantly lower in digital-friendly tasks (M=2.82, SD=1.03) than in paper-friendly tasks (M=6.33, SD=.58), $T(11) = 13.99$, $P < .01$; similarly the Tablet PC was rated significantly lower in paper-friendly tasks (M=4.33, SD=.92) than in digital-friendly tasks (M=6.22, SD=.76), $T(11) = -6.26$, $P < .01$. This result highlights the combined advantages of PapierCraft in terms of both paper and digital affordances, which is demonstrated in Figure 44.

We also examined the qualitative user evaluation, which is consistent with the above quantitative analysis. Participants commented that: “[PapierCraft] allows [people] to use the paper and still supports the same functionalities of Tablet PC," and "[PapierCraft is] easy to use and with comfort of using paper," and "[PapierCraft is]innovative, interesting and efficient, especially with [copying] figures and looking for words." Participants enthusiastically embraced PapierCraft's in-situ digital functions within paper documents. They gave "digital functions on paper" a high score (M = 6.33, SD = .78), with comments like: "Can't survive without them !!!" and "[I like it because there is] no need to put down the pen." Thus, in general, PapierCraft successfully demonstrated its combined merits of paper and computers.

Of course, with such novel techniques, some participants were also concerned about the initial difficulty for new users. Some pointed out, "It's useful, depend[ing] on people's habit of reading" and "I haven't get used to using electronic devices on paper, but it can be improved." To explore user experience in the long-term, a longitudinal study is needed.

To better understand the user responses and the pros and cons of each interface, we investigated specific sub-tasks one by one, as follows. For each sub-task, we report the repeated measures 1 way ANOVA on the user responses (summarized

Subtasks	Found Main Effect: Interface Type			Normal Paper		PapierCraft		Dual-Tablet PCs	
	F	P	partial η^2	Mean	StdDev	Mean	StdDev	Mean	StdDev
Read	F(2, 22) = 15.02	< .01	.58	6.00	1.48	6.08	.79	4.42	.90
Annotate	F(1.19,13.12) = 21.44	< .01	.66	6.75	.45	6.33	.78	4.58	1.51
Note	F(1.29,12.91) = 17.50	< .01	.64	6.73	.47	6.27	.79	4.46	1.64
Navigate/Browse	F(2, 22) = 22.09	< .01	.67	6.17	1.34	6.17	1.34	3.92	1.17
Spatial Layout	F(2, 22) = 13.18	< .01	.55	6.08	1.24	6.08	1.24	4.25	1.87
Compare	F(1.03, 11.35) = 10.68	< .01	.49	6.25	1.36	6.13	1.32	4.25	2.30

Table 4. Results of repeated measures 1 way ANOVA on the user experience of the paper-friendly tasks

Subtasks	Found Main Effect: Interface Type (except *)			Normal Paper		PapierCraft		Dual-Tablet PCs	
	F	P	partial η^2	Mean	StdDev	Mean	StdDev	Mean	StdDev
*Anno. Use	F(1.28,14.13) = 3.78	= .06	.26	4.17	2.17	5.83	1.19	5.33	1.23
Share	F(2, 22) = 26.23	< .01	.71	2.83	1.59	5.75	1.42	6.25	1.06
Ext. Info. Retrieval	F(1.19,13.11) = 80.11	< .01	.88	2.58	1.24	6.50	.67	6.42	.90
Info. Transfer	F(1.10, 12.09) = 66.23	< .01	.86	2.46	1.31	6.42	.67	6.42	.79
Keyword Finding	F(2, 22) = 107.05	< .01	.91	2.04	.81	5.83	1.03	6.33	.49

Table 5. Results of repeated measures 1 way ANOVA on the user experience of the digital-friendly tasks.

in Table 4 and Table 5) and discuss our findings.

6.3.5 Discussion about Paper-friendly Tasks

We first examined the sub-tasks that are closely related to paper affordances, including read, annotate/note, navigate/browse, spatial layout, and compare.

6.3.5.1 Reading

We ran repeated measures 1 way ANOVA on reading user experience, and found technique to be a main effect (P<.01). A post-hoc pair-wise comparison suggested that normal paper (P<.01) and PapierCraft (P<.01) got significantly higher ratings than the Tablet PC (details in Table 4).

This result seems inconsistent with Morris's user study, which claims that recent computing devices such as the Tablet PCs have proved to be comparable , or superior to, paper in reading, annotating, and note-taking [Morris, et al., 2007]. This inconsistency might be attributed to the hardware (in terms of resolution, contrast, weight, size, and thickness), participant background, testing tasks, and lighting conditions in our experiment. We will study this issue in the future.

We also found that document appearance affects user experience. Three participants complained that, although similar to normal paper, PapierCraft's humanseeable black dot pattern in the background is somehow distracting. One immediate solution is to tune the pattern printer's tone to reduce the pattern darkness up to a point that the digital pen can still recognize. Another solution is to use special human-invisible, but infrared-absorbed, ink cartridges [Yousaf and Lazzouni, 1995], but the cost will be higher and the digital pen may need some changes to recognize the special ink.

Form factor also affects the user reading behavior. Most participants tended to move and hold the paper documents with an angle during reading. Two participants even did that with the Tablet PCs (Figure 45), although they admitted it was a little awkward. A lighter, thin and ductile display is the key for such interaction.

6.3.5.2 Navigate/Browse

Repeated measure 1 way ANOVA on the experience of navigate/browse showed technique to be a main effect ($P<.01$). A post-hoc pair-wise comparison confirmed the significantly higher user preference of normal paper ($P<.01$) and PapierCraft ($P<.01$) to the Tablet PC (details in Table 4).

One of the reasons for this has to do with the software buttons (size 25 pixel*25 pixel) for page flipping. Participants said: "The button is tiny and hard to select on Tablet PC" and "[The] button in Tablet PC is not sensitive." The problem can be addressed by installing hardware buttons around screen

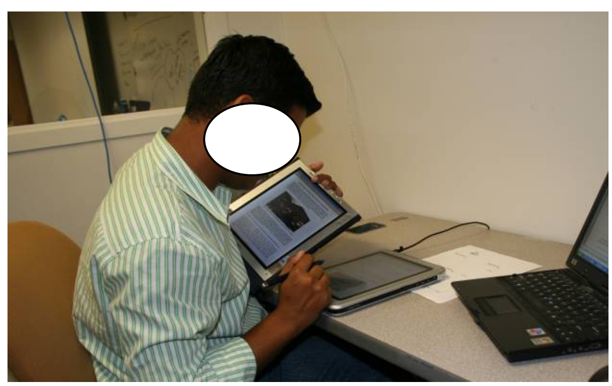


Figure 45. A participant held the Tablet PC for a comfortable reading angle.

edges like the Sony Reader, which can also save precious screen real state and provide tangibility to users [Sony, 2006]. In our experiment, we did not use this solution due to the limits on the availability of hardware.

On the other hand, although normal paper and PapierCraft were better accepted, their advantages may be counteracted by the arising difficulty in managing a large amount of paper sheets. As one participant pointed out, "For tablet PC, you have to go to pages by click, and for paper, paper gets messy, you lose the page numbers." And another participant liked the Tablet PC more, because "Tablet PC was easiest as it took least efforts (due to simple clicks)." This suggests that for navigating and browsing a large amount of documents, traditional paper affordances might not be the best match. Instead, computer-based methods like Speed-Dependant Automatic Zooming [Igarashi and Hinckley, 2000], Flipper [Sun and Guimbretière, 2005], and Space Filling Thumbnails [Cockburn, et al., 2006] may be better. However, this does not mean that paper is useless: People can first use digital media to quickly navigate and narrow down the interesting document content to a relatively small scope, and then switch to paper copies for local navigation.

6.3.5.3 Spatial layout and page comparison

The spatial page layout was often changed by participants during navigation and page comparison. Repeated measure 1 way ANOVA on user responses to the experience of spatial layout found technique to be a main effect ($P<.01$). A post-hoc pair-wise comparison showed that normal paper ($P<.01$) and PapierCraft ($P<.01$) received significantly higher ratings than the Tablet PC (details in Table 4).

Although participants admitted that the paper was much easier to move around for a comfortable layout on the desk, manually arranging a large amount of page documents may lessen the original paper advantage. As one participant said "(Paper, PapierCraft) rearranging within the pile might take some time. In the tablet PC, clicking might take more time if not done properly," and "It is not easy to put two Tablet PCs on top of each other. On the contrary, the paper gets hidden by other paper and the pen can be hidden underneath paper." Again, this implies that the advantages of paper should be qualified to a small set of pages.

Moreover, we ran the same test on the experience of page comparison, finding technique, again, to be a main effect ($P<.01$), thus indicating that normal paper ($P<.01$) and PapierCraft ($P<.01$) were thought to be significantly better than the Tablet PC (details in Table 4). Though rated lower than the other two, dual Tablet PCs were appreciated by participants: "Having 2 Tablet PCs does help a lot." This result re-confirmed the findings of O'Hara [O'Hara and Sellen, 1997] that multiple page operations can be better served with large and/or multiple displays. In this direction, the dual-display E-Book reader [Chen, et al., 2008] is on the right track among purely digital solutions. However, the current hardware still prevents users from arranging two tablets as easily as paper. Further, participants were also concerned about the costs of two computers.

6.3.5.4 Annotating and Note-taking8

In our experiment, the summary and quiz answers could be directly typed on the laptop, so no participants really took notes on any blank paper or on the Tablet PC. The evaluation on note-taking was mainly based on participant's experience of annotating, so the results of the 2 sub-tasks are very similar. Repeated measures 1 Way ANOVA on the annotating user experience indicated technique to be a main effect ($P<.01$). A post-hoc pair-wise comparison further revealed that normal paper ($P<.01$) and PapierCraft ($P<.01$) received significantly higher scores than the Tablet PC (details in Table 4).

We focused on two design factors with regard to writing, namely the display surface and the pen. Our experiment revealed several important issues. First of all, similar to what we found in the gesture command experiment, participants complained about the inaccuracy of writing on the Tablet PC. Participants 12, 16, and 8 respectively commented: "[The] Tablet PC is not accurate," and "[A shortcoming of the Tablet PC is its] slippery surface," and "Taking notes on [the] Tablet PC is terrible because it could not pick up my small hand movements." Again, this urges us to improve the physical properties of the screen and pen tip, e.g. increasing the screen softness, pen-screen friction, and display resolution, in order to make writing more comfortable and precise, which is very important for small scope operations like keyword selection. Furthermore, the limited screen real estate is also an issue. Participant 6 said: "[The Tablet PC] can't write as much in the margins."

---

[8] "annotation" means free form handwritings within the reading material; "note" means those on separate paper sheets.

Another factor in the writing experience was the pen. Repeated measure 1 way ANOVA on user response to experiences with the pen found pen type to be a main effect, $F(2, 22) = 6.94$, $P < .01$, partial $\eta^2 = .39$, and the normal ink pen ($M = 6.75$, $SD = .62$) was significantly preferred to the stylus on theTablet PC ($M = 5.08$, $SD = 1.51$, $P < .05$) and the PapierCraft digital pen ($M = 5.5$, $SD = .91$, $P < .05$). The stylus's main problems included its small size, the difficulty in pressing the barrel button, and the slippery screen. The lack of stylus experience among users is also another cause of this preference. One participant said: "I feel restricted by stylus[It's]. harder to write with it." The normal ink pen is a good reference for us to improve the stylus design.

For the PapierCraft feedback pen, the main issue was its big size, its unbalanced weight, and its uncomfortable finger coordination (to hold the button while drawing a pen gesture). Participants commented that the "digital pen is still heavier+bulky," and "PapierCraft [is] big, heavy. pressing button and writing together is hard." However, we think this is mostly caused by the current implementation limits, and do not see it as a fundamental design problem. In the future, a slimmer digital pen integrated with multimodal feedback modules will address these concerns at large.

6.3.6 Discussion about Digital-friendly Tasks

We investigated tasks that rely more on digital functions, including annotation management, sharing, external information retrieval, cross-page information transfer, and keyword search.

6.3.6.1 Annotation Management and Use

Repeated measure 1 way ANOVA on the user experience of annotation management found a marginally significant difference among the interfaces (P = .06, details in Table 5). This result was a bit of a surprise, since we thought the automatically generated digital snippets in the PapierCraft and the Tablet PC conditions should significantly improve the user performance in composing the summaries.

By looking into detailed user comments and post-experiment briefings, we identified several important issues that pushed users away from exploiting the digital tools. First, the full page context for snippets is very important. In our current design, like XLibris [Schilit, et al., 1998], we only inflated the bounding box of an annotation cluster[9] about 2 text lines, which proved not to be enough. Participant 8 complained: "I want to see notes in the original context rather than searching the individual group of texts (in the Snippet Reviewer) nearby and then put all in the same place." The position and the layout of annotations within the original page should have been retained to help users restore a more comprehensive, both psychologically and visually, context established in the first place. This feature was missing in the experiment application, but has been implemented in other PapierCraft applications.

Another cause of these results is the failure of the underline recognition algorithm for irregular user input. Sometimes, when drawing a line for some important sentences, participants did not really care about the precise position of the line, which may have been curved and away from the targeted text. In this case, the line acted more like a rough reminder for the reader in the on-going deep reading,

[9] See chapter 4 for how the system clusters individual strokes into clusters based on their positions.

rather than an explicit input for the computer recognizer. As a result, the system extracted some unwanted text for users, who then simply abandoned the snippets at altogether. Further study is needed for a more robust algorithm to address this problem.

Possible user behavior change was another aspect that we were interested in. Although there were no explicit commands required, the auto-text-extraction did affect user behavior sometimes. One participant mentioned that he paid more attention to drawing regular underlines with PapierCraft and theTablet PC than with paper, because he knew that the precise underline could improve the extraction. It would be interesting to explore how people can adapt to a recognition-based interface to receive better service.

We also noticed that there were two participants who used only the snippets for summary, without reviewing the original document at all. They mentioned that such a method was a good match for the given task, i.e. writing a 1 summary sentence for each paragraph, but might not be their usual work style.

6.3.6.2 Information Sharing

Related to annotation management is information sharing. Repeated measures 1 way ANOVA on user responses to the sharing experience revealed technique to be a main effect ($P<.01$). A post-hoc pair-wise comparison suggested that normal paper was rated significantly lower than PapierCraft ($P<.01$) and the Tablet PC ($P<.01$, details in Table 5). Participants appreciated the convenience of digital annotations in this regard. For instance, participants 8 and 13 respectively said: “Once digitalized, PapierCraft and Tablet PC are both convenient to share, however it is much easier to annotate and take notes with PapierCraft," and "[PapierCraft and Tablet PC] software tools makes sharing easier."

6.3.6.3 Retrieve external information

Again, repeated measures 1 way ANOVA on the user responses to the retrieval experience confirmed a significant difference among the three interfaces ($P<.01$). A post-hoc pair-wise comparison suggests that PapierCraft ($P<.01$) and the Tablet PC ($P<.01$) received higher ratings than normal paper (details in Table 5). This can be attributed to the first two interfaces' high efficiency and accuracy in transferring keywords and URLs from a document to the web browser. In particular, for web page opening, we noticed that every participant made at least one typing error when manually transcribing the URLs from normal paper. They complained that: "[Paper] needs to type and scan by eye!"

Participants appreciated the handy in-situ web search command available directly in the reading material. Participant 14 said: "I am usually frustrated when I don't know the meaning of a word and hesitate to find it down on web search." Actually, we noticed that while reading for the summary, participants 14 and 15 started to use the web search command for unfamiliar words, despite the fact that the command was supposed to be used later when answering the quiz questions. This suggests that the function is well-accepted and easily learned by users.

6.3.6.4 Information transfer

Repeated measures 1 way ANOVA on the user rating of the information transfer showed that technique makes a significant difference to the user experience ($P<.01$). A post hoc pair-wise comparison uncovered that PapierCraft ($P<.01$) and the Tablet

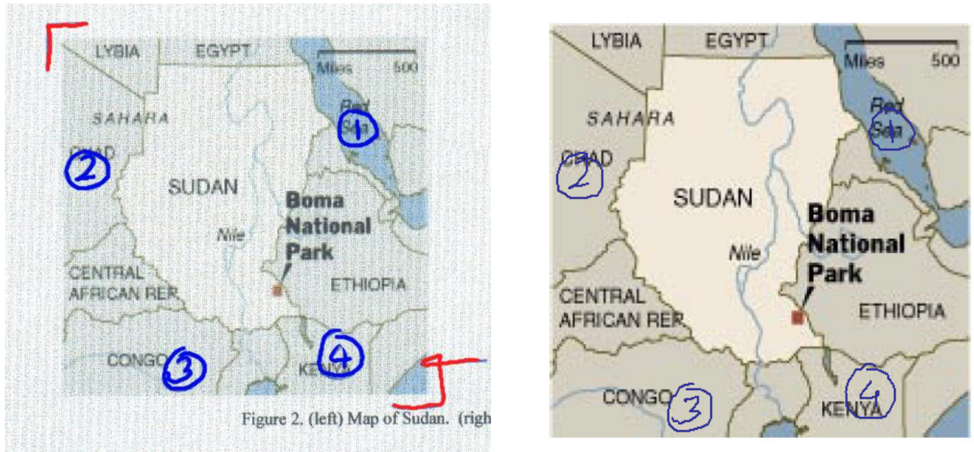


Figure 46. An example of pictures copied from paper with annotations, in which the participant intuitively described the positions of the POI (point of interest) with hand-written numbers. (Left) the marks on paper, highlighted for clarity (Right) the segment copied into the laptop

PC ($P<.01$) are thought significantly better than normal paper (details in Table 5) for this task.

This trend matches that fact that the copy/paste function was the most frequently used command in the experiment for both the summarization and the quiz questions. Users tended to use copy/paste whenever it was available, even though sometimes it may take more time to do pen-keyboard switching and draw the command gesture than to simply type a few words.

The copy/paste function helps participants in many respects. First, participants used the copied text as a base to compose a summary. The Snippet Reviewer can also provide text, but due to the lack of context and the addition of some unwanted text, participants tended to explicitly apply copy commands for the summary.

Importantly, the copied text was not simply kept intact in the resulting summary. By manually comparing the text selected by the copy command (identified by the drawn copy gestures and logs) against the resultant summary, we found that many times the two were actually different, since the participants had rephrased text and/or changed word order. One explanation for this “copy-without-use” phenomenon is that the copied text actually served as a context for composition, and not as a specific part of the summary. The benefit of this practice is that users do not have to switch focus between their summary and the original article. This phenomena also confirms the popularity of the copy/paste function in summarization in Morris’s work [Morris, et al., 2007].

Second, participants also extensively adopted the copy/paste function in the quiz section, as it was easier to convey 2D information with an annotated picture than with pure text. For example, our statistics show that 97.2% of quiz questions for which a picture copy/paste could be used were actually answered with copied annotated pictures. This demonstrates the popularity of the copy/paste function in such tasks.

6.3.6.5 Keyword finding

Finally, we ran repeated measures 1 way ANOVA on the keyword finding user experience, and found again that technique was a main effect ($P<.01$). A post-hoc pair-wise comparison showed PapierCraft ($P<.01$) and the Tablet PC ($P<.01$) were rated significantly higher than normal paper (details in Table 5). The digital searching facility was warmly embraced by participants. Interestingly, we noticed that, although for a few cases the participants might have directly located the keyword by just skimming the text, they still used the “find” command, which is supposed to lower the users’ cognitive load.

PapierCraft received a relatively lower rating than the Tablet PC, since PapierCraft cannot highlight target words on paper and further requires extra attention to the pen's LED color. However, participants thought such search-on-paper was cool and useful when only pen and paper were available. Another issue with PapeirCraft is the unwanted pen ink created when a user scans the pen in the margin to locate the next target line. These gesture marks, like those of the copy command, were not useful and were actually distracting once the command was issued. As we discussed before, the paper is actually only a transient media in PapierCraft, and one can re-print a clean version with only the needed marks. Another way of dealing with this problem may be to use a digital pen that works while hovering on paper within a certain distance, so that users can choose whether or not leave ink on printouts.

6.3.7 Summary

Our experiment has successfully proven the positive effects of in-situ digital functions and paper-like display physical quality, and has further demonstrated the combined paper-computer advantages of PapierCraft. Together, the results confirmed our main hypothesis that PapierCraft can bridge the paper-computer gap by integrating the affordances of the two media.

Our observation of and discussions with participants also suggests some interesting points for our future design. For example, the main complaints of PapierCraft converged on the following aspects:

1. The digital pen is too big and heavy, and it is hard to press the button;
2. The dot background is distracting;
3. The pen only works on the special pattern paper;
4. There is no highlight available on paper for keyword finding; and
5. The marks on the paper are not erasable or undoable.

The first 3 complaints are specific to the current implementation, and can be addressed with improved pen manufacturing and better recognition algorithms. Items 4-5 are more fundamental issues related to paper interfaces. For item 4, stronger visual feedback on paper is needed. One possible solution to this is to use portable projectors [Song, et al., 2006]. For item 5, we argue that paper should be used just as a transient media and computer interfaces will take on the intensively interactive tasks like editing and redo/undoing (with the information captured on paper). Actually, our Session Reviewer provided an example that helps users to redo/undo previous commands issued on paper (for more details, see Chapter 4).

For Tablet PCs, participants preferred their strong digital affordances, like intuitive interface for keyword searching, the ability to undo operations, and the ability to navigate among a large number of pages. The main complaints focus on the physical properties of the Tablet PC, like the limited screen size, its weight, the slippery surface, its thickness, and the software design for page navigation. Without a doubt, enhancing these capabilities is the direction in which the future document-operation-oriented computer interface should proceed.

Further, some user comments are applicable to both PapierCraft and computer interfaces:

1. The pen gesture is restricted, as no additive drawing is allowed (e.g. in the experiment, a lasso and its pigtail must be drawn continuously without pen-lifting in the middle). This is not a fundamental limitation of PapierCraft, but a matter of implementation, which could be addressed with a more advanced gesture recognition module.

2. The coordination between the mode-switching button and the gesture drawing was uncomfortable to some participants. Maybe we can put the button in the non-dominant hand, as Li suggested [Li, et al., 2005].
3. The relative advantages of paper and computers in navigation and spatial arrangement depends on the amount of document pages. It would be interesting to explore how to determine the optimal media, or more generally the appropriate number of displays, for a given set of pages.
4. The spatial layout of the original pages is important contextual information for extracted document snippets. An interface with quick context-snippet switching would be helpful.

Finally, this experiment is limited to a laboratory scale. In the future, we would like to deploy the system in a real scenario and conduct a longitudinal test to examine PapierCraft user experience in the long-term.

6.4 Summary of Evaluation

We have evaluated PapierCraft at three different levels, namely the *command-component*, *whole-command,* and *application* levels. By comparing PapierCraft with typical settings in real life - Tablet PCs and normal paper - we have proven the effectiveness of our design at the three levels.

At the command-component level, the pen-top feedback was proven effective in helping the novice user learn a new set of command types, significantly reduces the experienced users' error rate, and encourages error correction. At the whole-command level, the experiment shows that after a reasonable training time (~30min), PapierCraft users can achieve a performance comparable to Tablet PC users in using the gesture-based command system. Finally, at the application level, the test shows the paper-computer-combined affordances of PapierCraft in supporting active reading and demonstrates a positive user acceptance.

We also reaped rich insights about the limitations of PapierCraft, for example, users informed us of the uncomfortable feedback pen and pattern background, the restricted gesture recognizer, the qualified paper advantages in navigation and spatial layout, as well as the importance of whole document page context for serious reading. These insights suggest the direction in which our future research should proceed.

Chapter 7: Applications and Real-life Deployment[10]

PapierCraft was initially motivated by Active Reading, but its supporting techniques can be extended to other application areas. To demonstrate this potential extension, we have designed, built and evaluated two systems, ButterflyNet [Yeh, et al., 2006] for field biology and PaperCP [Liao, et al., 2007] for e-learning. These systems not only confirm the possible applications of paper-based interfaces like PapierCraft, but also bring us valuable practical experiences of the real life deployment of the interfaces.

7.1 ButterflyNet

ButterflyNet [Yeh, et al., 2006] is a mobile multimedia system, which helps field biologists capture, structure, access and transform data collected in field. It was done in collaboration with Rohn Yeh, Scott Klemmer, Brian Lee, Boyko Kakaradov, Jeannie Stamberger and Andreas Paepcke at Stanford University.

ButterflyNet was motivated by the increasing burden for biologists to manage a large amount of field data spanning physical artifacts and digital media. On one hand, field biologists' practice depends on paper notebooks as the central organizing tool, considering its shortcomings necessary to gain the reliability and flexibility of paper (see Figure 47**Error! Reference source not found.**). On the other hand, field

[10] Portions of section 7.1 were originally published by the author, Ron B. Yeh, Scott Klemmer, François Guimbretière, Brian Lee, Boyko Kakaradov, Jeannie Stamberger, and Andreas Paepcke in [Yeh, et al., 2006]; Portions of section 7.2 were originally published by the author, François Guimbretière, Richard Anderson, Natalie Linnell, Craig Prince and Valentin Razmov in [Liao, et al., 2007].

Figure 47. A) Field biologists choose paper notebooks because they are portable, readable outdoors, robust to harsh field conditions, and have infinite "battery life." B) As seen on this office desk, paper notebooks support flexible input and output. C) However, like Tracy Storer's notes from 1925 (in CAS archives), most notes are locked in storage, their value lost to those who might benefit from them.

biologists rely on computers to analyze data, and must transform their work to do so. This tension suggests a wholesale replacement of paper in current practices. However, a wholesale replacement of paper can be problematic, as evidenced by Sellen and Harper's work [Sellen and Harper, 2003]. Instead, we argue that it is better to design technologies that complement paper tools: the bits in our computers should be aware of the atoms of our world [Ishii and Ullmer, 1997]. Thus, we believe that *next generation tools should support the capture of heterogeneous data, aid the transformation process, and yet preserve the best aspects of current paper-centric practices.*

The following sections are organized as follows. The next section summarizes the observational study of field biologists. Following that, we present the two primary contributions. The first is ButterflyNet, a system comprising interaction techniques—informed by the observational study—that leverages digitally augmented paper notebooks as the central structuring tool for capturing, organizing (through automatic and manual techniques), transforming, and sharing heterogeneous data. The second contribution is a first-use study of this system, and the lessons we learned. The study demonstrated that *automatic association was highly successful, and that manual associations show promise for some users.*

7.1.1 Practices of Field Biologists and Design Implications

Part of our interest in studying field biologists is to use an understanding of this highly mobile community to inform mobile interaction design. Designing from a deep understanding of a *particular* community can provide insights valuable in a broader context.

7.1.1.1 Capture and Access of Heterogeneous Data

Field biologists capture handwritten notes, digital photos, audio, video, sensor readings, GPS data, and physical specimens. By examining how these are currently managed, we make a case that new technologies must support the rich capture and access of this heterogeneous data.

Paper notebooks are a field biologist's central organizing tool (see Figure 47). They take their notebooks everywhere, using them as *the definitive record* of all procedures, measurements, and results. In the field, biologists use notebooks to capture observations that may lead to new hypotheses. This practice emphasizes careful documentation with descriptions of the day's work, the time and date, weather, participants' names, and pictorial annotations such as maps. Our colleagues at Stanford university examined 13 notebooks from five biologists (471 total pages), and found that notebooks primarily contain tabular data and descriptive prose, augmented with charts, pictures, sketches, pasted-in-sheets, and bulleted lists.

Field biologists supplement their notes with specimens, photos, GPS data, audio and video. Physical specimens help biologists understand ecosystems. For example, CAS (California Academic of Science) owns millions of specimens. Field biologists use photos and video to record experimental data, observations, and context to supplement their notes and specimens. One use of photos is to identify species where collecting specimens is not desired. For example, some of the biologists we work with use cameras to “trap” mammals at Jasper Ridge. The biologists use the photos to identify animals, in an effort to model their movement. Photographs also aid collaboration, as they can convey the feeling of an ecosystem to other scientists. Biologists can also use photos to locate sites in locations where GPS data is not available, such as under a rainforest canopy (or as backup in case GPS data is lost). When GPS is available, many biologists use commercial receivers to capture the geographic data. One of our interviewees uses GPS to track the spread of invasive ant species. And as for audio, one ornithologist the Stanford colleagues spoke with captures bird calls while conducting his research in India. He correlates his notes with the audio of the calls, and sends ones he cannot identify to a local expert for help.

Finally, field biologists use sensors to record environmental parameters (*e.g.,* temperature, solar radiation, wind speed, humidity, and precipitation). Portable, inexpensive, low power, and reliable sensors such as the iButton have enabled environmental data collection in harsh situations, and the advent of battery-powered wireless sensor networks [Culler and Mulder, 2004] offers even richer environmental monitoring. While sensor data can be exported to PCs, current tools cannot associate these data with a biologist's own observations, making the understanding of natural systems fractured.

In short, field biologists gather information from a diverse set of sources, yet have *little support for coordinating and distilling* this information. Transforming the information into analyzable forms is labor intensive and error prone, as the information may be scattered across different locations. There is limited support for organizing, searching, and sharing. Moreover, there is no tractable method for ascertaining a particular result's data lineage. And while scientists struggle with these tasks, valuable research remains trapped in paper notebooks and in digital storage.

Technology makes it possible to *overcapture*[11] in the field; however, as we found, solutions for rapidly harnessing this rich data are limited. Improving this situation can have a significant impact. Technology that supports mobile capture and access should strive to meet several design goals. First, it should support handwritten notes and the other types of data that field biologists work with, such as specimens and digital photos. Second, it must support the robustness requirements of the domain. Finally, the design must remain flexible, enabling biologists to include new input streams as needed.

7.1.1.2 Data Transformation and Tools Integration

While much of a biologist's research is organized *on paper*, interpretation requires that data be entered into *computers*. Based on the interview conducted by our colleagues at Stanford university, we learned that a big limitation of current practice is that transcribing data from paper notebooks to spreadsheets is painfully slow.

[11] people may capture data more than needed at a time, and hope the data could be useful in the future

Interviewees asked for OCR software to import handwritten tables into Excel. One interviewee described his bee experiments in Costa Rica, where he and collaborators spent six hours a night transcribing datasheets. The ornithologist who worked in India spent multiple 12-hour sessions correlating audio with his notes, transcribing the information into a database.

New technologies need to support efficient *transformation* of data from the captured format (*e.g.,* handwriting) to the computer world. While fully automated solutions are tempting, they will not work in all cases. Current solutions are error prone, and the process of manually transforming some data plays a cognitive role in helping the biologist assimilate her research. The design goal, then, is to provide a hybrid solution, where the biologist can oversee the computer transformation of data. One such design is where a person manually verifies handwriting recognition results.

In addition, systems in this area must also integrate with downstream tools, to enhance usability and increase adoption. For writing publications, the interviewees use Microsoft Word. For statistics, they used Excel, SAS, JMP, or SPSS. For capturing geography metadata, they use GPS receivers in the field and GIS software at the field station.

7.1.1.3 Robustness

Paper notebooks can take extraordinary amounts of abuse before failing. Data can be salvaged from a notebook that is torn in half, dropped to the ground, or subjected to a downpour. The same cannot be said about modern portable computers. Field systems should follow suit by being robust and offer graceful degradation.

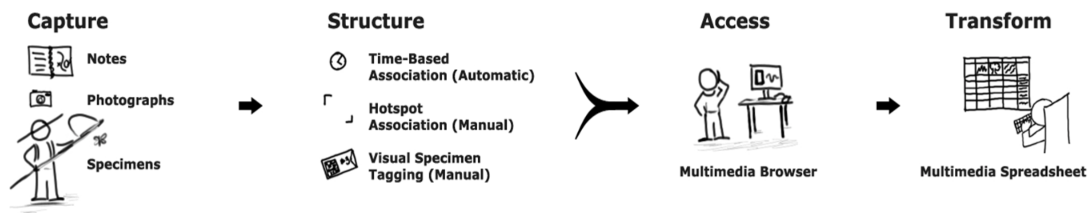


Figure 48. ButterflyNet contributes techniques that facilitate the capture, structure, access, and transformation of heterogeneous information.

7.1.2 The ButterflyNet System

Informed by this study, we designed ButterflyNet, a capture and access system for notebook-centric mobile work. With ButterflyNet, field scientists can capture, organize, and share heterogeneous research data, including notes, photos, and specimens (see Figure 48). By recognizing the centrality of paper notebooks in current practice, ButterflyNet allows users to be immediately familiar with its primary interactions. This section describes these interactions and how they support field biology work practices.

7.1.2.1 Heterogeneous Capture

ButterflyNet supports the capture of handwritten notes, digital photographs, and physical specimens. To capture handwritten notes, a field biologist uses the Anoto digital pen system (we use Nokia SU-1B pens with Bluetooth [Nokia, 2004]). While ink is physically laid down on paper, the pen's camera tracks a dot pattern printed on that paper and digitally captures which page and where on the page the writing occurs; it even annotates every stroke with the current time and date. When the user synchronizes the pen with a PC, the digitized notes are uploaded. We decided on Anoto pens because they afford graceful degradation. Unlike pure digital solutions, if the pen's digitizer were to fail, users would still be able to record observations, as the paper and inking pen provide redundancy. Conversely, if a physical notebook is lost or otherwise unavailable, the electronic version can be used.

To capture photographs, a user employs a digital camera. For richer interactions, we prototyped a custom “smart” camera (see Figure 50.A), our functionality prototype of a successor to contemporary digital cameras. With the smart camera, users can perform on-the-spot annotations of photos by marking on the LCD screen with a stylus. The smart camera also communicates wirelessly with the pen, offering real-time visual and audio feedback for in-the-field interactions. This smart camera was prototyped with an OQO handheld [OQO, 2005] running Windows XP with a webcam affixed to the back. This is a functionality prototype; we presume that a production implementation would provide a sleeker form factor. (Given current technology trends, we anticipate this will be a camera phone.)

To capture physical specimens, biologists use tagged coin envelopes (see Figure 49 D). Using coin envelopes to collect specimens was a practice observed in our field work. The tags enable ButterflyNet to uniquely identify specimens.

7.1.2.2 Information Association within A Spectrum of Granularities

ButterflyNet provides several techniques to associate captured data. Association between heterogeneous data is important as it “glues” together pieces of data, possibly scattered among various media, into a meaningful story about the field work. The field study by our Stanford colleagues found that systems must provide both low-threshold and high-ceiling interactions [Myers, et al., 2000] — easing adoption for novices while providing control to experts. In response, we designed and

Figure 49. Visual specimen tagging enables a biologist to associate a physical specimen with its photos and annotations. The biologist uses an envelope enhanced with a 2D barcode, a human readable ID, and digital paper. He A) takes a photo with the tag in view, B) writes an annotation on the Anoto-enabled envelope, and C) places the specimen in the envelope. D) ButterflyNet detects the barcode and establishes the association between the photo, the annotation, and the specimen.

implemented three techniques to associate and structure information at three different granularities, which ranges from coarse to fine grains spanning a spectrum.

The first technique is *automatic time-based correlation*, an extremely low-threshold technique that does not require biologists to alter current practices. Photos, notes, and other data that contain timestamps are automatically associated by ButterflyNet during capture. For example, if a biologist writes an observation at 3:23 PM and takes a photo shortly thereafter, the photo and those notes would be associated. Although easy to use, this technique may lead to very coarse association. For instance, the biologists may take ten photos before taking field notes to describe the photos, in which it is hard for the system to know which sentence is for which photo.

To provide more precise, explicit control over media association, ButterflyNet provides two manual techniques, namely *visual specimen tagging* and *hotspot association*. *Visual specimen tagging*, enables users to associate physical specimens with photos and handwritten annotations (see Figure 49). The user places the desired specimen in a coin envelope enhanced with a 2D barcode and Anoto paper. Annotations written on the paper will be associated with the barcode, and thus, the specimen. Additionally, any photo containing this barcode will also be associated with the specimen. When taking a photograph that is related to a particular specimen, the user places the envelope such that the barcode appears in the photo. ButterflyNet detects the tag in the image, extracts the ID, and establishes the association. This technique aligns well with field biologists' existing practice of using envelopes to store specimens and other physical artifacts.

The ability of cameras to read the tag enables ButterflyNet to establish associations between photos, specimens, and notes. This design has several advantages: visual tags can be created by users with commodity hardware (printers); the tags can be read with commodity hardware (cameras); and the tag includes a human-readable ID. Since humans can also read the tag, end users can perform manual association if the barcode recognition fails.

More control of the information association is enabled by another technique, *hotspot association*, which allows for manual spatial arrangement of text and photos. Biologists can associate a photo with a specific area of a notebook page (see Figure 50). To invoke a hotspot association, the user captures a photo (or browses to a photo) and then draws two brackets in her notebook. This hotspot is later visualized as a photograph that has been resized to fit into the frame. Our smart camera provides real-time multimedia feedback for hotspots; it beeps and displays a temporary popup

Figure 50. To create paper-photo association, a user A) captures or browses to a photo, then B) draws the hotspot gesture into the notebook using the digital pen. C) The smart camera provides real-time visual/audio feedback to confirm the association. D) The ButterflyNet Browser renders the associated photo within the hotspot brackets, inline with the digitized notes.

to confirm that the hotspot association has been created. The audio feedback is an important design feature, as in the field, users may not actually be looking at the camera while creating the hotspot. The hotspot interaction extends prior work in smart-paper systems [Dymetman and Copperman, 1998, Klemmer, et al., 2003, Luff, et al., 2004] by enabling end users to author associations on-the-fly.

The three techniques span the spectrum of association granularity, and allow biologists to make different trade-offs between efforts (in field) and granularities, so that users have flexibility to choose specific tools depending on their goals.

7.1.2.3 Rich Information Access

In addition to the capture and association techniques presented above, ButterflyNet supports rich information access through the ButterflyNet Browser (see Figure 51). After the biologist imports her data, she can use the browser to visualize her notes and photographs in a rich browsing interface. The *content panel* (Figure 51B) shows the information the user is currently focused on (digitized field notes by default). The

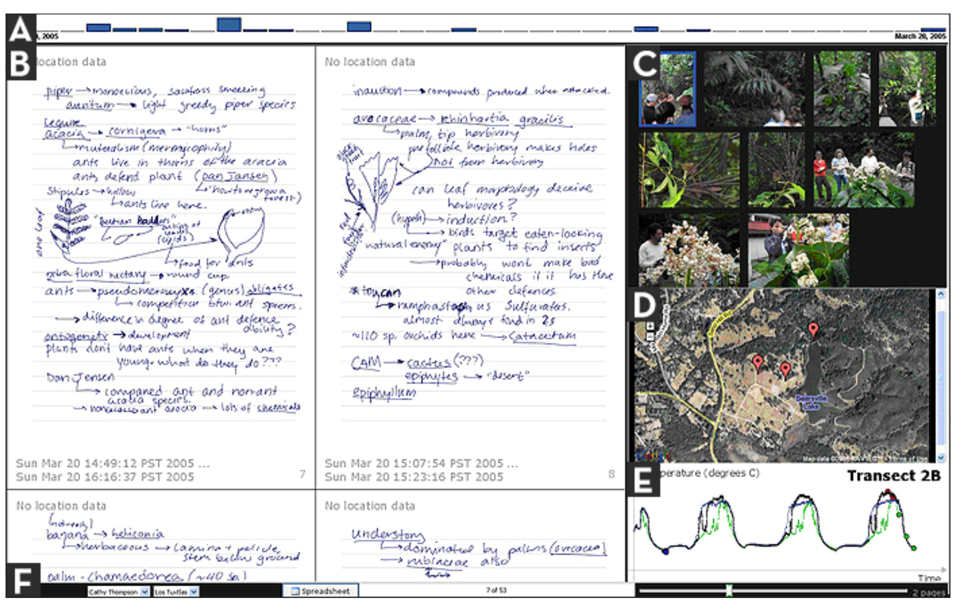


Figure 51. The ButterflyNet Browser. A) A timeline visualization of captured notes. The browser presents digitized field notes in the main panel (B), and associated media in the context panel (C). Maps (D) and sensor data (E) were not used in the study.

photo *context panel* (Figure 51C) shows time-associated photos. For example, if a user views notes from 3:23 PM on March 23, 2005, she will see photographs taken on or near that time in the context panel.

The browser provides a direct manipulation interface for navigating the data. The timeline visualization (Figure 51A) allows users to jump to content by date and time. The height of each bar represents the quantity of data at that time interval. Users can jump to specific pages with the navigation bar (Figure 51F), or show multiple pages by zooming out (via a slider on the navigation bar). The bar also lists shared notebooks, which the user can view by selecting from a dropdown menu.

ButterflyNet also enables users to access research data using their physical notebook. With this technique, a user taps the page with his digital pen, and the ButterflyNet Browser responds by presenting the digital version of that page and all associated data. With this technique, a user can also retrieve hotspot-associated photographs by tapping inside a hotspot frame (in the physical notebook) with the digital pen. The retrieved photograph appears in the browser or on the smart camera.

7.1.2.4 Enhancing Data Transformation and Integration

Finally, ButterflyNet enhances data transformation through a multimedia spreadsheet, which contributes several novel organization and visualization techniques (see Figure 52). First, the spreadsheet assists with transcription of tabular data. Users can select handwritten data in the browser and send it to a window that hovers over the spreadsheet. As the biologist types, a placeholder moves down the page to help her keep track of which row she is currently transcribing, eliminating the need to look back and forth between a physical notebook and the computer display.

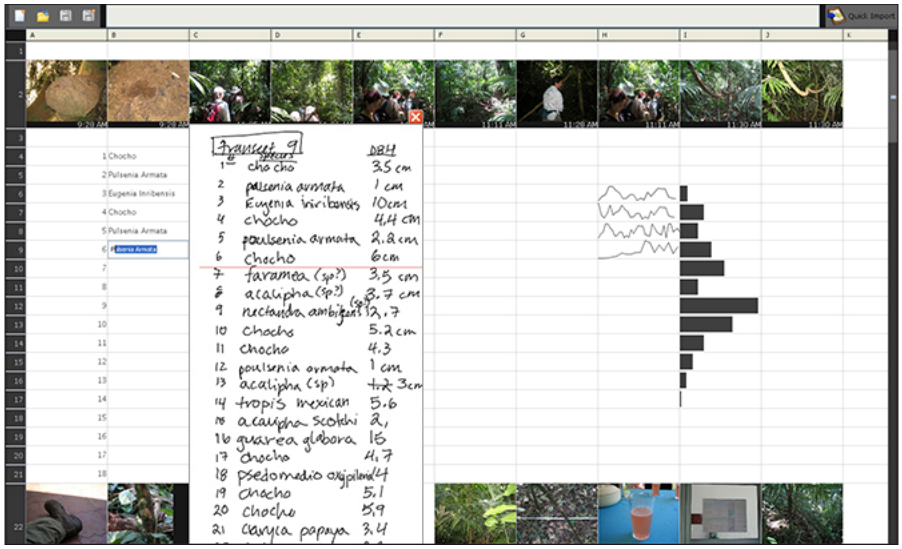


Figure 52. The spreadsheet assists with transformation of field data. A window displays digital ink, while a marker visually tracks which row the user is transcribing. One can assign photos, time series graphs, or visual percentage bars to individual cells.

The spreadsheet enables users to embed photographs and charts into individual cells. (In Excel, these objects cannot be placed in a cell; they float loose.) This feature is accessed through a context menu that is updated with new content as the browser views new pages. Like the smart camera, the spreadsheet is a prototype of the salient aspects of a future system. Currently, it serves as a ButterflyNet-integrated springboard that can export to industry standards.

To further facilitate transformation and sharing, the user can select any data in the browser, and export to the system clipboard. The physical notebooks can also be used to export data to the spreadsheet. When the spreadsheet is open, a user can draw a pair of hotspot-like brackets on a page to specify a region of interest. ButterflyNet detects the paper gesture, extracts the selection from the corresponding digital notes, and exports it to the multimedia spreadsheet.

7.1.2.5 Extensibility

ButterflyNet was architected with extensibility in mind. In the future, we may extend the system to associate and present a wider variety of data, including audio, video, GPS logs (Figure 51D), and sensor data (Figure 51E). If notes are georeferenced, a map will show relevant locations. If there are sensor readings that were logged at the same time as captured notes, they will also appear in the context panel.

We will also continue to explore the tangible navigation of media. With the smart camera, a biologist can now retrieve associated photos by tapping the digital pen to a relevant notebook page. This device ensemble approach for in-the-field retrieval is valuable in mobile settings, where screen real estate is intrinsically limited for individual devices.

7.1.3 Evaluation

We conducted a first-use study of ButterflyNet, focusing on interactions with three data types (photos, notes, and specimens) and three hypotheses:

H1:The field capture techniques (digital notebook, hotspot association, and visual specimen tagging) enable media association with minimal overhead.

H2: The ButterflyNet Browser presents a fast and rich information view by presenting photographs both in a context panel and inline with notes (through hotspots).

H3: The spreadsheet facilitates the transformation of data.

Sessions were held at the Jasper Ridge Biological Preserve (JRBP), and lasted 2.5 hours per participant (we paid $45 cash). The 14 participants (six male; eight female) included JRBP docents, PhD students in biology, and professional researchers. Field experience ranged from none (for a single docent), to 1-2 years (most docents), to several years (for PhD students), up to 18 years (for one professional). Five of the 14 had more than 10 years of field research experience.

Figure 53. A participant uses the smart camera to take a photo.

We asked participants to go to the field to collect photos, notes, and specimens, and then use that day's data to create a spreadsheet to present to colleagues. The design of this task was informed by our field study. Specifically, we modeled the task to mimic a day of field research, as our Stanford colleagues witnessed in the Los Tuxtlas rainforest. The first hour of the study comprised fieldwork, where the participant carried a backpack (with water and equipment), a field notebook and digital pen, a digital camera (Canon SD300), the smart camera, and tagged specimen envelopes. The reason that participants carried two cameras was that at the time of the study, hotspot association required the smart camera's features, while the consumer digital camera's higher resolution yielded more reliable recognition of the specimen tags. We envision that future cameras will provide the smart camera functionality.

In the field, biologists used three techniques:

1. For each oak gall they found in a 2m × 40m line transect (a standard field sampling method), they recorded the distance of the gall along the transect, its size (large, medium, small), its color (dark, bright), and a photo.
2. At three points along the transect, they photographed the habitat using the smart camera, and associated it with a hotspot in their notebook (see Figure 53).
3. At three different points on the transect, they used a visual specimen tag to photograph, annotate, and collect a physical specimen of their choice.

These subtasks mirror everyday field tasks — collecting measurements, photos, and specimens. Back at the field station, the participant filled out a 15-question survey of their background and their opinions on the field task.

Next, the participant engaged in a lab task (also informed by our need finding). The participant was asked to use the browser and spreadsheet to create a spreadsheet with photos and measurements, for explaining the data to collaborators. As an incentive, we awarded the author of the "most useful spreadsheet" a $10 gift certificate (the winner was chosen after all studies were completed). The lab task ended with a second 15-question survey to gauge the lab tools and ButterflyNet in general. Finally, we conducted an informal debriefing interview with the participant. Other than this interview, and a tutorial of ButterflyNet, the participants completed the tasks on their own, while the experimenters observed (capturing video and handwritten notes).

7.1.3.1 Results

This section highlights several outcomes of the user study, discussing how they will impact our future work. We organize the results around ButterflyNet's key features, and refer to specific observations, questionnaire results, coded free-form responses, and hypotheses where appropriate.

Media Association

Participants readily understood the automatic, time-based association. However, at the time of the study, ButterflyNet associated media at a fixed (and coarse) granularity — the context panel showed all photos captured within the time span of the current page. Unfortunately, the users recorded many measurements and photos per page, and sometimes needed finer associations than ButterflyNet provided (e.g., there might be several photos of different galls all at 1:24 PM). To negotiate the spreadsheet task, then, some participants would find anchor images in the browser (e.g., the dark and small outlier gall at 1:24 PM), and then interpolate the rest (e.g., the subsequent photos at 1:24 PM must be associated with the measurements immediately after the small and dark gall). Thus, we see that capture and access systems need to provide the user a way to adjust and visualize the granularity of automatic associations.

Participants were excited about the possibilities presented by hotspot association (the two-bracket gesture for associating photos to parts of a page). People mastered the gesture quickly. One participant found it efficient enough to draw in every row of measurements, to achieve a one-to-one association with photos. During the debrief interview, a different participant mentioned that ButterflyNet, with its

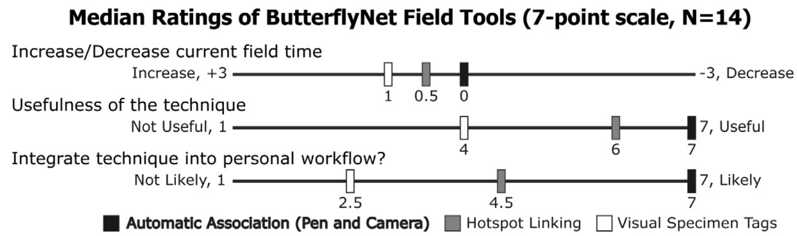


Figure 54. Participants found automatic association most applicable to their current work. Hotspot linking shows promise, and visual specimen tagging may suit only some biologists.

hotspot-based and time-based association techniques, would be perfect for her travel journal; this comment points toward general applicability of these association techniques.

Study participants were also able to quickly learn and apply the visual specimen tagging technique. However, we did notice that occasionally, the visual tag would not be recognized, due to tall grasses occluding parts of the barcode. Fortunately, in this case, the biologist would still be able make the association after the fact, as the visual tag includes a human-readable number (see Figure 49.D).

Figure 54 shows the participant response to the association technique questions (we use the median to analyze the ordinal data). These results partially support H1. Participants felt that automatic association would not increase field time, and were positive toward the technique's potential usefulness. Through automatic association, ButterflyNet presents an informal UI, such that the in-the-field focus—when time is expensive—is on documentation, rather than interface manipulation. And though flexibility over the window of automatic association would improve the experience, the system was already performing better than today's jury rigged solutions.

However, the data show that participants felt that hotspot association and specimen tagging slightly increased field time, and felt that specimen tagging would have to improve before they would use it in their own work. This response to visual specimen tagging may have several explanations. First, biologists may be reluctant to use tools that increase field time by any amount. Second, not all of our subjects collect specimens in their work, and thus have no use for the tagged envelopes. Finally, it may be due to limitations in our current implementation—we currently do not provide functionality beyond linking tagged photos with annotations and do not provide solutions for the occasional barcode recognition problem (*e.g.,* by manually presenting the barcode again in a more controlled environment).

As our study implementation addressed photo-based tasks, our data analysis partitioned the participants by how much they value photos in their work. In this case, opinions about the association techniques diverged significantly. In all cases, the likelihood that the subject would use the technique ranked higher for those who valued photos, showing that participants who use photos are particularly excited about ButterflyNet's potential. For instance, when asked if she would use ButterflyNet's field tools into her work, a veteran of more than 10 years responded with straight 7's (the highest rating). She takes 10-20 photos per day, and views photos as extremely important (7 out of 7). She stated that she found the ability to find photos and associate them with spreadsheet cells perfect for her work with animal teeth. After the study, she requested a copy of ButterflyNet to use in her current work measuring jaw bones (through photos).

Rich Information Access

Participants readily understood the ButterflyNet Browser's presentation and access interface. In our questionnaire, we attempted to determine the usefulness of this

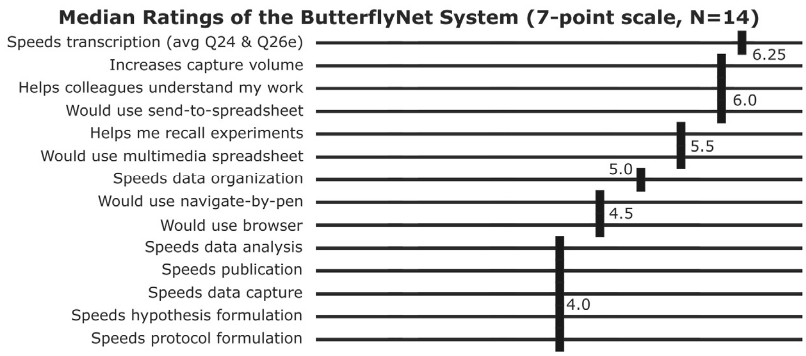


Figure 55. Participants reported that ButterflyNet would help them transcribe data faster, and capture more heterogeneous information.

interface. Figure 55 summarizes the evaluations for 14 likelihood variables in a 1 to 7 scale (1 for *very unlikely*; 7 for *very likely*). The top advantages participants saw were that ButterflyNet would help them to capture and transcribe more data. Additionally, it would help them recall experiments better. These lend support to H2, that the browser provides rich information access.

Transformation and Integration

Participants successfully completed the lab task, and generally perceived that the transcription helper would speed up transcription. We find that the tools integrate well with current practice (12 of 14 reported regular spreadsheet use, the highest rating in a 7-point scale). In the free-form responses, eight mentioned that they liked the association of photos with notes. Six liked the tools for exporting data. Six wrote that digital backup for notes would be invaluable. Thus, ButterflyNet aided transformation (H3) and integrated well with the participants' current practices (see Figure 55).

Graceful Degradation

The study also reflected how ButterflyNet supports graceful degradation. Very occasionally, the digital pen would miss a few letters or numbers in participants' handwriting. Perhaps there was dirt on the page, or perhaps the pen was used too close to the edge of a page (where the pen's camera cannot decode the dot pattern). The few users who encountered missing data in their digitized notes quickly switched to their physical notebook, where the data was faithfully captured with actual ink. These participants seemed comfortable defaulting to the physical notebook when the digital representation was incomplete.

Gesture Recognition

The recognition of hotspots is good. The recall rate was 78.3% (54 of 69 attempted were correctly recognized); the precision rate was 88.5% (of the 61 recognized, 7 were false positives). However, many errors arose from a single participant's data, whose hotspots were smaller than our threshold. Without this data, the recall rate was 93.3% (42 of 45), and the precision rate was 91.3% (4 of 46).

Our fieldwork found that participants would rather save field time, even if it resulted in more work later. Thus, we made a design tradeoff to make the hotspot gesture as lightweight as possible. The normal PapierCraft gesture engine requires a pigtail loop at the end of all gestures to enhance recognition. We removed this to achieve simpler gestures. Additionally, when the study was conducted, ButterflyNet did not have modes to switch between gesture and ink, so all strokes were potential hotspots. This design achieved simpler field interaction at the expense of recognition rates. However, our latest feedback pen can mitigate this mode-switching issue and enable users to edit associations between potential hotspots and their photos (*e.g.,* by deleting false hotspots).

Possible Limitations

The freeform questionnaire feedback pointed to possible limitations. First, participants felt that while the aided transcription was faster, it was still tedious. To address this, we are currently integrating handwriting recognition into ButterflyNet and exploring the UI implications. Second, a few participants voiced concern about the need to use a special pen, and were worried they might lose it in the field.

The data indicate a slight negative correlation between expertise and opinions, though not all expert participants currently use photos. For example, one expert who gave low ratings studies bat calls and takes zero pictures per day. When we described in debriefing that future versions would handle audio, he said that then, ButterflyNet would prove extremely valuable to him.

The data shows that *experts who use photos find the pen and notebook interaction useful*. The manual techniques did not fare as well; we note that they must prove valuable *beyond* automatic association. Additionally, participants only had limited exposure to them in the lab.

Much of the support for our hypotheses comes from questionnaire results. While the ratings generally support ButterflyNet's lightweight interactions (H1), fast and rich information view (H2), and efficient transformation of data (H3), one must keep in mind that each session took no more than 2.5 hours, and that a longitudinal evaluation would be much more reliable. We leave this for future work.

7.1.4 Future Work

The results from this study point toward some exciting opportunities. An important step will be to study how biologists can use ButterflyNet to interact with data outside of photos and notes. The studied system did not include any GPS or sensor data features. The freeform responses did show that while participants found the integration of photos to be useful, many stated that adding GPS integration would prove extremely helpful. We plan to integrate GPS, sensor data, audio, and video into future versions of ButterflyNet. One particular point of interest is automatic correlation based on other metadata facets, such as location.

Also, while the hotspot interaction currently works only for cameras, there is no reason why it cannot be generalized. As long as a device can record the timestamp of captured or browsed-to data, it can leverage hotspots. Thus, in the future, a field biologist may be able to associate video, GPS, or sensor data using simple hotspot gestures.

7.2 PaperCP

PaperCP is a joint project with Richard Anderson, Natalie Linnell, Craig Prince and Valentin Razmov at the university of Washington. It explores the use of paper-based interfaces for Active Learning. Active Learning refers to augmenting the traditional lecture with student-participation activities such as brainstorming, quizzing, and polling. Also vital to Active Learning is sharing (e.g., displaying) student responses as part of a lecture. Because of this two-way instructor-student communication, Active Learning increases student engagement, helps with the construction of knowledge, and improves the level of understanding of students, as well as the instructors' awareness of it [Razmov and Anderson, 2006].

Designing a system to support Active Learning is challenging because of the tension between traditional physical interfaces and newer electronic ones. Traditional printouts and transparencies are easy to read and write on, convenient to navigate, and easy to manipulate by hand. But the manual distribution, collection, summarization, and display of the physical artifacts are often inefficient and distracting. To address this issue, fully digital systems have been developed [Anderson, et al., 2004, Dufresne, et al., 1996, Ratto, et al., 2003, Wilkerson, et al., 2005]. For instance, Classroom Presenter (CP) [Anderson, et al., 2004], a digital Active Learning system, allows the instructor to deliver slides and gather student responses wirelessly via networked pen-based Tablet PCs. Despite the digital solutions' advantages in data transfer and archiving, some drawbacks are associated with these systems: a degraded reading and writing experience due to limited screen size and screen resolution, the cost of the devices, and the limitations imposed by battery life. To ease the tension between physical and digital affordances, a natural solution is to integrate them to create a better overall user experience.

In this project, we investigate how to combine the advantages of physical artifacts like paper with the convenience of an electronic communication and

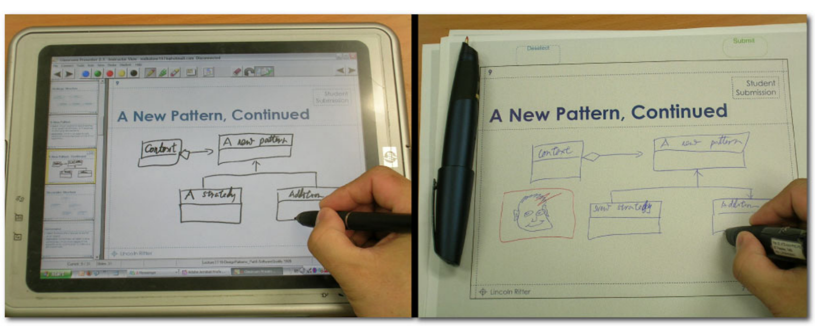


Figure 56 (Left) The original Tablet PC interface of the Classroom Presenter system. (Right) The new equivalent interface, PaperCP, based on PapierCraft, which consists of two Bluetooth digital pens and printouts.

archiving infrastructure. Specifically, based on a communication model for Active Learning, we propose a new paper-based interface, PaperCP (Paper Classroom Presenter) (Figure 56-right), for Classroom Presenter, aimed at addressing the interaction and cost-benefit problems of the fully digital system. Our physical interface allows students to use Anoto-enabled slide printouts as an input interface, so that users can still enjoy the inherent advantages of paper. Using a digital pen, students can write directly on the handouts and can electronically submit their handwritten notes to the instructor, thereby maintaining two-way communication with the instructor. Furthermore, the compatibility of paper and digital interfaces allows multiple heterogeneous interfaces (i.e., paper and Tablet PC) to be simultaneously deployed with our system, so that users can choose which system to use for a given Active Learning activity.

To evaluate this system, we deployed it during four regular class sessions of an actual Software Engineering course at the University of Washington. Using qualitative in-class observations in addition to quantitative results from questionnaires and user logs, our study confirmed the feasibility of implementing and deploying PaperCP in a real-use scenario. The study also revealed that the choice of a print layout and digital pen configuration has a large impact on the perceived tangibility advantage of the physical interface. Finally, our experiences provide insight into designing new interfaces that combine paper and digital affordances.

7.2.1 A Communication Model of Active Learning

Active Learning involves students performing activities in the classroom and communicating with other students and the instructor. Here we focus on the student-instructor interactions, which can be characterized by the following communication model.

As illustrated in Figure 57, there are two parties in the model, the instructor and the students. The instructor navigates through slides, presenting prepared lecture material or showing student artifacts, perhaps adding on-the-fly comments or sketches according to the students' understanding level. Each student follows the presentation; navigating and annotating his/her own copy of the lecture materials, as well as taking notes.

Active Learning is achieved by the two parties via three main communication channels (Figure 57): First, the instructor uses the *individual delivery channel* to distribute activities and lecture materials to individual students, e.g., traditional paper handouts, transparencies, or digital PowerPoint slides. These materials are relatively static through the course of the class and are intended for the students' personal use. The distribution typically occurs just once, at the beginning of a lecture. The

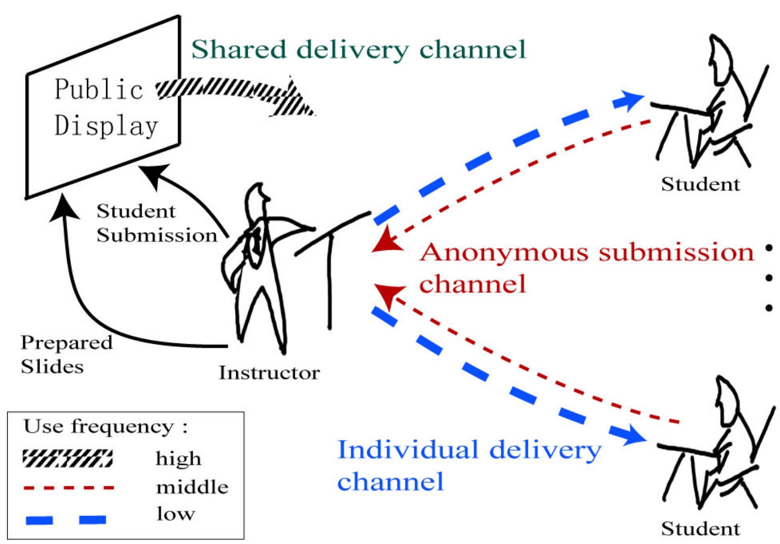


Figure 57. A communication model of Active Learning. It consists of three channels denoted by dashed lines, whose thickness corresponds to the amount of data transmitted over each specific channel.

channel's digital implementation is highly efficient. In comparison, delivering physical handouts before class is a burden, but will not severely affect what happens during the class time.

At certain points during the lecture, the instructor announces prepared activities to involve students in thinking and presenting ideas, such as drawing workflow diagrams, ranking key factors, selecting a multiple choice answer, or writing snippets of source code. Then, students use the *anonymous submission* channel to anonymously submit to the instructor answers or artifacts that they dynamically create during class. This channel is often accessed several times during a class session. Compared to handing in physical artifacts, electronic submission is much more efficient. It is important to note that the amount of data (e.g., brief comments, ranking, polls, as well as rich responses like graphs or drawings) traveling from the students to the instructor is usually smaller than in the reverse direction. This makes it possible to use a simple student interface with only inking functions to support Active Learning. The support for anonymous artifact submission is important for encouraging shyer students to take part in classroom activities too.

After collecting student submissions, the instructor uses the *shared delivery* channel, usually a public display, for showing selected student-submitted artifacts. She may comment on the student answers, lead discussion on the open questions, and elicit further activities. Thus, the students not only receive feedback about their level of understanding, but are also encouraged to think more deeply about the lecture material. This channel is the dominant channel for class-wide presentation and is the focus of classroom discussions. The implementation of this channel increasingly employs digital projectors, which take the place of traditional overhead projectors or whiteboards, and accordingly student submissions need to have some electronic form to be displayed and discussed on the digital projectors.

7.2.2 Classroom Presenter: A System Supporting the Model

The PaperCP system is an extension of the Classroom Presenter system (Figure 58). Classroom Presenter employs wirelessly connected Tablet PCs for the two-way instructor-student communication. The instructor Tablet PC acts as a server, while the student Tablet PCs are clients. The individual delivery channel is implemented with IP multicast, through which all slides of a lecture can be efficiently delivered from the server to each student device at the beginning of the class. When the instructor reaches a slide with a prepared question, each student writes a response directly on their Tablet PC and digitally submits it via point-to-point connections to the instructor station. This is the anonymous submission channel. In addition, a public display

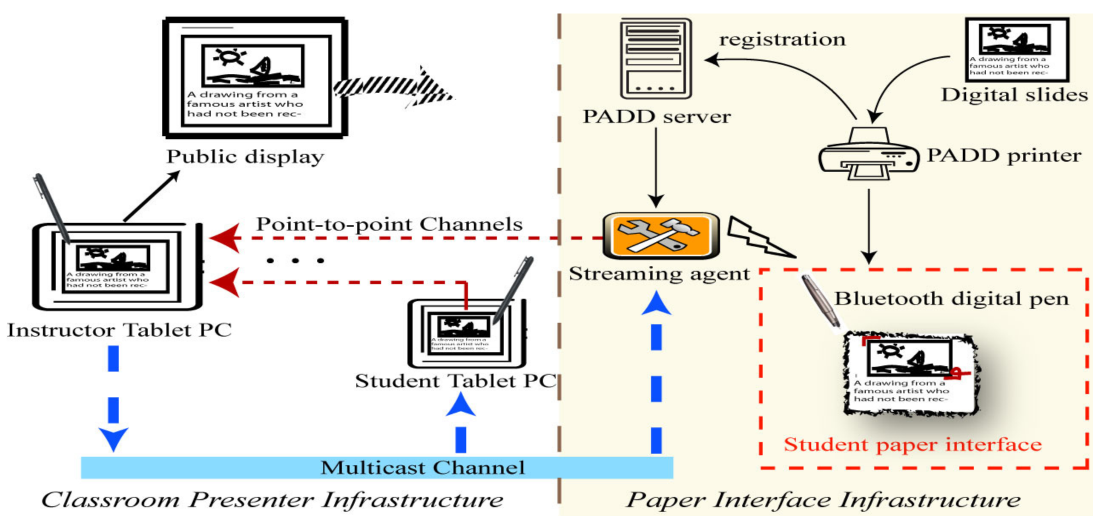


Figure 58. Architecture of PaperCP system: an integration of the Classroom Presenter Infrastructure (left area) and the Paper Interface Infrastructure (right area). The three communication channels are denoted by dashed arrowed lines. The system supports the concurrent use of the student Tablet PC interface and the paper interface.

connected to the instructor station is used as the shared delivery channel, which the instructor uses to display selected student submissions and offer her comments.

Classroom Presenter highlights the advantages of digital affordances:

- Efficiency: It makes instructor-student communication less distracting.
- Flexibility: Instructors can edit slides or student-submissions on-the-fly.
- Compatibility: It is compatible with existing practices using a data projector and digital slides.

However, there are drawbacks of the Tablet PC interface in terms of the interaction experience and the cost-benefit alignment:

- Tablet PCs are still relatively inferior to paper in terms of readability, writability, tangibility, and social acceptance.
- Computers can be distracting, as students may be tempted to use other unrelated applications (e.g., instant messaging or email) in class.
- Taking notes on a Tablet PC may be incompatible with some students' existing paper-based note taking styles.
- The cost of a Tablet PC may be too high for some students to own one.

In contrast to the Tablet PC interface, traditional physical printouts and transparencies are easy to read and write on, flexible in spatial layout, readily manipulated by hand, and relatively cheap. We explore how to integrate these advantages of physical interfaces into the highly efficient communication infrastructure of Classroom Presenter, in order to achieve a better balance between physical and digital affordances.

7.2.3 Designing a Paper-based Interface for Classroom Presenter

The following principles guided our design:

Paper affordances. Constraints on paper-based note-taking or annotating should be minimized since the paper affordances are the key to overcoming the limitations of the digital interface.

Efficient communication. The paper interface should support efficient student submissions, a key enabling aspect of Active Learning communication.

Compatibility. The paper-based interface should be deployable alongside a Tablet PC interface for flexibility in choosing and comparing interfaces.

Realistic deployment. The implementation should be suitable for real classroom deployment, so that realistic user experiences can be observed.

Based on these principles, we first examined the Active Learning communication media according to the characteristics of relevant interactions. For instructor interactions, the purely digital interface is believed to work best. First, the instructor needs an interface that allows her to review and selectively display digital student submissions that are dynamically created in class, which is impossible with a purely paper interface like PaperPoint [Signer, 2005]. Although an additional computer interface could be used for this task, frequent switching between paper and computer interfaces may be inconvenient and distracting to the instructor.

For student interactions, however, a paper-based interface is preferred because of its better trade-off between physical and digital affordances. First, paper possesses good interaction advantages as discussed above and a digital pen is much cheaper than a Tablet PC. Second, as used in PaperPoint [Signer, 2005], the new Bluetooth digital pens make it possible to capture and submit students' handwriting on paper in real time. Thus, a paper interface for digital submission is technically possible.

As a result, we devised an architecture that mixes paper and computer components (Figure 58). The instructor interface remains unchanged, but the student interface can be implemented either on paper (the part in the dashed box at the right side of Figure 58) or on a Tablet PC. Both implementations share the same underlying Classroom Presenter infrastructure. The paper interface consists of only Bluetooth digital pens and slides printed on Anoto paper (Figure 59). Using digital pens, students can annotate the handouts or take notes as if using a normal pen and paper, and, more importantly, they can issue commands to delete or submit specific notes on paper via the underlying electronic communication channels.

7.2.3.1 Student Note-taking and Submission

The use of digital pens and printed slides is fully compatible with existing pen-and-paper note-taking practices. Students' writing on the printout is automatically captured by the digital pen. However, due to the static nature of printed content, we need special mechanisms to implement student submission, equivalent to that of the Tablet PC interface.

In the simplest case, the instructor uses a dedicated slide to solicit a submission from students, and the written artifacts on the slide are expected to be submitted. In such a case, students can submit their writing by simply ticking (i.e., drawing a check mark as illustrated in Figure 59) the printed button labeled "submit" on the handouts. All digital notes captured from the slide are immediately sent to the

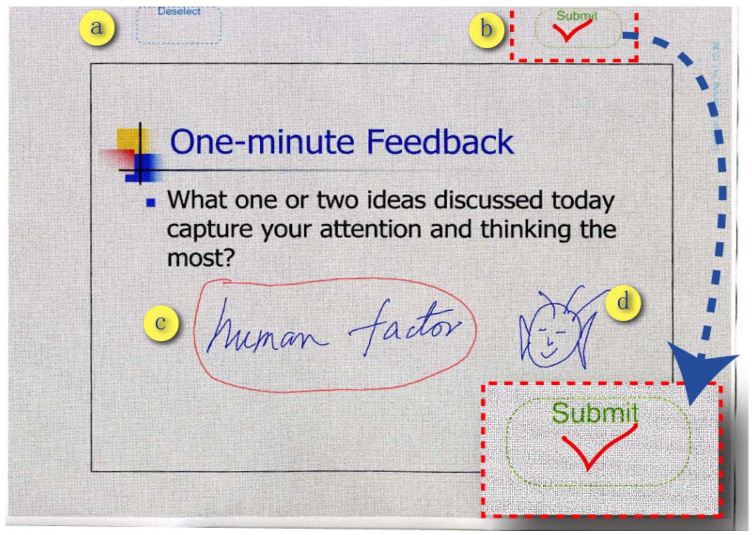


Figure 59. A paper interface. (a) printed button “deselect”. (b) printed button “submit”. The inset illustrates a button ticking mark. (c) lasso selection to submit. (d) personal doodling, not for submission. Further, the area within the frame is “public” and the rest is “private”.

instructor’s computer. Our experiments show that such button clicking is very robust and easy to use.

However, when personal notes and activity answers occur in the same slide, we need to distinguish the public notes, which the student is willing to show to the class, from the private ones, which are for the student’s private use (e.g. personal comments or doodles like (d) in Figure 59). Similar privacy issues are discussed in systems such as Stitching [Hinckley, et al., 2004], which supports varying cross-Tablet PC interaction patterns according to the collaboration levels of co-located users. PaperCP focuses on sharing notes with all class members via the public display, and thus presents as small a cognitive footprint as possible.

7.2.3.2 Advanced Features

While the Tablet PC interface provides dynamic visual feedback for distinguishing notes, e.g., by changing color of selected strokes, it is impossible for a paper-only interface to take the same approach. Instead, we examined three different methods for public-private note selection, namely spatial differentiation, pen-switching differentiation, and gesture differentiation. The adopted strategy was to combine spatial and gesture differentiation.

Spatial differentiation. The idea was borrowed from systems like SharedNotes [Greenberg, et al., 1999] in which a specific region within a slide is defined as a "public" area and the rest of the slide is a "private" area. In our case, only notes within the public area (the area within the frame, see Figure 59) may be shown on the public display. This design is intuitive and robust, but it prevents users from writing personal comments near pertinent information in the public area. Furthermore, users must determine a priori what to submit and what not to submit, which is not compatible with the typical user experience. Thus we turn to pen-based strategies.

Pen-switching differentiation. Another strategy is to use two pens: one for "public" notes and the other for "private" notes. Although this method can overcome the spatial constraint, our pilot test showed that this method also suffered from the a priori decision problem, and changing the type of a written stroke is often awkward. Furthermore, frequently switching pens turns out to be a non-trivial extra burden for users. So, we excluded this design.

Gesture differentiation. Here we take the ink/gesture approach like the original PapierCraft design (Chapter 4): *ink strokes* are used to add notes or annotations at any location, and *gestures strokes* to issue commands like selecting ink strokes for submission. This method provides good spatial flexibility and avoids the a priori decision problem.

For distinguishing between ink and gesture strokes, our interface takes an explicit mode-based approach. At the time of this project, we did not have the mode-switch button installed on the digital pens, we decided to use two pens, one for ink strokes and the other for gesture strokes. This two-pen configuration is far less problematic than that of the *pen-switching differentiation* due to the lower frequency of changing pens: users can first write free-form notes with the ink pen then select a subset of the content for submission with the gesture pen. Note that at this point the users can change their minds about any previously written strokes. Of course, the interaction can be refined with our latest feedback pen (Chapter 5), and the basic design with ink-gesture switching still stands.

For easiness-flexibility tradeoff, we opted to combine the *spatial* and *gesture differentiation* methods as follows. If there is no selection gesture in the "public" area, all strokes in public area are sent, otherwise only the selected strokes are submitted. To further reduce the burden of switching pens, we allow submission with either pen. Thus, if a student uses only the simple *spatial differentiation*, she can keep using the ink pen for both writing and ticking the submission button.

Deleting unwanted content is another important issue. In many cases, simply crossing out unwanted strokes may be enough, but sometimes students want to remove certain writing from the digital record for neatness or privacy. To this end, PaperCP supports two deleting gestures, a zigzag, which removes strokes crossed by the gesture, and a lasso with zigzag inside, which deletes strokes inside the lasso. Of course, without physical erasing, the digitally deleted strokes will still remain on the printout. For the sake of simplicity, we have not implemented "undo" for stroke deletion.

7.2.3.3 System Implementation

Figure 58 illustrates the system architecture, in which the Streaming Agent plays a vital role in bridging the gap between the paper interface and the digital infrastructure. The agent receives handwriting captured by the digital pen via a Bluetooth connection, and contacts the PADD server for physical-to-digital mapping information, which was registered when the printouts were generated (refer to [Guimbretiere, 2003] for details). With the mapping information, the agent translates the strokes from physical page coordinates into a digital counterpart and then processes the data in the digital domain. Much like a standard student CP client, the agent communicates with the instructor CP station to receive broadcast slides and submit student input over a point-to-point channel. Thus, the new system scales similarly as the original Classroom Presenter [Anderson, et al., 2004] system, which can usually handle a classroom of about 30 student tablets.

The streaming agent implements the exactly same communication protocols as the original student CP, so the paper-based interface is completely transparent to the rest of the CP infrastructure. One agent is needed for each paper interface user, and we use one PC near a user to run only one agent for simplicity. For larger classes and to minimize deployment costs, it is desirable to employ a Bluetooth infrastructure with multiple access points [Bluegiga] distributed in the classroom, so that all digital pens are within Bluetooth signal range and multiple agents can share computing resources on one host computer.

7.2.4 Exploratory User Study

To examine the feasibility of our new paper interface and to explore possible design issues, we conducted an exploratory user study using PaperCP alongside the original Tablet PC-based system. Specifically, we focused on the following aspects of the system:

- **Student-instructor communication**: whether or not PaperCP can effectively support student-instructor communication for Active Learning.
- **Interface integration**: whether or not the paper interface can be naturally and efficiently integrated into Active Learning with little disruption.
- **Gesture commands**: whether or not the gesture operations on the paper interface can achieve the designed functionality.

7.2.4.1 Experiment Setting

The general goal of the experiment was to get a real sense about how a paper-interface works. We ran the experiment in a real-life scenario, instead of a lab setting, for a more realistic evaluation. During our evaluation, we changed as little as possible the instructor's lecture material, teaching style, and schedule, and did not force students to do any special actions. Finally, experiment data logging was done in the background without interference with participants and strictly kept anonymous.

We deployed the system in an undergraduate Software Engineering class at the University of Washington. A 20-minute training session was first conducted to allow all students to try out the new paper interface and to answer questions. Students were asked to write their answers on handouts and submit them to the instructor, who then showed the submissions on a public display. Subsequently, we conducted four formal experimental sessions (each lasting 60 minutes) in regular classes on four days within a period of two weeks. During the sessions, the instructor used the Classroom Presenter infrastructure to present slides, collect student submission, and conduct in-class discussion as is usual for the course. The students, our participants, used either the Tablet PC interface or the paper counterpart for the Active Learning interactions.

To limit the variance introduced by different subjects and lecture topics in each class session, half of the students used the paper interface and the other half used the computer interface. Each student alternated between the two interfaces across sessions. At the end of each session, every student was asked to fill out a very brief questionnaire about the interface that he/she used during that session. After the final (fourth) session, they were asked to answer an overall comparison questionnaire.

For qualitative measurements, we used Likert-scale questionnaires about the users' perceived difficulty level of specific actions with an interface, such as note-taking, submission, and erasing. For quantitative measurements, we instrumented the two interfaces, and logged important events such as pen property changes, strokes, gestures, slide navigation, and submission.

7.2.4.2 Apparatus and Participants

During an experiment session, each participant was given a PaperCP interface or a Tablet PC running Classroom Presenter. In the current PaperCP implementation, we used a Tablet PC to run the Bluetooth data processing program for each participant, but it was placed several feet away from the participant, to minimize distraction. To reduce the user experience variance caused by the different size and layout of slides on the different interfaces, we intentionally printed one slide on one letter-sized sheet of paper, and made it roughly the size of its digital counterpart on a Tablet PC. For better navigation flexibility, we did not staple the handout pages.

All eight registered students for the class participated in the user study without pay. According to the background survey, two of the participants use laptops and another participant uses a Tablet PC to take notes occasionally. Seven participants frequently use normal pen and paper for notes. None of them had ever used a digital pen, but all of them had had experience with Classroom Presenter in previous courses.

7.2.4.3 Experiment Results and Discussion

We report the user experiences and lessons learned from the experiment with respect to our axes of evaluation: Student-instructor communication, Interface integration, and Gesture commands. Due to the small number of participants and high variability in the data, we focus here on qualitative rather than statistical analysis of the collected data.

Student-Instructor Communication

There were 11 class activities in total during the four experimental sessions, or about 3 per session. The 11 class activities covered a wide range of question types, including drawing diagrams, ranking items, brainstorming answers to open-ended questions, commenting source code, drawing curves, and so on. Figure 60 illustrates such a digital student submission from the paper interface, in which the instructor added the comments in green during the public discussion.

Generally, all 11 activities went smoothly without any show-stopping technical problems. The paper interface was well-received by the students. In terms of

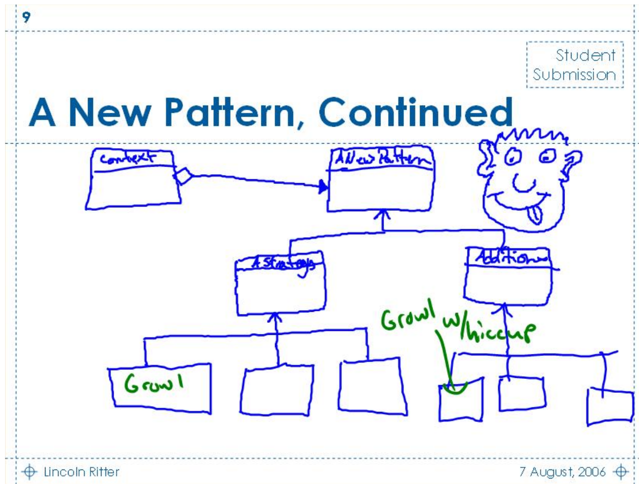


Figure 60. An example of a student submission from the paper interface. The green strokes are the instructor's comments

the workflow, both interfaces successfully sent student submissions in real time. The paper interface was used by students as actively as the Tablet PC interface. According to our log data, the instructor received 33 submissions from paper interfaces and 29 from Tablet PCs during the experiment, and all participants had submissions via both interfaces. This suggests a high level of robustness for the paper interface. As a result, both instructor and students were able to focus on the Active Learning process, and not be distracted by issues with the technology.

We also found that the unfamiliar paper interface may have caused usability problems. For example, participant P1 complained "the pen didn't send what you wrote exactly". The log shows P1 mistook the "deselect" button for "deleting", and his personal doodling had been submitted accidentally, which may have led to his negative impression. To avoid such issues, more user training and/or stronger real time feedback are needed for the new paper interface.

Note that the number of activities was limited by the available time, as each activity involved a series of actions including question announcement, student thinking, answer collection, submission comments and discussion. Plus, given the small class size, the instructor commented on almost every student submission to encourage student participation.

Interface Integration

Here we consider the interface integration in terms of interface compatibility, user interaction and workflow. First, the paper interface is confirmed to be compatible with the original Tablet PC interface, because in the experiment both interfaces worked concurrently without interference. This is important to supporting heterogeneous device deployment as well as varying user preferences and needs.

Second, students could easily integrate paper interaction with the learning activities. They spread out and browsed the handouts on their desks, wrote answers with pens and submitted results on their paper. Participant P2 preferred the paper interface because of the high degree of control over the handouts, noting "Sometimes, we can not control slides using Tablet PC". However, two other participants, P3 and P4 complained of "too much paper to flip through", indicating unexpected inconveniences of the new interface.

Looking further into the questionnaire comments and logs, we identify two main sources of this problem: 1) the one-slide-per-page layout forces students to flip paper for every slide. Given an average of about 30 slides per session, manual flipping was indeed distracting and required more user effort. 2) Unstapled paper slides require more effort for the students to keep things organized; the original intent was for flexible navigation and comparison. As a result, such negative effects counteract paper's advantages of quick browsing, convenient bi-manual manipulation and flexible spatial layout [Sellen and Harper, 2001]. Several students suggested using paper slides only for the submission slides, so that they could enjoy the writing experience of paper but avoid annoying paper flipping. Printing multiple slides per page is another way to reduce the interference.

Finally, for the workflow, it is revealed that PaperCP has a potential drawback in out-of-class logistics: because the printing takes time, the instructor usually has to finalize the slides the day before classes at the latest. This may prevent lecturers from doing “last-minute” work, a flexibility which some like. Moreover, once the slides are printed out, it becomes hard to change or even add slides. These workflow problems could be solved by an optimized printing facility for Anoto-enabled handouts.

Gesture Commands

Here, we examine the effectiveness of gesture commands for the selective submission and deletion functions. In general, students seldom used the lasso to select partial notes for submission on either the paper or Tablet PC interfaces. The two interfaces each had only one user of the lasso selection. This phenomenon can be attributed to the design of the presentation slides: the submission slides are usually dedicated to the activity, so almost all user writing on those slides were answers for class activities; thus few lasso gestures were required to distinguish public notes from private ones.

The deletion gesture also suffered from infrequent use. This could be attributed to the weak feedback of the paper interface, which the users were not used to. The inconvenience of pen-switching is another possible reason. This suggests the importance of stronger feedback and single-pen operations. We expect such issues could be addressed with our latest feedback pen (Chapter 5).

7.2.5 Future Work

Our preliminary experiment has effectively proven the feasibility of the paper interface and its compatibility with existing practices. It has also revealed challenges in the design of the paper interface. In response, we will investigate appropriate layouts of printed slides. Specifically, we will consider factors such as the number of sheets of paper, the space for pen input, and the content of slides, as well as students' note-taking styles. This will help us to better understand the previously revealed problems and to validate proposed solutions.

Moreover, as the experiment analysis suggests, real-time feedback is the key for complex interactions on paper. It is useful to enhance PaperCP with our new stand-alone feedback pen, which provides multimodal pen-top feedback mechanism compatible with existing pen-and-paper interaction (Chapter 5). Furthermore, considering users' high likelihood of working in a computer-rich environment, it will be interesting to combine the electronic and paper interfaces, e.g., providing digital visual feedback on a handheld device for paper interaction and incorporating multimedia data into student submissions. Similar methods are used in systems like Paper++ [Norrie and Signer, 2003] and PaperLink [Arai, et al., 1997], which employ a separate display or PDA to render dynamic content associated with specific regions in paper documents. Indeed, in our later application-level evaluation of PapierCraft, we have implemented such functions, like googling within paper and copy-paste from printouts to a PC (Chapter 6, Section 3). These latest techniques can be used to address many of the issues that we found in PaperCP deployment.

7.3 More Thoughts of Deployment in the Real World

The above evaluation focuses on the interaction aspects of the paper interface. It is also useful to examine the deployment aspects. We deployed PapierCraft at UCSD for researchers there to test its use in a real academic setting. The testing is informal, but still gives us insights about the use of paper interfaces in the real world.

Regarding software, the current system requires eight different programs for the server and client sides, including the third-party APIs for digital pen synchronization, PDF manipulation and handwriting recognition. According to our testing at UCSD and UMD, the first-time setup was not complex, and no special software maintenance was needed afterwards. (see https://wiki.cs.umd.edu/DeviceLab/index.php?title=PapierCraft for more details of PapierCraft installation and setup)

Concerning hardware, the primary issue was the two-round printing: Users first print infrared-opaque dot patterns, and then infrared-transparent document contents on top of the patterns. Lack of such a printer that can automatically and precisely perform the two-round printing, PapierCraft users have to do this manually. They print the patterns with a laser printer, followed by document content with an inkjet printer (see PADD [Guimbretiere, 2003] for more details). This manual two-round printing was shown inefficient and error-prone in real deployment.

First, this printing procedure is very susceptible to paper-jam, sticky paper (two sheets are attached to each other) and wrong starting page IDs set by the user.

These errors lead to the wrong registration of hard copies, totally ruining the physical-digital mapping. Second, the printing approach requires careful calibration to align the two printers' coordinate systems, which depends on the movable mechanical parts. We usually need to do one calibration for every ~100 pages. Neverthless we do not think these issues as the fundamental limitation of PapierCraft, because a printer that can print the patterns and document together will solves these problems at large.

The battery life is another concern. Currently, our Logitech IO2 Bluetooth digital pens can last about 2~3 hours for non-stop use in Active Reading. The pen-top feedback control module has a separate battery with 150mAH capacity, which can last at least 3 hours with normal use intensity of pen gestures in our experiments. Although this battery life length is just comparable to a normal laptop, PapierCraft is more robust by supporting *graceful degradation* [Yeh, et al., 2006]: Even if the battery runs out, users can still use the digital pen like a normal inking pen to annotate printouts. In contrast, a laptop out of battery is nothing but a bulk of metal and plastic. Although such good robustness comes from paper itself, not from the PapierCraft infrastructure, the point is that PapierCraft can *always* supports the *bottom line* use of normal pen and paper, which is not true in the case of computers.

Cost is also an important issue for real deployment. Currently, a Logitech Bluetooth digital pen costs about $200, and the pen-top feedback control board about $50. The cost for the blank Anoto pattern notes is about 5 cents per page, and could be lower in the future with massive production.

Some people are worried about the environmental impact of PapierCraft, because it might stimulate consumption of more paper, and eventually more trees. In fact, we believe that it could *reduce* the tree consumption: PapierCraft treats paper as a transient media, from which it captures and archives user input in digital form. Therefore the PapierCraft paper can be recycled sooner than normal one. This quick recycling might limit the impact on trees, and on the whole environment in long term [McDonough and Braungart, 2002].

Chapter 8: Conclusion

In this dissertation, we explored a paper-based interface – PapierCraft - to improve interaction with digital documents. By prototyping and evaluating PapierCraft, we have demonstrated the feasibility, usability, and the potential applications of this novel interface. From this research, we obtained valuable lessons and experiences that have helped us better understand the pros and cons of paper and computers, and that have helped shape the future active reading devices. In particular, we made 4 specific contributions: *the PapierCraft command system*, *the multimodal pen-top feedback*, *the uniform infrastructure for mixed-media interaction,* and *the systematic evaluation* of a paper interface.

8.1 Contributions

8.1.1 PapierCraft Pen-gesture Command System

The core technique of PapierCraft is the command system for paper-based interactions, of which the challenge is the inherent static nature of paper. To address this issue, we have designed a set of self-explaining pen gestures, which use as feedback the ink of the gestures and do not rely on any electronic screens or projectors. Our preliminary testing suggests that the ink-only feedback can be enough for some relatively simple interactions such as copy/paste and hyperlinking [Liao, et al., 2008] .

8.1.2 Multimodal Pen-top Feedback

The multimodal pen-top feedback is one step towards conquering the paper passiveness for more interactive paper-based tasks. To study its general characteristics and design principles, we have built a multimodal feedback pen, which provides visual, tactile, and auditory feedback in the form of a digital pen. Using the feedback pen as an experiment platform, we conducted a user study, which has successfully showed the effectiveness of the pen-top feedback in helping novice users learn the PapierCraft interface, reducing experienced users' error rate, and encouraging error corrections.

8.1.3 The evaluation and applications of PapierCraft

The main hypothesis of this dissertation is that PapierCraft can help bridge the paper-computer gap by providing both digital functions and a full range of paper affordances. To test this hypothesis and evaluate PapierCraft at an application level (in contrast to the evaluations that focused on specific design factors), we conducted an end-to-end experiment. We compared normal pen-paper, PapierCraft, and a Tablet PC interface in a simulated setting of active reading. The results support our hypothesis in that users appreciate the combined merits of PapierCraft in comparison to the other two conditions. We also built and evaluated two paper-interface applications in the areas of field biology and e-learning. These applications have not only confirmed the feasibility and usability of the interface, but have also revealed practical issues with regard to printing and robustness.

8.1.4 Infrastructure Unifying Paper-Computer Interaction

Finally, to support the command system and the feedback pen, we designed and implemented a distributed infrastructure accommodating mobile users and heterogeneous working media. We extended the existing digital-only infrastructure to the physical domain for cross-device and cross-media operations, therefore providing a supporting platform for bridging paper and computers.

8.2 Future Work

Going beyond this dissertation, we envision a Ubiquitous Document Environment (UDE), in which users can access digital documents at any time, anywhere, via any media. This is similar to the concept of Ubiquitous Computing coined by Weiser [Weiser, 1993], but has a different emphasis on the diversity of media. UDE users may adopt any medium for their tasks, including physical (e.g. paper, walls, tables), digital (e.g. desktop screens, cell phones, tablet PCs, large displays, projectors), or mixed media. These media, although varying in specific affordances, interact with each other through an underlying infrastructure and offer a seamless and consistent user interface.

A scenario of UDE could be as follows. Researcher Alice, when taking the metro to her office, notices a public large screen showing a piece of interesting news about recent progress in decoding human genes. She then uses her camera cell phone to take several snapshots of the screen, with which UDE automatically starts a search for related information. When arriving at her office, Alice finds the relevant articles and multimedia materials ready on her desktop computer, and the most relevant articles have been printed for easy reading. Alice then begins to read, flip through, and annotate the article. At the same time, the infrastructure detects Alice's on-going interaction with the documents and proactively serves her potentially useful information. For example, the infrastructure can generate "see also" links and project them onto the paper, which dynamically changes based on Alice's current document content and personal reading history. She can easily browse the related information and excerpt important text into her "ubi-notebook". Two hours later, she stops the reading session and leaves for a business trip to New York. On the airplane, she simply opens the unfinished session on her laptop PC, and the previous context, including the annotations, and the related links and ubi-notebooks, are recovered and re-organized to be best adapted to the tablet PC screen.

Obviously our work in this dissertation is just a preliminary step toward this vision. Along the path leading to the ideal UDE, possible future research directions include better visual feedback mechanisms, generalized paper-based interfaces, multiple display interfaces, unifying infrastructures, and so on.

First, we would like to explore high fidelity visual feedback for PapierCraft, as the current LED-based approach can hardly present rich information, which is however, the key to most document interfaces (except those for the visually impaired). One approach is to install a mini-projector [LightBlueOptics, 2005] on the feedback pen and project information directly on paper. Another is to use a nearby mobile device such as a PDA or a cell phone. Although such hardware settings have been adopted by existing systems like Paper++ [Norrie and Signer, 2003] and most recently PenLight [Song, et al., 2006], several research problems still remain unsolved, including how to compensate the projector-pen's movement and hand occlusion for a stable projection and natural interaction, how to reduce the distraction of eye focus switching between a pen and a PDA, and, when multiple visual feedback channels are available (e.g. the LEDs, projectors, and cell phones are all used), how to decide which device to render what information for optimal user experiences. To answer these questions, we need to look further into the devices' affordances, characterize their roles in pen-paper interactions, and conduct iterative designs along this line of thinking.

The second important topic is to generalize the PapierCraft interface, avoiding being tied to the Anoto pen and the dot-pattern paper, for the reason that they may be not be available or allowed (depending on the circumstances), especially on some legacy documents. Therefore, it would be very interesting and valuable to study other techniques for real-time document identification and pen tracking that do not rely on any special markers or patterns within paper documents *and* still retain the original pen-paper flexibility. Some candidates include Scale-Invariant Feature Transform (SIFT) [Lowe, 2004], Brick Wall Coding (BWC) [Erol, et al., 2008], and Locally Likely Arrangement Hashing (LLAK) [Nakai, et al., 2005]. These algorithms enable document recognition from a partial image of the document without any special markers. To fit these algorithms to the generalized pen-paper interaction, it would be important to address the following research questions: How much portion of a document should be pictured to be recognized? How do the image distortion and lighting conditions affect the recognition rate? Where should the camera(s) be installed on the pen (which is related to the camera view angle and hand occlusion)? How does the size of the indexed document database affect the recognition rate? And what feedback information can and should be presented without disturbing users' on-going task if the recognition confidence is not high enough?

The general document recognition and tracking mechanisms could be applied to other camera-based devices other than pens. For example, a camera cell phone may be used as an optical mouse to point to a word or to act as a "magic lens" [Hecht, et al., 2007] to browse a map on paper or on a large display. This phone-paper/screen interaction can be used to manipulate the corresponding digital document. This basic idea is not new [Hecht, et al., 2007, Rohs, 2004], however most of existing systems require visual barcodes for recognition, which are not only visually obtrusive but also occupy document space. The above markerless recognition algorithms can address these problems at large. Along these lines, we may explore more research problems such as how to improve the target-acquisition performance by addressing inadvertent hand movement and the delayed and low-quality phone-captured image, and how to improve the user experience with the phone's parallax and occlusion issues.

Besides the above possible future work in the physical interface domain, we are also interested in the purly digital interface domain. This field has been advanced with new display techniques such as the reflective bi-stable display E-ink [E-Ink], which only consumes power on refreshing and makes practical multiple-display e-Book readers. The recent dual-display reader [Chen, et al., 2008] is one effort in this direction. In the future, we may further study how multiple display settings can affect user experience in reading. For example, how many tablet-size displays are optimal for an active reading task? When multiple displays are available, how is the information optimally distributed among them to take advantage of each? How do the different affordances or form factors for various displays affect user interactions with them?

From a broader view, the multiple displays, including, paper, projectors, cell phones, and screens, are all components of Ubiquitous Document Environment. They need to be connected to provide users with a unified and consistent experience of document manipulation. Toward this goal, the fluidity of the cross-device interaction is the core issue. The related usability issues lie in all levels of UDE: for instance, at the infrastructure level, it needs to be determined how to securely and reliably connect/disconnect devices without complicated and frustrating setup and authentication. And at the application level, it needs to be determined how to easily migrate on-going applications and documents across devices without worry about the different naming mechanisms, access controls, and formats. Although there has been active research in these fields [Carzaniga, et al., 2001, Hinckley, et al., 2004, Johanson, et al., 2002], further work is definitely needed to answer the questions.

To summarize, we are envisioning a Ubiquitous Document Environment. The paper-based interface PapiercCraft, the main topic of this dissertation, is just a step toward this goal. In the future, we will expand our research to include visual feedback mechanisms, general document recognition/tracking methods, interactions with multiple displays and devices, as well as an exploration of the underlying infrastructure for UDE.

Appendix 1: Pen-top Feedback Study Questionnaire

Background / User ID ___

1. In which age group are you in?
1) 15 ~ 20
1) 20 ~ 30
2) 30 ~ 40
3) above 40

2. Your gender ?
1) Male
2) Female
3) N/A

3. What is your education level ?
1) High school
2) College
3) Graduate
4) Doctor
5) Others (please write) ___________

4. How many years have you used computers? ____________ years

5. How many hours do you use a computer per day on average ? ___________ hours

6. How many years have you used a pen-computer? ___________ years

7. How many years have you used a digital pen ? _____________years

Task Load Index Worksheet / User ID ___ Condition : Dummy Pen (D)

Please answer the following questions based on the technique you used on a scale of 1 (low) – 7 (high).

1. Mental Demand — How much thinking was required to use the device?

1 2 3 4 5 6 7

2. Physical Demand—How much physical effort or coordination was required to use the device?

1 2 3 4 5 6 7

3. Temporal Demand — How much time pressure did you feel under while performing the task?

1 2 3 4 5 6 7

4. Performance — How well do you think you performed the task? For example, do you think you were able to select the required menu item quickly?

1 2 3 4 5 6 7

5. Effort — To accomplish your level of performance how hard did you have to work (both mentally and physically)?

1 2 3 4 5 6 7

6. Frustration level — How discouraged, irritated, stressed or annoyed did you feel while completing the task?

1 2 3 4 5 6 7

Task Load Index Worksheet / User ID ___ Condition : Tablet PC (D)

Please answer the following questions based on the technique you used on a scale of 1 (low) – 7 (high).

1. Mental Demand — How much thinking was required to use the device?

1 2 3 4 5 6 7

2. Physical Demand—How much physical effort or coordination was required to use the device?

1 2 3 4 5 6 7

3. Temporal Demand — How much time pressure did you feel under while performing the task?

1 2 3 4 5 6 7

4. Performance — How well do you think you performed the task? For example, do you think you were able to select the required menu item quickly?

1 2 3 4 5 6 7

5. Effort — To accomplish your level of performance how hard did you have to work (both mentally and physically)?

1 2 3 4 5 6 7

6. Frustration level — How discouraged, irritated, stressed or annoyed did you feel while completing the task?

1 2 3 4 5 6 7

Task Load Index Worksheet / User ID ___ Condition : Feedback Pen (D)

Please answer the following questions based on the technique you used on a scale of 1 (low) – 7 (high).

1. Mental Demand — How much thinking was required to use the device?

1 2 3 4 5 6 7

2. Physical Demand—How much physical effort or coordination was required to use the device?

1 2 3 4 5 6 7

3. Temporal Demand — How much time pressure did you feel under while performing the task?

1 2 3 4 5 6 7

4. Performance — How well do you think you performed the task? For example, do you think you were able to select the required menu item quickly?

1 2 3 4 5 6 7

5. Effort — To accomplish your level of performance how hard did you have to work (both mentally and physically)?

1 2 3 4 5 6 7

6. Frustration level — How discouraged, irritated, stressed or annoyed did you feel while completing the task?

1 2 3 4 5 6 7

Task Load Index Worksheet / User ID ___ Condition : Dummy Pen (G)

Please answer the following questions based on the technique you used on a scale of 1 (low) – 7 (high).

1. Mental Demand — How much thinking was required to use the device?

1 2 3 4 5 6 7

2. Physical Demand—How much physical effort or coordination was required to use the device?

1 2 3 4 5 6 7

3. Temporal Demand — How much time pressure did you feel under while performing the task?

1 2 3 4 5 6 7

4. Performance — How well do you think you performed the task? For example, do you think you were able to select the required menu item quickly?

1 2 3 4 5 6 7

5. Effort — To accomplish your level of performance how hard did you have to work (both mentally and physically)?

1 2 3 4 5 6 7

6. Frustration level — How discouraged, irritated, stressed or annoyed did you feel while completing the task?

1 2 3 4 5 6 7

Task Load Index Worksheet / User ID ___ Condition : Tablet PC (G)

Please answer the following questions based on the technique you used on a scale of 1 (low) – 7 (high).

1. Mental Demand — How much thinking was required to use the device?

1 2 3 4 5 6 7

2. Physical Demand—How much physical effort or coordination was required to use the device?

1 2 3 4 5 6 7

3. Temporal Demand — How much time pressure did you feel under while performing the task?

1 2 3 4 5 6 7

4. Performance — How well do you think you performed the task? For example, do you think you were able to select the required menu item quickly?

1 2 3 4 5 6 7

5. Effort — To accomplish your level of performance how hard did you have to work (both mentally and physically)?

1 2 3 4 5 6 7

6. Frustration level — How discouraged, irritated, stressed or annoyed did you feel while completing the task?

1 2 3 4 5 6 7

Task Load Index Worksheet / User ID ___ Condition : Feedback Pen (G)

Please answer the following questions based on the technique you used on a scale of 1 (low) – 7 (high).

1. Mental Demand — How much thinking was required to use the device?

1 2 3 4 5 6 7

2. Physical Demand—How much physical effort or coordination was required to use the device?

1 2 3 4 5 6 7

3. Temporal Demand — How much time pressure did you feel under while performing the task?

1 2 3 4 5 6 7

4. Performance — How well do you think you performed the task? For example, do you think you were able to select the required menu item quickly?

1 2 3 4 5 6 7

5. Effort — To accomplish your level of performance how hard did you have to work (both mentally and physically)?

1 2 3 4 5 6 7

6. Frustration level — How discouraged, irritated, stressed or annoyed did you feel while completing the task?

1 2 3 4 5 6 7

Overall Evaluation User ID ___

Please answer the following questions based on the techniques you used on a scale of 1 (low) – 7 (high).

1. Generally speaking, do you think the pen-top feedback helps you reduce errors?

1 2 3 4 5 6 7

2. Generally speaking, do you think the pen-top feedback helps you get more confidence about your options?

1 2 3 4 5 6 7

3. Generally speaking, do you think the pen-top feedback helps increase the task completion speed (the time to SUCCESSFULLY finish a task)?

1 2 3 4 5 6 7

4. To what extent do you think the shining color during drawing is helpful to your operations?

(as beginner) 1 2 3 4 5 6 7

(as expert) 1 2 3 4 5 6 7

5. To what extent do you think the fading color for confirmation is helpful to your operations?

(as beginner) 1 2 3 4 5 6 7

(as expert) 1 2 3 4 5 6 7

6. To what extent do you think the voice is helpful to your operations?

(as beginner) 1 2 3 4 5 6 7

(as expert) 1 2 3 4 5 6 7

7. To what extent do you think the vibration for ambiguity warning is helpful to your operations?

(as beginner) 1 2 3 4 5 6 7

(as expert) 1 2 3 4 5 6 7

8. To what extent do you think the sound for border crossing is helpful to your operations?

(as beginner) 1 2 3 4 5 6 7

(as expert) 1 2 3 4 5 6 7

9. Open question : in your opinion, what's the best aspect about the feedback pen, compared to the Tablet PC and the dummy Pen?

10. Open question : in your opinion, what's the worse aspect about the feedback pen, compared to the Tablet PC and the dummy Pen?

11. Do you have any suggestions or comments to help us improve the design?

Thank you !

Appendix 2: Gesture Command Study Questionnaire

Background / User ID ___

1. In which age group are you in?
1) 15 ~ 20
1) 21 ~ 30
2) 31 ~ 40
3) above 40

2. Your gender ?
1) Male
2) Female
3) N/A

3. What is your education level ?
1) High school
2) College
3) Graduate
4) Doctor
5) Others (please write) ___________

4. How many years have you used computers? ____________ years

5. How many hours do you use a computer per day on average? ___________ hours

6. How many hours do you use paper for reading/writing per day on average? ____ hours

7. How many years have you used a stylus on a Tablet or a PDA ? ___________ years

8. How many years have you used a digital pen? _____________years

Task Load Index Worksheet / User ID ___ Condition : Digital Pen

Please answer the following questions based on the technique you used on a scale of 1 (low) – 7 (high).

1. Mental Demand — How much thinking was required to use the device?

(beginning) 1 2 3 4 5 6 7

(end) 1 2 3 4 5 6 7

2. Physical Demand—How much physical effort or coordination was required to use the device?

(beginning) 1 2 3 4 5 6 7

(end) 1 2 3 4 5 6 7

3. Temporal Demand — How much time pressure did you have while performing the task?

(beginning) 1 2 3 4 5 6 7

(end) 1 2 3 4 5 6 7

4. Performance — How well do you think you performed the task? For example, do you think you were able to select the required document segments and menu items quickly?

(beginning) 1 2 3 4 5 6 7

(end) 1 2 3 4 5 6 7

5. Effort — To accomplish your level of performance how hard did you have to work (both mentally and physically)?

(beginning) 1 2 3 4 5 6 7

(end) 1 2 3 4 5 6 7

6. Frustration level — How discouraged, irritated, stressed or annoyed did you think while completing the task?

(beginning)	1	2	3	4	5	6	7
(end)	1	2	3	4	5	6	7

Task Load Index Worksheet / User ID ___ Condition : Tablet PC

Please answer the following questions based on the technique you used on a scale of 1 (low) – 7 (high).

1. Mental Demand — How much thinking was required to use the device?

(beginning) 1 2 3 4 5 6 7

(end) 1 2 3 4 5 6 7

2. Physical Demand—How much physical effort or coordination was required to use the device?

(beginning) 1 2 3 4 5 6 7

(end) 1 2 3 4 5 6 7

3. Temporal Demand — How much time pressure did you think under while performing the task?

(beginning) 1 2 3 4 5 6 7

(end) 1 2 3 4 5 6 7

4. Performance — How well do you think you performed the task? For example, do you think you were able to select the required document segments and menu items quickly?

(beginning) 1 2 3 4 5 6 7

(end) 1 2 3 4 5 6 7

5. Effort — To accomplish your level of performance how hard did you have to work (both mentally and physically)?

(beginning) 1 2 3 4 5 6 7

(end) 1 2 3 4 5 6 7

6. Frustration level — How discouraged, irritated, stressed or annoyed did you think while completing the task?

(beginning)	1	2	3	4	5	6	7
(end)	1	2	3	4	5	6	7

Overall Evaluation   User ID ___

Please answer the following questions based on the techniques you used on a scale of 1– 7.

1. Do you think the scope selectors are easy to **understand**? (1 for "Very Difficult" and 7 for "Very Easy")

(Underline)	1	2	3	4	5	6	7
(Lasso)	1	2	3	4	5	6	7
(Margin bar)	1	2	3	4	5	6	7
(Cropping marking)	1	2	3	4	5	6	7

Feel free to elaborate here: ____

2. Do you think the pigtail command selector is easy to **understand**? (1 for "Very Difficult" and 7 for "Very Easy")

1 2 3 4 5 6 7

Feel free to elaborate here: ____

3. Do you think the scope selectors are easy to **memorize**? (1 for "Very Difficult" and 7 for "Very Easy")

(Underline)	1	2	3	4	5	6	7
(Lasso)	1	2	3	4	5	6	7
(Margin bar)	1	2	3	4	5	6	7
(Cropping marking)	1	2	3	4	5	6	7

Feel free to elaborate here: ____

4. Do you think the pigtail command selector is easy to **memorize**? (1 for "Very Difficult" and 7 for "Very Easy")

1 2 3 4 5 6 7

Feel free to elaborate here: ____

5. What do you think of the **success rate** of using the scope selectors to select the requested document segments and keywords? (1 for "Very Low", 7 for "Very High")

(Underline on Paper)	1	2	3	4	5	6	7
(Underline on PC)	1	2	3	4	5	6	7
(Lasso on Paper)	1	2	3	4	5	6	7
(Lasso on PC)	1	2	3	4	5	6	7
(Margin bar on Paper)	1	2	3	4	5	6	7
(Margin bar on PC)	1	2	3	4	5	6	7
(Cropping marking on Paper)	1	2	3	4	5	6	7
(Cropping marking on PC)	1	2	3	4	5	6	7

Feel free to elaborate here: ____

6. What do you think of the **success rate** of using the pigtail to select the requested commands? (1 for "Very Low", 7 for "Very High")

(On Paper)	1	2	3	4	5	6	7
(On Computer)	1	2	3	4	5	6	7

Feel free to elaborate here: ____

7. What do you think of the **easiness rate of reading** the target document segments? (1 for "Very Uncomfortable", 7 for "Very Comfortable")

(On Paper)	1	2	3	4	5	6	7
(On Computer)	1	2	3	4	5	6	7

Feel free to elaborate here: ____

8. What do you think of the **easiness rate of writing** the gestures? (1 for "Very Uncomfortable", 7 for "Very Comfortable")

(On Paper)	1	2	3	4	5	6	7
(On Computer)	1	2	3	4	5	6	7

Feel free to elaborate here: ______________________________

9. What do you think of the **gesture-drawing speed**? (1 for "Very Slow", 7 for "Very Fast")

(On Paper)	1	2	3	4	5	6	7
(On Computer)	1	2	3	4	5	6	7

Feel free to elaborate here: ______________________________

10. Generally speaking, do you think the pen-top feedback **useful** in doing the tasks? (1 for "Very Useless", 7 for "Very Useful")

1 2 3 4 5 6 7

Feel free to elaborate here: ______________________________

11. Specifically, do you think each of the pen-top feedback mechanisms **useful**? (1 for "Very Useless", 7 for "Very Useful")

(Voice for scope selection)	1	2	3	4	5	6	7
(Voice for menu navigation)	1	2	3	4	5	6	7
(LED for mode-switch)	1	2	3	4	5	6	7
(LED for confirmation)	1	2	3	4	5	6	7
(LED for menu navigation)	1	2	3	4	5	6	7
(Vibration for warning)	1	2	3	4	5	6	7

Feel free to elaborate here: ______________________________

12. Open question : in your opinion, what are the **Best and/or Worst** aspects about the pen gestures?

13. Open question : in your opinion, what are the **Best and/or Worst** aspects about the paper interface, compared to the Tablet PC?

14. Do you have any suggestions or comments to help us improve the design?

thank you !

Appendix 3: Active Reading Study Articles & Problem Sets

Testing Article 1: Montana Dam

Montana Dam Is Breached, Slowly, to Restore a Superfund Site

Milltown Dam, a symbol of industrial progress that became a symbol of destruction, was recently breached, and two parts of the Clark Fork River were joined again. There was no dynamite, no wrecking balls, no "blow and go" removal. Instead, an earthen dam blocking a specially built channel was removed to allow a small trickle of water to flow

Figure 1. The 100-year-old dam is to be removed, and parts of the Clark Fork River will be re-joined.

through and gradually grow larger. The main part of the dam will be demolished over two years. When the project is complete, it will cost $120 million.

Taking out the 1908 structure is the thorniest part of one of the largest toxic waste cleanups in the country, in what is known as the Clark Fork Basin Superfund Complex. The slow-motion breach at the end of March was intended to minimize the effects of releasing of sediment contaminated with heavy metals captured behind the dam. "The slower it goes, the better," said Sandy Olsen, head of the remediation division in the Montana Department of Environmental Quality. "It's not as dramatic. But there are fewer and less intense impacts on the fish."

(Dam Site: http://www.co.missoula.mt.us/wq/Milltown_Dam/Milltown%20Dam.htm)

Last fall, the reservoir was lowered and workers removed 700,000 cubic yards of sediment behind the dam. An additional 1.5 million cubic yards of contaminated sediment is still to be removed. "We had to do it slowly because we had to control the scour," said Matt Fein, who oversaw the project for Envirocon, an environmental remediation business in Missoula. A high volume of rushing water would have scoured the remaining tons of toxic debris and other sediment off the river bottom and sent it downstream to choke the river and kill fish. The river, the largest in Montana, flows through Missoula, a few miles downstream, and eventually into Idaho. It is a prized trout fishery.

To allow the slow removal, water was diverted to a new course. As the redirected flow churned up uncontaminated sediment, it was blended with clean water flowing over the dam. An estimated 300,000 tons of sediment will move downriver in the next few months, much of it in the spring runoff. Three million tons of uncontaminated sediment

Figure 2. Geographic location of the Milltown Dam. The Clark Fork River flows across counties, Missooula, Powell, Granite and Silver Bow.

will flush downriver in coming years. In the next two years, contractors will dismantle the rest of the 28-foot-high dam near the confluence of the Blackfoot River and the Clark Fork.

(web cam: http://www.clarkfork.org/programs/milltown.htmlhttp://www.clarkfork.org/programs/milltown.html)

The river is being monitored to gauge how the breaching affects fish. Eventually, the river should be cleaner, which should help the fish, including the threatened bull trout. “There are about 500 fish per mile,” said David Schmetterling, a biologist with the Montana Department of Fish, Wildlife and Parks. “Once the river is restored, we could see twice as many fish.” In March, one of 15 trout fitted with transmitters in their stomachs swam through the site of the old dam and upriver 10 miles, one of the first fish to make the run from below the dam in a century.

Since the 1860s, when mining began, mineral- and arsenic-laden waste — arsenic was used to separate metal from rock — from the Butte mines 120 miles south, atop the Continental Divide, has flowed into the headwaters of the Clark Fork. Flooding, especially a ferocious incident months after the dam was completed in 1908, sent tons of arsenic, copper and other heavy metals into the river. The last stop for most of the waste, though, was at this dam. Six million cubic yards of mine waste gathered behind it and backed up on the flood plain. In 1981, officials discovered that water backed up behind the dam had forced the arsenic into nearby groundwater and contaminated wells in the settlement of Milltown, home to several dozen residents. The area was listed as a federal Superfund site in 1983.

Although the sediment has very low levels of arsenic, the arsenic has leached into the groundwater over decades. Since last October, workers have been loading waste on a 45-car train, hauling it 90 miles up river each day to a small town called Opportunity and dumping it into an existing waste site. The additional 1.5 million cubic yards will be removed through 2009. The other waste has been stabilized and will be left in place. All told, enough sediment — a fine-grained clay — will be removed to fill 679 Olympic-size swimming pools. After the dam is removed, more tailings along the river upstream will be reclaimed.

(Resident Opinions: http://www.missoulian.com/specials/milltown/history.html)

In some places, the ground is turquoise from high levels of copper from the mines. “It might take 12 or 15 more years to finish the Clark Fork,” said John Wardell, regional director of the Environmental Protection Administration. The water in the reservoir dropped 14 feet when the dam was breached. As the water flows again, officials estimate it will take 4 to 10 years for the wells to be flushed clean.

Officials planned the release before spring runoff, when flows were low. Biologists from the Montana Department of Fish, Wildlife and Parks have placed trout in cages above and below the dam to see whether copper and arsenic concentrations would become lethal. So far, the fish have survived.
Many residents doubted that an effort would be made to cleanse the area. ARCO, the oil company that is now BP-ARCO, bought the Anaconda Copper Mining Company in 1977 and inherited the clean-up bill. Metal produced from the mine was negligible, and ARCO closed it in 1983. Officials contended that the mine waste was better left in place. But in February 1996, a 14-foot-thick ice jam careered down river, leading to fears that it would take out part of the dam and unleash layers of waste. The Montana Power Company, which owned the dam then, hastily drew down the water. The ice, no longer floating, was stranded just above the dam. But the sudden release of water scoured a four-foot-thick layer of heavy metals off the river bottom and sent it over the dam and downstream. A result, officials said, was a huge fish kill. The next spring, biologists counted the number of catchable rainbow trout and found that the fish had decreased nearly two-thirds.

(EPA: http://www.epa.gov/region8/about/lab/index.html)

ARCO has spent nearly $1 billion cleaning up all the Anaconda properties. As big as the Superfund cleanup here is, residents hope it is the beginning of a trend. “There’s 150,000 abandoned mine sites and tens of thousands of miles of logging road in Montana,” said former Representative Pat Williams, who works at the Center for the Rocky Mountain West, a research organization. “This project can be the epitome of a new restoration economy in this state.”

Figure 3. The breaching Milltown Dam and surrounding terrain.

Part 1. Summarization

4. Skim the article, annotate or take notes just as you usually do. Especially, you may underline **topic sentences** and circle **keywords**.

5. Write a **thesis statement** (1~2 sentences) for the main idea of this article.

[write here]

6. Write and *__speak__* *short* and *simple* **summary sentences** (**1** for each original paragraph), using your topic sentences, annotations and notes. Keep the summary in the **same logic order** as the original article.

[write here]

Part 2. Study of more details

1. Web search of keywords

Find the **highlighted** words in the following pages, draw a **star mark** in the margin of the word's line, **underline** the words, **google** it, and then copy one sentence explanation from **wikipedia**.

1.1 [paste here]

1.2 [paste here]

1.3 [paste here]

----

2. Web page information acquisition

Open the following **web pages** in the following pages, from each of which, copy one picture, whatever you choose, into this document.

2.1 [paste here]

2.2 [paste here]

2.3 [paste here]

----

3. Answer the following questions with **text, figures or sketches**, whatever you feel most effective and efficient

3.1 In Figure 1, find the following objects: **mountain**, **river**, and the **dam**, and roughly describe their relative positions in the picture.

3.2 In Figure 2, find these county names around the Clark Fork river: (1) **Granite** (2) **Powell** (3) **Missoula** (4) **Silver Bow**, number them and briefly describe their locations relative to the map.

3.3 Compare figure 1 and 3, find **Three** objects (e.g constructions, scenes) appearing in both figures, number them, and then briefly describe their locations in the pictures.

----

7. Some details of an related article

Answer the questions below by searching for keywords in the following article to locate the relevant sentences (up to 2 minutes for each)

4.1 What is Sandpoint?

4.2 What is Stimson Lumber?

4.3 Who is the owner of the Redneck Auto garage?

Former Company Town Faces Uncertain Future

BONNER, Mont. — For the past century, residents here have known two constants. They worked at the local lumber mill, where a seemingly endless supply of timber from the mountains kept saws whirring. And they played at the Milltown Reservoir, fishing and swimming behind a dam that was built at the confluence of the Clark Fork and Blackfoot Rivers to supply electricity to the mill.

Now the mill has closed, the dam is being torn down and a multimillionaire developer from Missoula, Mont., Scott Cooney, is buying up Bonner, one of the nation's last company towns. The changes — social, economic and environmental — are turning "everyone's world upside down," said Amanda Henderson, 25, whose husband, Mike, was laid off from the mill. "Some changes can be for the better," Ms. Henderson said. "But with the mill gone, there isn't a whole lot out here."

Mr. Cooney said he planned to transform this unincorporated working-class community of several hundred residents into a modern "Mayberry R.F.D.," with new and renovated homes, upscale shops and "green" manufacturers along the Blackfoot River, which Norman Maclean made famous in his fly-fishing novel "A River Runs Through It." "I'd like to take the cyclical nature of the wood-products industry out of here and give people consistent economic engines for the next 100 years," Mr. Cooney said.

He has been working with residents to retain some of Bonner's timber heritage, including reusing hand-hewn timbers from the dam for homes and other new buildings. He also says he wants Bonner to remain affordable, with new homes ranging from $80,000 to $250,000 and current residents given the first chance to buy the renovated mill homes.

Still, many residents worry that Mr. Cooney is trying to create a wealthy playground like Coeur d'Alene or Sandpoint in Idaho. He has raised monthly rents on the older mill homes to $650, from $450, despite peeling paint, cheap sawdust insulation and moss that blankets some roofs. Winter heating bills run as high as $400 a month, forcing some residents to cover drafty windows with bubble wrap.

Gary Caluori is a single father who worked at the mill for 15 years, has lived in several company homes and would like to buy one, but he said he was struggling just to pay the rent. "People don't like Cooney jacking up the rent, and they worry about what he might do here," Mr. Caluori said. "People want Bonner to stay small. We don't want the community to grow." Another longtime worker at the plant, Gary Tobol, has raised four children with his wife, Sandra, in a mill house. "It has been a one-company town for so long," Mr. Tobol said. "Everything rises or falls with the economies of the logging industry."

Since 1886, when the first log was cut, the Bonner mill has changed ownership several times and survived economic downturns. But the current owner, the Stimson Lumber Company, of Portland, Ore., decided recently to shut it down. Company officials cited the ailing housing market, foreign competition and declining timber prices. "It's sad," said Jeff Webber, Stimson's vice president for manufacturing. "If a business can't stay competitive, then I'm not sure it's worth keeping it open."

Stimson sold all 42 company-owned houses for an undisclosed price to Mr. Cooney, who said he planned to restore the 1930s-era cottages and create a National Historic District along the tree-lined main street opposite the mill. He said he hoped to buy up the rest of Stimson's timber operations. This year, he bought a 116-acre log yard and wants to buy the company's remaining 155 acres. Stimson officials would not comment on negotiations with Mr. Cooney, but Mr. Webber said the company had asked Gov. Brian Schweitzer to help find a manufacturer who could take over running the plant.

Most residents have never cashed a paycheck other than one from Stimson or its predecessors. They expressed hope that whoever acquired the mill would offer manufacturing jobs with wages to match those of Stimson, which paid $12 to $20 an hour.
Mr. Cooney said he envisioned light manufacturing operations having to do with solar and wind power, and specialty wood products. Ideally, he said, employers would offer workers perks like the free use of kayaks and mountain bikes for lunch-hour recreation.
Bonner retains a fierce community pride, but its once bustling character has been replaced by a forlorn air, a near-ghost town where the last few loads of logs outnumbered the few mill workers who remained when the plant shut down last month.

The Hendersons still live in one of the dilapidated mill houses, but Mr. Henderson has taken a job helping to demolish the Milltown Dam, part of the cleanup of one of the nation's largest Superfund complexes, a toxic legacy from the mining of copper and other heavy metals that took place in the area. He has also hung a sign reading "Redneck Auto" outside his garage, hoping to make a few extra dollars as a shade-tree mechanic. The Hendersons' neighbor Dawn Krueger, 53, described Bonner's current state as "all a jumble with families moving out and others trying to hang on without jobs." "We're a small community," Ms. Krueger said, "and we're all getting torn apart."

Shuttle to Take Big Science Lab to Space Station


Figure 1. (left) Kobo science laboratory. (right) The shuttle is ready to launch

The space shuttle Discovery is set to deliver the International Space Station's biggest room, in what its commander calls "a complicated, busy mission" that is scheduled to begin on Saturday.
A science laboratory, the second of three parts of a Japanese assembly called Kibo, will be the largest and most elaborate room at the International Space Station. The shuttle Discovery will deliver it. The new science laboratory is the second of three parts of a Japanese assembly called Kibo, which means hope. Only a few feet shorter than a big Winnebago, and much larger around, the new module fit inside the shuttle's payload bay only after astronauts removed an extension for the shuttle's robotic arm during the last mission and stored it at the station.

The cylindrical laboratory is nearly 37 feet long and 14.4 feet in diameter. The module is so heavy that much of its equipment was shipped up on that previous mission as well, in a small room known a logistics module. During the current mission, astronauts will also install the module's robotic arm, which will eventually be used in experiments placed on an external platform — Kibo's back porch — that will be carried to the station in a mission scheduled to take place next year. Kibo, pronounced ki-BO, will be managed by a control center in Tsukuba, Japan, along with the main mission control center in Houston.

(New York Times: http://www.nytimes.com/2008/05/31/science/space/31shuttle.html)

The commander for the 14-day mission, the 123rd in the history of the shuttle program, is Cmdr. Mark Kelly of the Navy, and the pilot is Cmdr. Kenneth T. Ham, also of the Navy. Commander Kelly is making his third trip to space; only one other member of the crew, Michael E. Fossum, a colonel in the Air Force Reserve, has been to space. He will be on his second mission. The other crew members are Karen Nyberg, Col. Ron Garan of the

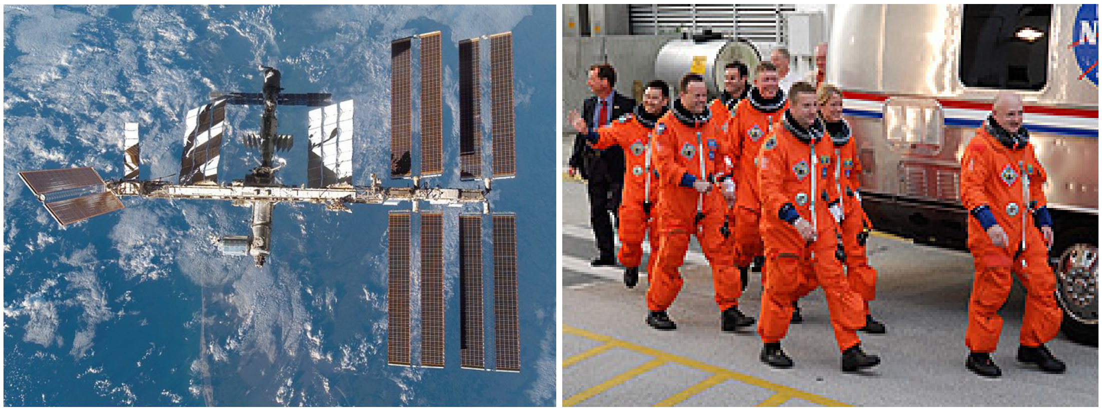


Figure 2. (left) International Space Station in 2008. (right) The shuttle crew

Air Force and Akihiko Hoshide of the Japan Aerospace Exploration Agency. Gregory Chamitoff will be going to the station to begin a rotation there, replacing Garrett E. Reisman, who has been aboard the station since March.

The new mission includes three spacewalks to help install Kibo, perform station maintenance and test techniques for cleaning a troubled rotary joint that is a critical part of the station’s power supply. That joint, 10 feet in diameter, rotates one of the station’s sets of solar arrays so that they face the Sun during each orbit. But the joint has been idle since last year, when it was found to be damaged by metal shavings that peppered its inner workings and were being ground in by the operation of the joint.

(NASA Kennedy Space Center: http://www.nasa.gov/centers/kennedy/home/index.html)

Several spacewalks in the past year have been devoted to examining the damage, but the cause of the problem and the precise part that was being ground away by the rotating

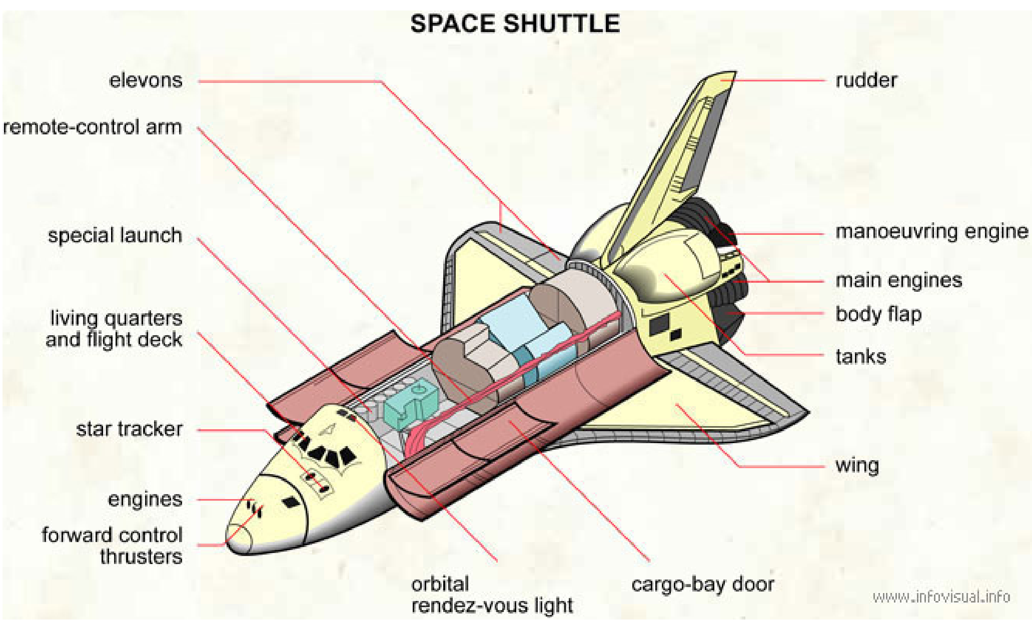


Figure 3. The structure of a space shuttle

joint are still unclear. Although the station has the power it needs now even with a stationary joint, it cannot reach its full functional size without the energy boost from the joint's rotation. During this mission, astronauts will test techniques that might be used to clean off the shavings.
"We're literally going out there with the kind of tools you'd have in your garage," said Colonel Fossum, the lead spacewalker for the mission. The astronauts will use a putty knife to smooth the surface of the "race ring," the part that has been most damaged by the errant particles, and grease and cloths to see what works best at the task. Later crews will try to correct the problem that caused the shavings by either replacing the source of the grinding or, if it cannot be tracked down, to switch to the use of a second, backup race

Figure 4. An overview of the shuttle launching field in NASA Kennedy Space Center

ring that is already part of the joint assembly. "There's a very large ring out there," Colonel Fossum said. "It's going to be a lot of work to tackle the whole thing." The crew will also perform science experiments during the mission in fields that include space medicine, biology and Earth observation.
While no technical issues stand in the way of launching, there was some question as to whether the mission should begin before a mystery is resolved: a recurring malfunction in the Russian Soyuz return modules. In April, three spacefarers, including the station's commander, Peggy Whitson of the United States, had a wild ride back to Earth in a Soyuz whose propulsion module failed to separate from the crew module until well into the descent. The malfunction sent the capsule into a backup mode of return that is called a ballistic entry with G-forces that were much higher than usual and a steep trajectory that put it hundreds of miles off course. The cause of the problem — the second in a row for the Soyuz, and the third in five years — is still under investigation by the Russian space agency.

(Space Shuttle History: http://history.nasa.gov/shuttlehistory.html)

NASA engineers and mission managers discussed putting off the mission until the investigation could be completed, since the Soyuz is used as a lifeboat in case of problems with the station. But at a news briefing on May 19, William Gerstenmaier, associate administrator for space operations at NASA, said managers decided to go forward because the chances of an emergency that would require the station to be evacuated are low (he cited a figure of 1 in 124), and added that the landings, even with the discomfort of ballistic entry, have been safe. “For emergency return, Soyuz is O.K.,” Mr. Gerstenmaier said.

This shuttle mission also involves the first external fuel tank to incorporate, from the start, all of the changes NASA has come up with to minimize the loss of insulating foam during launching. Previous tanks had to be modified to include the changes. Mission managers plan to get photos and videos of the tank to see how well the changes work. Falling foam doomed the shuttle Columbia and its crew in 2003. Redesigning the tanks has been a high priority for NASA, but since it takes years to make tanks, the full effect of the redesign effort had yet to come together until this flight.

The effort to rework the process has caused delays in flights down the line. Last week, NASA announced that it was pushing back the launching dates of its next two shuttle missions. A flight to perform servicing on the Hubble Space Telescope that was originally scheduled for August has been moved to Oct. 8. An October flight has been shifted to November. A sixth shuttle flight for this year that had been planned for

Figure 5. Previous configuration of the International Space Station

December might slip to 2009. Those delays are a “small price to pay,” said John Shannon, the shuttle program manager, “for all the improvements we’re getting on this tank.”

Part 1. Summarization

8. Skim the article, annotate or take notes just as you usually do. Especially, you may underline **topic sentences** and circle **keywords**.

9. Write a **thesis statement** (1~2 sentences) for the main idea of this article.

[write here]

10. Write and ***speak*** *short* and *simple* **summary sentences** (**1** for each original paragraph), using your topic sentences, annotations and notes. Keep the summary in the **same logic order** as the original article.

[write here]

Part 2. Study of more details

2. Web search of keywords

Find the **highlighted** words in the following pages, draw a **star mark** in the margin of the word's line, **underline** the words, **google** it, and then copy one sentence explanation from **wikipedia**.

1.1 [paste here]

1.2 [paste here]

1.3 [paste here]

---

3. Web page information acquisition

Open the following **web pages** in the following pages, from each of which, copy one picture, whatever you choose, into this document.

2.1 [paste here]

2.2 [paste here]

2.3 [paste here]

---

3. Answer the following questions with **text, figures or sketches**, whatever you feel most effective and efficient

3.1 In figure 2 (left), find **solar array joints** of the international space station, and briefly describe their location relative to the station.

3.2 In figure 4, find and number the following objectives, and describe their position in the picture: (1) **launching tower**, (2)**ocean**, and (3)**highway**.

3.3 Compare the recent International Space Station (figure 2) and its previous configuration (figure 5), find and number **three** differences, and roughly describe their location in the pictures.

----

11. Some details of an related article

Answer the questions below by searching for keywords in the following article to locate the relevant sentences (up to 2 minutes for each)

4.1 What did Michael Leinbach talk about the launch?

4.2 What did Julie Payette talk about the Russian engineering?

4.3 Who is Michael D. Griffin?

Shuttle Discovery Heads Toward the Space Station

KENNEDY SPACE CENTER, Fla. — The shuttle Discovery blasted its way into orbit on Saturday through wispy clouds against blue skies on its way to deliver a bus-size laboratory to the International Space Station. The column of smoke, bright white against the brilliant day, cast a shadow to the east as the shuttle ascended, and the sound waves made the air shudder.

A first look at the video from the ascending craft showed about five pieces of insulating foam falling off the shuttle's external fuel tank, said William Gerstenmaier, the space agency's associate administrator for space operations, at a news conference an hour after launching. But he said that none of the shedding was a source of worry, because it all occurred after the time during the ascent when falling foam presents a threat to the delicate heat shielding of the shuttle. Even those pieces that struck the shuttle appeared to bounce off harmlessly, Mr. Gerstenmaier said. "We don't think that's a big deal for us," he said. The shuttle will be closely inspected as it approaches the space station and after docking, he said. In a business in which delays are standard operating procedure, both the weather and the technical gremlins that often bedevil launching attempts caused no problems.

"It's a gorgeous day to launch," said Michael Leinbach, the launching director, giving approval for Discovery's ride. Cmdr. Mark E. Kelly of the Navy, who is the shuttle commander, replied, "Stand by for the greatest show on Earth."
The laboratory, the $1 billion Kibo module, is the largest and the second part of three shuttle payloads that will bring the full Kibo assembly up to the station. It will be the largest "room" on the station, and will eventually include an exposed area, like a back porch, where some experiments will be exposed to the harsh vacuum and temperature extremes of space.

The pilot for the mission, the 123rd in the history of the shuttle program, is Cmdr. Kenneth T. Ham, also of the Navy. Commander Kelly is making his third trip to space; only one other member of the crew, Michael E. Fossum, a colonel in the Air Force Reserve, has been to space. He will be on his second mission. The other crew members are Karen L. Nyberg, Col. Ronald J. Garan Jr. of the Air Force and Akihiko Hoshide of the Japan Aerospace Exploration Agency. The seventh member of the crew, Gregory E. Chamitoff, will be staying aboard the station to begin a six-month rotation there, and will replace Garrett E. Reisman, who has been aboard the station since March.

Discovery's crew members will be showing up with a last-minute addition to their cargo: replacement parts for a broken toilet aboard the station. The toilet has separate systems for dealing with solid and liquid waste. The unit that stopped working last week was supposed to direct urine flow and separate the liquid from air for storage. Two replacement units that were on board the station have also failed.

Julie Payette, a Canadian astronaut, said that despite the many toilet jokes that had been made in the news media over the past week, "We actually take this extremely seriously. In our book, the hygiene cabinet — the toilet — is perhaps one of the most important systems on any spacecraft." It should go without saying, Ms. Payette said, that "we're humans." "We generate waste," she continued. "We need a way to dispose of it." But she expressed confidence the Russians would be able to repair the system, because Russian engineering tends to be robust and repairable. "They have really good engineers," she said.

The mission includes three spacewalks to help install Kibo, perform station maintenance and to test techniques for cleaning a malfunctioning rotary joint that is a critical part of the station's power supply. That joint, 10 feet in diameter, rotates one of the station's enormous solar arrays so that it faces the Sun during each orbit. The National Aeronautics and Space Administration idled the joint last year, when it was found to have been damaged by metal shavings that fouled its inner workings and were being ground in by the operation of the joint.

Mr. Gerstenmaier said at the news conference that the station would probably be able to operate into next year before the problems limited the use of the growing station and the joint would have to be repaired. At the news conference, Michael D. Griffin, NASA's administrator, beamed as he talked about a week in which NASA not only launched a shuttle crew but also landed a robotic craft, Phoenix, on Mars. He joked, "It's so great that not even having to do a press conference — two press conferences in a week — can ruin it.” But, he added: “It is not easy. We could talk until 6 a.m. tomorrow and I wouldn’t touch all the details that would demonstrate how hard it is. And yet these teams make it look easy.”

<u>*Testing Article 3: Sudan Anima*</u>

In Sudan, an Animal Migration to Rival Serengeti

The first aerial survey of southern Sudan in 25 years has revealed vast migrating herds, rivaling those of the Serengeti plains, that have managed to survive 25 years of civil war, the Wildlife Conservation Society and Southern Sudan will announce today at a news conference in New York.

Figure 1. Some animals, like white-eared antelopes, are thriving in Sudan

(New York Times: http://www.nytimes.com/2007/06/12/science/12migr.html)

J. Michael Fay, a conservationist at the Wildlife Conservation Society and explorer-in-residence at the National Geographic Society, who has participated in the surveys, said in a telephone interview from Chad that southern Sudan's herds of more than a million gazelle and antelope may even surpass the Serengeti's herds of wildebeest, making the newly surveyed migration the largest on earth. "It's so far beyond anything you've ever seen, you can't believe it," Dr. Fay said. "You think you're hallucinating."

Southern Sudan, an area of about 225,000 square miles, sits between the Sahara and Africa's belt of tropical forests. Wildlife biologists have long known that its grasslands, woodlands and swamps were home to elephants, zebras, giraffes and other animals. Before the civil war, an estimated 900,000 white-eared kob (a kind of antelope) had been seen migrating there. But in 1983 wildlife research ground to a halt with the outbreak of civil war. Rebel fighters of the Sudan People's Liberation Army battled government forces, as well as Arab militias that swept down from the north on horseback. In the next two decades, more than two million people died. In 2005 the Sudanese government and the rebels signed an agreement, establishing the Government of Southern Sudan.

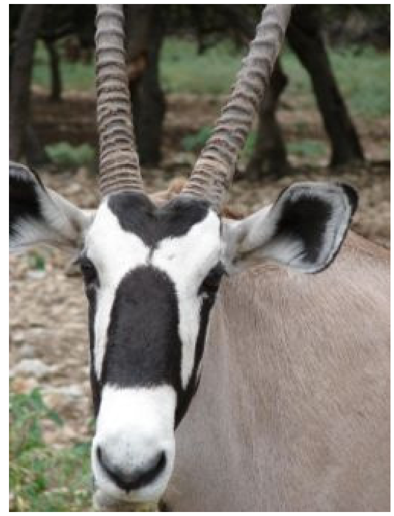


Figure 2. (left) Map of Sudan. (right) An oryx

Wildlife biologists could only wonder what happened to Sudan's animals during that time. Experience has shown that wars can be devastating to wildlife. As peacetime protections collapse, poachers sweep in to kill animals for meat, horn and ivory. Armies shoot game to feed themselves. "In places like Angola and Mozambique, the parks just got wiped out," Dr. Fay said. In the 1990s, pilots returning from relief missions to Southern Sudan told bleak stories. "People were saying that wildlife is finished there," said Paul Elkan, the director of the Wildlife Conservation Society's Southern Sudan Country Program, in a telephone interview from Nairobi. Some species, like the oryx, a long-horned antelope, were thought to have been wiped out.

(Sudan Civil War: http://en.wikipedia.org/wiki/Second_Sudanese_Civil_War)

But signs of hope turned up near the end of the war. Malik Marjan, a Sudanese graduate student at the University of Massachusetts, conducted a ground survey in Boma National Park. He and his colleagues saw healthy populations of white-eared kob. Last January, Mr. Marjan joined Dr. Fay and Dr. Elkan in the first aerial survey of Southern Sudan in 25 years. On their first day of surveying in Boma, they flew over thousands of white-eared kob. Dr. Fay, who has flown more than 70,000 miles of aerial surveys in Africa, was taken aback. "As soon as we saw that, we said, 'This place is insane.' " For the next month, Dr. Fay and his colleagues retraced the path of the last aerial surveys before the war. The white-eared kob were joined by hundreds of thousands of mongalla gazelles and tiang, a species of antelope. They formed a gigantic column that stretched 30 miles across and 50 miles long. "It was just solid animals the whole way," Dr. Fay said.

The biologists estimated there were 1.3 million kob, tiang and gazelle in their survey area. That is close to the size of migrating herds of wildebeest on the Serengeti, long considered the biggest migration of mammals. But Dr. Fay and his colleagues suspected that because they were replicating prewar survey methods, their estimates were low. New survey methods, such as digital photography, were likely to raise it above the Serengeti. "My personal feeling is that it's the biggest migration on earth," Dr. Fay said, "but we just haven't proved it yet." Other animals are also thriving in parts of Southern Sudan, including elephants, ostriches, lions, leopards, hippos and buffalo. Biologists have even spotted oryx, which were thought to be extinct.

But some species are faring badly. Southern Sudan used to be home to many zebras. In the 1982 survey, scientists estimated that 20,000 were living in Boma National Park alone. The Wildlife Conservation team found no zebras in Boma at all, and only a few elsewhere. The scientists also observed that most species suffered badly in the western part of the region. In 1981, about 60,000 buffalo lived in Southern Sudan National Park. Now, Dr. Fay said, "Not one buffalo did we see."

Figure 3. (left) National Parks in Southern Sudan. (right) A kob

(Wildlife Conservation Society: http://www.wcs.org/353624/wcs_southernsudan)

Geography may explain much of their results. Poachers on horseback could ride into the western part of Southern Sudan, but the Nile River and a giant swamp called the Sudd proved to be an impenetrable shield protecting the eastern region of Southern Sudan. Migrating animals also fared better than animals that stayed put year-round. "Their wet-season refuge is very isolated, so even if they were heavily hunted in the dry season, they would have a buffer," Dr. Elkan said.

The survey was conducted by the Wildlife Conservation Society in cooperation with the Government of Southern Sudan. The government is already taking steps to protect its wildlife, said Maj. Gen. Alfred Akwoch, undersecretary of the Ministry of Environment, Wildlife Conservation and Tourism. The Sudan People's Liberation Army is deploying some of its soldiers to protect the parks. "We are training them now with the basic knowledge of wildlife conservation," General Akwoch said.

It will also be necessary to balance the conservation of wildlife with the economic recovery from the war, Dr. Elkan said. “You have oil exploration in the northern part of the Sudd already,” he said. “Oil permits have already been handed out throughout most of the migratory corridor for the tiang and the white-eared kob.” The government is rebuilding roads and schools, and people are returning to their farms. “This place is hopping,” Dr. Fay said.

Dr. Fay said he thought Southern Sudan could attract eco-tourists in the future. He also plans to use the new survey to lobby donor nations to set aside some of their aid to Southern Sudan for managing natural resources. “I’m going to keep hammering away at these guys that natural resources management is as important for people as it is for keeping elephants alive,” Dr. Fay said. “If we can’t invest in what might be the largest wildlife migration on earth, then we may as well close up shop and go home.”

(Animal Paradise: http://www.africapavilion.org/country/sudan/03_e.htm)

Part 1. Summarization

12. Skim the article, annotate or take notes just as you usually do. Especially, you may underline **topic sentences** and circle **keywords**.

13. Write a **thesis statement** (1~2 sentences) for the main idea of this article.
[write here]

14. Write and ***speak*** *short* and *simple* **summary sentences** (**1** for each original paragraph), using your topic sentences, annotations and notes. Keep the summary in the **same logic order** as the original article.
[write here]

Part 2. Study of more details

3. Web search of keywords

Find the **highlighted** words in the following pages, draw a **star mark** in the margin of the word's line, **underline** the words, **google** it, and then copy one sentence explanation from **wikipedia**.

1.1 [paste here]

1.2 [paste here]

1.3 [paste here]

----

4. Web page information acquisition

Open the following **web pages** in the following pages, from each of which, copy one picture, whatever you choose, into this document.
2.1 [paste here]

2.2 [paste here]

2.3 [paste here]

----

3. Answer the following questions with **text, figures or sketches**, whatever you feel most effective and efficient

3.1 Find all the **dark brown** kobs in figure 1, and indicate their locations in the picture.

3.2 In figure 2, find these places: (1)**Red sea**, (2)**Chad**, (3)**Congo** and (4)**Kenya**, number them, and describe their positions relative to Sudan.

3.3 Compare the **oryx** (figure 2) and **kob** (figure 3), find **three** differences of their bodies, number the differences, and describe the locations.

----

15. Some details of an related article

Answer the questions below by searching for keywords in the following article to locate the relevant sentences (up to 2 minutes for each)

4.1 What happened in Kenya for animal protection?

4.2 In which year did Zaire gain independence?

4.3 How many French security experts were hired for the animal protection in Congo?

War and Politics Threaten Congo's Endangered Rhinos

If the endangered northern white rhinos are driven to extinction, which many experts predict, it will be politics, and not just poachers, that finishes them off.

With fewer than a dozen still alive in the wild, the northern white rhinoceros is considered by conservationists to be the most endangered large mammal on earth. Besides those found in zoos in San Diego and the Czech Republic, where they have not reproduced well, the rhinos are believed to exist only in Garamba National Park, a rugged place near the border with Sudan that is full of wildlife and lush vegetation but also men with guns.

"I do not believe that any rhinos will survive the year," predicted Thomas J. Foose, program director at the International Rhino Foundation, which is based in the United States and has been working for years in Garamba, the last refuge for the northern white rhino. The immediate culprits, according to conservation groups, are poachers from an offshoot of the janjaweed, the Arab militia groups that have been pillaging villages in the Darfur region of Sudan. Rather than attacking people, these militias are on a mission to make money. They steal over the border to kill elephants and rhinos, leaving the carcasses and taking the valuable tusks and horns, which are carried back in long donkey trains.

These militias have proved particularly violent and, as a result, difficult to combat. But the greatest threat to the rhinos is political, specifically a growing Congolese nationalism that has undercut protection efforts, including a last-ditch program to move five of the remaining animals to safety in Kenya.

That plan set off an anticolonial uproar, with opponents likening it to the days when Congo exported its wealth to European nations, by force. Rumors circulated that foreigners were buying up the rhinos at low prices, paying off corrupt officials and spiriting the animals out of the country. One newspaper in Kinshasa, the capital, described the Western conservationists as "modern-day poachers," and Congolese politicians seized on the white rhino as a symbol of national pride, off limits to exploitive outsiders.

A decades-old Western-financed project to train and pay Congolese park rangers to fight off the poachers was abandoned after similar accusations surfaced that the Westerners were stealing the animals and selling them abroad, a charge that the Western conservation groups strongly deny. "It is sad that politics, not poaching, will probably kill these rhinos," said Emmanuel de Merode, who was running the European Union project before it was shut down. White rhinos, known scientifically as Ceratotherium simum, weigh up to 6,000 pounds and are the second-largest land mammal species, behind the elephant. They get their name not from their color, experts say, but from the Afrikaans word weit, meaning wide, which was used to describe their mouths.

South Africa has a white rhino population of about 11,000, making them the most abundant kind of rhino in the world. But the going has been much tougher for the northern subspecies, which used to be found in several countries in eastern and central Africa.

The animals' decline has closely tracked Congo's chaotic past. There were anywhere from a thousand to several thousand of them when the country, then Zaire, gained independence from Belgium in 1960. Their numbers fell steadily over the decades, partly because of a long civil war in neighboring Sudan. As two armed insurrections ravaged eastern Congo in the 1990's, the population plummeted to around 30.

Other unique animals found in Congo have managed to endure the fighting. The population of mountain gorillas, also found in neighboring Uganda and Rwanda, has actually grown in recent years. The okapi, a bizarre-looking relative of the giraffe that is found here in Epulu, about 150 miles south of Garamba, is hanging on.

The fact that the northern rhinos survived this long is the result of an international conservation effort, now collapsed, that for decades had supported Congolese rangers, who had acted as bodyguards for the rhinos. The rhinos' horns are a valuable prize, sought after in Asia for their medicinal value, and in the Middle East, where they are carved into dagger handles.

The latest troubles began in 2003, with the outbreak of the Darfur conflict and the appearance of the Arab militias, which presented a new, more organized and far more deadly threat than did previous poachers. Last year, two South Africans who had been brought in as trainers for the rangers were wounded in their first clash with the poachers. Three French security experts were then hired by the European Union last fall to lend the experience they had gained fighting poachers in the Central African Republic. But the last of them pulled out in recent weeks in the furor surrounding the failed attempt to send five of the animals to Kenya.

That deal, struck in January between conservationists and officials at the Congolese Institute for Conservation of Nature, was intended to give the rhinos a chance to breed in peace. The plan was to return them to Congo sometime in the future, to a more stable park. "We believed the translocation of the rhino to a more secure locale in Kenya was absolutely vital," Mr. Foose said in a telephone interview from Indonesia.

Training Article: Polar Bear

Figure 1. (left) A polar bear walks on the melting ice. (right) A polar bear family

Polar Bear Is Made a Protected Species

The polar bear, whose summertime Arctic hunting grounds have been greatly reduced by a warming climate, will be placed under the protection of the Endangered Species Act, Interior Secretary Dirk Kempthorne announced on Wednesday.

(Polar Bear International: http://www.polarbearsinternational.org/)

The polar bear is being stressed by melting sea ice but scientists say the species would not vanish entirely for a century or more. But the long-delayed decision to list the bear as a threatened species may prove less of an impediment to oil and gas industries along the Alaskan coast than many environmentalists had hoped. Mr. Kempthorne also made it clear that it would be “wholly inappropriate” to use the listing as a tool to reduce greenhouse gases, as environmentalists had intended to do. While giving the bear a few new protections — hunters may no longer import hides or other trophies from bears killed in Canada, for instance — the Interior Department added stipulations, seldom used under the act, that would allow oil and gas exploration and development to proceed in areas where the bears live, as long as the companies continue to comply with existing restrictions under the Marine Mammal Protection Act.

Mr. Kempthorne said Wednesday in Washington that the decision was driven by overwhelming scientific evidence that “sea ice is vital to polar bears’ survival,” and all available scientific models show that the rapid loss of ice will continue. The bears use sea ice as a platform to hunt seals and as a pathway to the Arctic coasts where they den. The models reflect varying assumptions about how fast the concentration of greenhouse gases in the atmosphere will increase. In prepared remarks, the secretary, who earlier in his

political life was a strong opponent of the current Endangered Species Act, added, “This has been a difficult decision.” He continued, “But in light of the scientific record and the restraints of the inflexible law that guides me,” he made “the only decision I could make.”
The Center for Biological Diversity, Greenpeace and the Natural Resources Defense Council filed suit in 2005 to force a listing of the polar bear. The center, based in Arizona, has been explicit about its hopes to use this — and the earlier listing of two species of coral threatened by warming seas — as a legal cudgel to attack proposed coal-fired power plants or other new sources of carbon dioxide emissions. But in both cases, the Bush administration has parried this legal thrust, saying it had no obligation to address or try to mitigate the cause of the species’ decline — warming waters, in the case of the corals, or melting sea ice, in the case of the bears — or the greenhouse-gas emissions from cars, trucks, refineries, factories and power plants that contribute to both conditions.

On Wednesday, Mr. Kempthorne specifically ruled out that possibility, saying, “When the Endangered Species Act was adopted in 1973, I don’t think terms like ‘climate change’ were part of our vernacular.” The act, he said, “is not the instrument that’s going

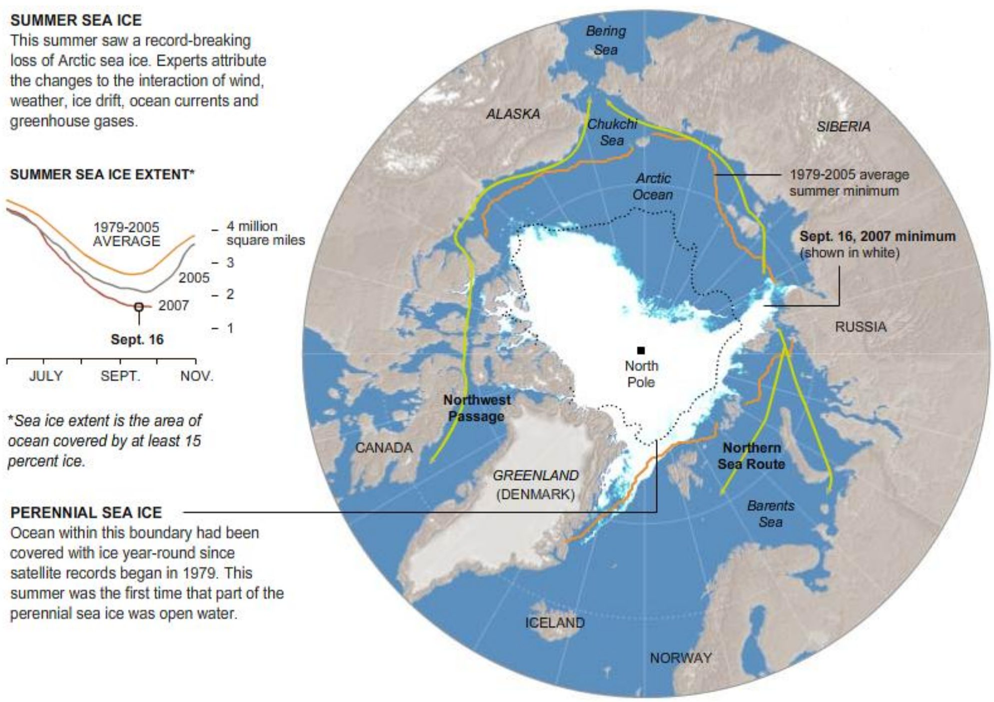


Figure 2. The map of North Pole

to be effective” to deal with climate change. Barton H. Thompson Jr., a law professor and director of the Woods Institute of the Environment at Stanford University, said the decision reflected the administration’s view that “there is no way, if your factory emits a greenhouse gas, that we can say there is a causal connection between that emission and an iceberg melting somewhere and a polar bear falling into the ocean.”

(Sea world: http://www.seaworld.org/infobooks/PolarBears/home.html)

Few natural resource decisions have been as closely watched or been the subject of such vehement disagreement within the Bush administration as this one, according to officials in the Interior Department and others familiar with the process. After the department missed a series of deadlines, a federal judge ruled two weeks ago that the decision had to be made by Thursday. In recent days, some officials in the Interior Department speculated that the office of Vice President Dick Cheney had tried to block the listing of the bear. People close to these officials indicated that two separate documents — one supporting the listing, and the other supporting a decision not to list the bear — had been prepared for Mr. Kempthorne. In an interview, Mr. Kempthorne and his chief of staff, Bryan Waidmann, said they had not discussed the decision with anyone in the vice president's office, though they did not dispute that two documents had been made available for the secretary's signature this week. "Let's say I had my options available," Mr. Kempthorne said.

The provision of the act that the Interior Department is using to lighten the regulatory burden that the listing imposes on the oil and gas industry — known as a 4(d) rule — was intended to permit flexibility in the management of threatened species, as long as the chances of conservation of the species would be enhanced, or at least not diminished. Kassie Siegel, a lawyer for the Center for Biological Diversity, said the listing decision was an acknowledgment of "global warming's urgency" but would have little practical impact on protecting polar bears. "The administration acknowledges the bear is in need of intensive care," Ms. Siegel said. "The listing lets the bear into the hospital, but then the 4(d) rule says the bear's insurance doesn't cover the necessary treatments."

(US Interior Department: http://www.doi.gov/)

The science on polar bears in a warming climate is nuanced, which allowed the administration to shape its decision the way it did. Over all, scientists agree that rising temperatures will reduce Arctic ice and stress polar bears, which prefer seals they hunt on the floes. But few foresee the species vanishing entirely for a century and likely longer. There are more than 25,000 bears in the Arctic, 15,500 of which roam within Canada's territory. A scientific study issued last month by a Canadian group established to protect wildlife said that 4 of 13 bear populations would most likely decline by more than 30 percent over the next 36 years, while the others would remain stable or increase.

M. Reed Hopper of the Pacific Legal Foundation, a property-rights group based in Sacramento, called the decision to list the polar bear "unprecedented" and said his group would sue the Interior Department over the decision. "Never before has a thriving species been listed" under the Endangered Species Act, he said, "nor should it be." John Baird, the environment minister for Canada, said Wednesday that the government would adopt an independent scientific panel's recommendation to declare polar bears a species "of special concern," a lower designation than endangered, and he promised to take other unspecified actions.

Management of the bear populations is the responsibility of Canadian provinces and territories. The territorial government of Nunavut, which is home to upward of 15,000 polar bears, had campaigned against new United States protections for the bear, largely because of worries that the lucrative local bear hunts by residents of the United States would stop when trophy skins could no longer be brought home.

(Discovery: http://dsc.discovery.com/news/2007/12/14/polar-bears-warming.html)

Figure 2. Other two kinds of bears, Giant Panda and Asiatic Black Bear.

Part 1. Summarization

16. Skim the article, annotate or take notes just as you usually do. Especially, you may underline **topic sentences** and circle **keywords**.

17. Write a **thesis statement** (1~2 sentences) for the main idea of this article.
[write here]

18. Write and ***speak*** *short* and *simple* **summary sentences** (**1** for each original paragraph), using your topic sentences, annotations and notes. Keep the summary in the **same logic order** as the original article.
[write here]

Part 2. Study of more details

4. Web search of keywords

Find the **highlighted** words in the following pages, draw a **star mark** in the margin of the word's line, **underline** the words, **google** it, and then copy one sentence explanation from **wikipedia**.

1.1 [paste here]

1.2 [paste here]

1.3 [paste here]

---

5. Web page information acquisition

Open the following **web pages** in the following pages, from each of which, copy one picture, whatever you choose, into this document.
2.1 [paste here]

2.2 [paste here]

2.3 [paste here]

---

3. Answer the following questions with **text, figures or sketches**, whatever you feel most effective and efficient

3.1 (figure 2) In the map, find and number these places: (1)**Alaska**, (2)**Russia**, (3)**Norway** and (4)**Canada**, describe their locations relative to North pole.

3.2 (figure 3) Find the perennial sea ice line (dot line), and indicate in which direction it is furthest and closest away from the 1979-2005 summer minimum sea ice line (in orange)?

3.3 (figure 1, 3) Compare Polar Bear (figure 1) and Giant Panda (figure 3), find 3 differences, and describe the difference locations.

----

19. Some details of an related article

Answer the questions below by searching for keywords in the following article to locate the relevant sentences (up to 2 minutes for each)

4.1 How many acres of polar bear habitat in the Chukchi Sea will be affected by the government policy?

4.2 Who is Dirk Kempthorne?

Of Two Minds on Polar Bears

Two agencies in the Department of the Interior are nearing significant yet contradictory decisions that will affect the fate of one of America's iconic animal species, the polar bear.

As early as this week, the Fish and Wildlife Service could list the polar bear as threatened under the Endangered Species Act, the result of severe habitat loss caused by global warming and the melting of Arctic sea ice. About the same time, the Minerals Management Service will announce its final decision to sell oil leases covering nearly 30 million acres of polar bear habitat in the Chukchi Sea off Alaska's northwest coast.

Listing the polar bear would trigger a series of protections, including, in time, identifying habitat critical to the bears' survival. It would also impose obligations on all federal agencies to avoid actions that could hurt the bears' prospects. But the minerals service, where the wishes of the oil and gas industry carry great weight, has a history of doing as it pleases. Environmental groups and members of the House and Senate are thus asking Dirk Kempthorne, the interior secretary, to declare a timeout, postponing Chukchi Sea lease sales for three years pending further scientific study.

The polar bears' plight raises larger issues, including the nation's reliance on fossil fuels, which produce the greenhouse gases that are destroying the bears' habitat. It also calls into question the Bush administration's unsustainable strategy of trying to drill its way to energy independence. Congress has finally recognized the pointlessness of that by passing an energy bill giving greater emphasis to conservation and alternative fuels.

The urgent and immediate question, though, is the future of the polar bear, which is bleak enough without further stresses. Everyone agrees that the overwhelming threat is the loss of sea ice, where the bears hunt for food and nurture their young. Yet there is also wide recognition among federal scientists, even in the minerals service, that the many activities associated with oil drilling — the seismic tests, the vast increase in ship traffic, the noise, the potential spills — can only weaken the bear's resilience.

Mr. Kempthorne should intervene, get his agencies on the same page and make clear that his first priority is to protect the environment and the polar bear.

Appendix 4: Active Reading Study Questionnaire

Background / User ID ___

1. In which age group are you in?
1) 15 ~ 20
2) 21 ~ 30
3) 31 ~ 40
4) above 40

2. Your gender ?
1) Male
2) Female
3) N/A

3. What is your education level ?
1) High school
2) College
3) Graduate
4) Doctor
5) Others (please write) ___________

4. How many years have you used computers? ____________ years

5. How many hours do you use a computer per day on average? ___________ hours

6. How many monitors do you usually use with your computer? __________

7. How many years have you used a stylus on a Tablet or a PDA ? ___________ years

8. How many years have you used a digital pen? _____________years

9. How many hours do you use paper for reading/writing per day on average? ____ hours

10. What is your major/profession? _________________

Task Load Index Worksheet / User ID ___ Condition : Paper

Please answer the following questions based on the technique you used on a scale of 1 (low) – 7 (high).

1. Mental Demand — How much thinking was required to use the device?

1 2 3 4 5 6 7

2. Physical Demand—How much physical effort or coordination was required to use the device?

1 2 3 4 5 6 7

3. Temporal Demand — How much time pressure did you have while performing the task?

1 2 3 4 5 6 7

4. Performance — How well do you think you performed the task? For example, do you think you were able to select the required document segments and menu items quickly?

1 2 3 4 5 6 7

5. Effort — To accomplish your level of performance how hard did you have to work (both mentally and physically)?

1 2 3 4 5 6 7

6. Frustration level — How discouraged, irritated, stressed or annoyed did you think while completing the task?

1 2 3 4 5 6 7

Task Load Index Worksheet / User ID ___ Condition : PapierCraft

Please answer the following questions based on the technique you used on a scale of 1 (low) – 7 (high).

1. **Mental Demand** — How much thinking was required to use the device?

1 2 3 4 5 6 7

2. **Physical Demand**—How much physical effort or coordination was required to use the device?

1 2 3 4 5 6 7

3. **Temporal Demand** — How much time pressure did you have while performing the task?

1 2 3 4 5 6 7

4. **Performance** — How well do you think you performed the task? For example, do you think you were able to select the required document segments and menu items quickly?

1 2 3 4 5 6 7

5. **Effort** — To accomplish your level of performance how hard did you have to work (both mentally and physically)?

1 2 3 4 5 6 7

6. **Frustration level** — How discouraged, irritated, stressed or annoyed did you think while completing the task?

1 2 3 4 5 6 7

Task Load Index Worksheet / User ID ___ Condition : Tablet PC

Please answer the following questions based on the technique you used on a scale of 1 (low) – 7 (high).

1. Mental Demand — How much thinking was required to use the device?

1 2 3 4 5 6 7

2. Physical Demand—How much physical effort or coordination was required to use the device?

1 2 3 4 5 6 7

3. Temporal Demand — How much time pressure did you have while performing the task?

1 2 3 4 5 6 7

4. Performance — How well do you think you performed the task? For example, do you think you were able to select the required document segments and menu items quickly?

1 2 3 4 5 6 7

5. Effort — To accomplish your level of performance how hard did you have to work (both mentally and physically)?

1 2 3 4 5 6 7

6. Frustration level — How discouraged, irritated, stressed or annoyed did you think while completing the task?

1 2 3 4 5 6 7

Overall Evaluation

Please answer the following questions on a scale of 1– 7 based on the experiments.

1. Do you think it is comfortable to **read**? (1 for "Very Difficult" and 7 for "Very Easy")

(Paper)	1	2	3	4	5	6	7
(PapierCraft)	1	2	3	4	5	6	7
(Tablet PC)	1	2	3	4	5	6	7

Feel free to elaborate here: ____

____

2. Do you think it is comfortable to **annotate**? (1 for "Very Difficult" and 7 for "Very Easy")

(Paper)	1	2	3	4	5	6	7
(PapierCraft)	1	2	3	4	5	6	7
(Tablet PC)	1	2	3	4	5	6	7

Feel free to elaborate here: ____

____

3. Do you think it is comfortable to **take notes**? (1 for "Very Difficult" and 7 for "Very Easy")

(Paper)	1	2	3	4	5	6	7
(PapierCraft)	1	2	3	4	5	6	7
(Tablet PC)	1	2	3	4	5	6	7

Feel free to elaborate here: ____

____

4. Do you think it is easy to use the laptop to **write** the summary? (1 for "Very Difficult" and 7 for "Very Easy")

1 2 3 4 5 6 7

Feel free to elaborate here: ____

____

5. Do you think it is easy to **navigate and browse** (e.g. flip pages back and forth) the documents and notes? (1 for "Very Difficult" and 7 for "Very Easy")

(Paper)	1	2	3	4	5	6	7
(PapierCraft)	1	2	3	4	5	6	7
(Tablet PC)	1	2	3	4	5	6	7

Feel free to elaborate here: ____

____

6. Do you think it is easy to **spatially arrange** the documents and notes on desk? (1 for "Very Difficult" and 7 for "Very Easy")

(Paper)	1	2	3	4	5	6	7
(PapierCraft)	1	2	3	4	5	6	7
(Tablet PC)	1	2	3	4	5	6	7

Feel free to elaborate here: ____

____

7. Do you feel comfortable to **compare** two document pages? (1 for "Very Difficult" and 7 for "Very Easy")

(Paper)	1	2	3	4	5	6	7
(PapierCraft)	1	2	3	4	5	6	7
(Tablet PC)	1	2	3	4	5	6	7

Feel free to elaborate here: ____

____

8. Do you feel comfortable to **use the pen/stylus**? (1 for "Very Difficult" and 7 for "Very Easy")

(Paper)	1	2	3	4	5	6	7
(PapierCraft)	1	2	3	4	5	6	7

(Tablet PC) 1 2 3 4 5 6 7

Feel free to elaborate here: ____

____

9. Do you think it is useful to **organize and manage** your annotations and notes to reuse them for later references? (1 for "Not useful at all" and 7 for "Very useful")
(Generally) 1 2 3 4 5 6 7

To what extent do these devices can help? (1 for "Very Little" and 7 for "Very Much")

(Paper) 1 2 3 4 5 6 7

(PapierCraft) 1 2 3 4 5 6 7

(Tablet PC) 1 2 3 4 5 6 7

Feel free to elaborate here: ____

____

10. Do you think it is convenient to remotely **share** your annotations and notes with other people (suppose no privacy issues) ? (1 for "Very Difficult" and 7 for "Very Easy")

(Paper) 1 2 3 4 5 6 7

(PapierCraft) 1 2 3 4 5 6 7

(Tablet PC) 1 2 3 4 5 6 7

Feel free to elaborate here: ____

____

11. Generally, do you think it is useful to have **digital commands**, like copy/paste and search, available directly on paper documents, even with a computer nearby? (1 for "Not Useful At All" and 7 for "Very Useful")

1 2 3 4 5 6 7

Feel free to elaborate here: ____

____

12. Do you think it is easy to **access external information** (e.g. do web search or open a hyperlink) from the document? (1 for "Very Difficult" and 7 for "Very Easy")

(Paper)	1	2	3	4	5	6	7
(PapierCraft)	1	2	3	4	5	6	7
(Tablet PC)	1	2	3	4	5	6	7

Feel free to elaborate here: ____
____

13. Do you think it is easy to **transcribe/copy-paste** information from the document or notes to your summary? (1 for "Very Difficult" and 7 for "Very Easy")

(Paper)	1	2	3	4	5	6	7
(PapierCraft)	1	2	3	4	5	6	7
(Tablet PC)	1	2	3	4	5	6	7

Feel free to elaborate here: ____
____

14. Do you think it is easy to **search** keywords within the document? (1 for "Very Difficult" and 7 for "Very Easy")

(Paper)	1	2	3	4	5	6	7
(PapierCraft)	1	2	3	4	5	6	7
(Tablet PC)	1	2	3	4	5	6	7

Feel free to elaborate here: ____
____

15. For all the testing tasks, please give an overall score for the three approaches

(Paper)	1	2	3	4	5	6	7
(PapierCraft)	1	2	3	4	5	6	7
(Tablet PC)	1	2	3	4	5	6	7

Feel free to elaborate here: ____
____
____

16. Open question : in your opinion, what are the **Best and/or Worst** aspects about the three different interfaces (normal paper, PapierCraft and Tablet PC)?

17. Do you have any suggestions or comments to help us improve the design?

thank you !

Bibliography

ADLER, A., A. GUJAR, L. B. HARRISON, K. O'HARA and A. SELLEN (1998), A diary study of work-related reading: design implications for digital reading devices. *Proceedings of CHI'98*, pp. 241-248.

ADLER, M. J. and C. VAN DOREN (1972), *How to Read a Book*. 1972, New York, NY: Simon and Schuster.

ALVARADO, C. and R. DAVIS (2004), SketchREAD: a multi-domain sketch recognition engine. *Proceedings of UIST'04*, pp. 23-32.

ANDERSON, R., R. ANDERSON, B. SIMON, S. A. WOLFMAN, T. VANDEGRIFT and K. YASUHARA (2004), Experiences with a tablet PC based lecture presentation system in computer science courses. *Proceedings of the 35th SIGCSE technical symposium on Computer science education*, pp. 56-60.

ANDERSON, R., T. VANDEGRIFT, S. A. WOLFMAN, K. YASUHARA and R. ANDERSON (2003), Interaction patterns with a classroom feedback system: making time for feedback. *Proceedings of CHI '03 extended abstracts*, pp. 880-881.

ANOTO http://www.anoto.com.

ANOTO (2002), Development Guide for Service Enabled by Anoto Functionality.

APITZ, G. and F. GUIMBRETIERE (2004), CrossY: A Crossing-Based Drawing Application. *Proceedings of UIST'04*, pp. 3 - 12.

ARAI, T., D. AUST and S. E. HUDSON (1997), PaperLink: a technique for hyperlinking from real paper to electronic content. *Proceedings of CHI'97*, pp. 327 - 334.

AVRAHAMI, D., S. E. HUDSON, T. P. MORAN and B. D. WILLIAMS (2001), Guided gesture support in the paper PDA. *Proceedings of UIST'01*, pp. 197 - 198.

BACK, M., J. COHEN, R. GOLD, S. HARRISON and S. MINNEMAN (2001), Listen reader: an electronically augmented paper-based book. *Proceedings of CHI'01*, pp. 23-29.

BALAKRISHNAN, R. and P. PATEL (1998), The PadMouse: facilitating selection and spatial positioning for the non-dominant hand. *Proceedings of CHI'98*, pp. 9 - 16.

BIEHL, J. T., W. T. BAKER, B. P. BAILEY, D. S. TAN, K. M. INKPEN and M. CZERWINSKI (2008), Impromptu: a new interaction framework for supporting collaboration in multiple display environments and its field evaluation for co-located software development. *Proceedings of CHI'08*, pp. 939-948.

BLUEGIGA Bluetooth Access Server,http://www.bluegiga.com/.

BRANDL, P., M. HALLER, J. OBERNGRUBER and C. SCHAFLEITNER (2008), Bridging the Gap Between Real Printouts and Digital Whiteboard. *Proceedings of AVI'08*, pp. 31-38.

BRUSH, A. J. B., D. BARGERON, J. GRUDIN and A. GUPTA (2002), Notification for shared annotation of digital documents. *Proceedings of CHI'02*, pp. 89-96.

BUXTON, B. (1987), Chunking and Phrasing and the Design of Human-Computer Dialogues. *Proceedings of IFIP World Computer Congress*, pp. 475 - 480.

CAMPBELL, C. S., S. ZHAI, K. W. MAY and P. P. MAGLIO (1999), What You Feel Must Be What You See: Adding Tactile Feedback to the Trackpoint. *Proceedings of INTERACT'99*, pp. 383-390.

CARZANIGA, A., D. S. ROSENBLUM and A. L. WOLF (2001), Design and evaluation of a wide-area event notification service. ACM Trans. Comput. Syst., 2001. **19**(3): pp 332-383.

CHEN, N., F. GUIMBRETIERE, M. DIXON, C. LEWIS and M. AGRAWALA (2008), Navigation Techniques for Dual-Display E-Book Readers. *Proceedings of CHI'08*, pp. 1779-1788.

COCKBURN, A., C. GUTWIN and J. ALEXANDER (2006), Faster document navigation with space-filling thumbnails. *Proceedings of CHI'06*, pp. 1-10.

CONROY, K., D. LEVIN and F. GUIMBRETIÈRE (2004), ProofRite: A Paper-Augmented Word Processor. *Proceedings of UIST'04 (Demo session)*.

CSIKSCZENTMIHALYI, M. (1991), *Flow: The Psychology of Optimal Experience*. 1991: HarperCollins.

CULLER, D. E. and H. MULDER (2004), Smart Sensors to Network the World. Scientific American, 2004. **290**(6): pp 84–91.

DE BRUIJN, O. and R. SPENCE (2000), Rapid serial visual presentation: a space-time trade-off in information presentation. *Proceedings of AVI'00*, pp. 189 - 192.

DOURISH, P., W. K. EDWARDS, A. LAMARCA, J. LAMPING, K. PETERSEN, M. SALISBURY, D. B. TERRY and J. THORNTON (2000), Extending document management systems with user-specific active properties. ACM Trans. Inf. Syst., 2000. **18**(2): pp 140-170.

DUFRESNE, R., W. GERACE, W. LEONARD, J. MESTRE and L. WENK (1996), Classtalk: A Classroom Communication System for Active Learning. Journal of Computing in Higher Education, 1996. (7): pp 3-47.

DYMETMAN, M. and M. COPPERMAN (1998), Intelligent Paper. *Proceedings of EP'98*, pp. 392 - 406.

E-INK http://www.eink.com.

EROL, B., E. ANTÚNEZ and J. J. HULL (2008), HOTPAPER: multimedia interaction with paper using mobile phones. *Proceedings of Proceeding of the 16th ACM international conference on Multimedia*, pp. 399-408.

FRANCIK, E. and K. AKAGI (1989), Designing a computer pencil and tablet for handwriting. *Proceedings of the Human Factors Society 33rd Annual Meeting*, pp. 445-449.

GAVER, W. W., R. B. SMITH and T. O'SHEA (1991), Effective sounds in complex systems: the ARKOLA simulation. *Proceedings of CHI'91*, pp. 85-90.

GELDARD, F. A. (1960), Some Neglected Possibilities of Communication. Science, 1960. **131**(3413): pp 1583-1588.

GIBSON, J. J. (1977)*, The Theory of Affordances*. 1977.

GREENBERG, S., M. BOYLE and J. LABERGE (1999), PDAs and shared public displays: Making personal information public, and public information personal. Personal Technologies, 1999. **3**(1).

GUIMBRETIERE, F. (2003), Paper Augmented Digital Documents. *Proceedings of UIST'03*, pp. 51 - 60.

GUIMBRETIÈRE, F., M. STONE and T. WINOGRAD (2001), Fluid interaction with high-resolution wall-size displays. *Proceedings of UIST'01*, pp. 21 - 30.

GUIMBRETIÈRE, F. and T. WINOGRAD (2000), FlowMenu: combining command, text, and data entry. *Proceedings of UIST'00*, pp. 213 - 216.

HARDOCK, G., G. KURTENBACH and W. BUXTON (1993), A marking based interface for collaborative writing. *Proceedings of UIST*, pp. 259-266.

HART, S. G. and L. E. STAVELAND (1988), Development of NASA-TLX (Task Load Index): Results of empirical and theoretical research, in *Human Mental Workload*, Editor^Editors. 1988, Elsevier Science. pp. 139 - 183.

HECHT, B., M. ROHS, J. SCHÖNING and A. KRÜGER (2007), Wikeye – Using Magic Lenses to Explore Georeferenced Wikipedia Content. *Proceedings of the 3rd International Workshop on Pervasive Mobile Interaction Devices (PERMID)*.

HECHT, D. L. (2001), Printed embedded data graphical user interfaces. IEEE Computer, 2001. **34**(3): pp 47-55.

HEINER, J. M., S. E. HUDSON and K. TANAKA (1999), Linking and messaging from real paper in the Paper PDA. *Proceedings of UIST'99*, pp. 179 - 186.

HINCKLEY, K., P. BAUDISCH, G. RAMOS and F. GUIMBRETIERE (2005), Design and analysis of delimiters for selection-action pen gesture phrases in scriboli. *Proceedings of CHI'05*, pp. 451-460.

HINCKLEY, K., G. RAMOS, F. GUIMBRETIERE, P. BAUDISCH and M. SMITH (2004), Stitching: Pen Gestures that Span Multiple Displays. *Proceedings of AVI'04*, pp. 23 - 31.

HINCKLEY, K., S. ZHAO, R. SARIN, P. BAUDISCH, E. CUTRELL, M. SHILMAN and D. TAN (2007), InkSeine: In Situ Search for Active Note Taking. *Proceedings of CHI'07*, pp. 251-260.

IBM (1998), CrossPadd, http://www.research.ibm.com/electricInk/.

IGARASHI, T. and K. HINCKLEY (2000), Speed-dependent automatic zooming for browsing large documents. *Proceedings of UIST'00*, pp. 139 - 148.

IREX.

ISHII, H. and B. ULLMER (1997), Tangible bits: towards seamless interfaces between people, bits and atoms. *Proceedings of CHI'97*, pp. 234-241.

JOHANSON, B., G. HUTCHINS, T. WINOGRAD and M. STONE (2002), PointRight: experience with flexible input redirection in interactive workspaces. *Proceedings of UIST'02*, pp. 227 - 234.

JOHNSON, W., H. JELLINEK, J. LEIGH KLOTZ, R. RAO and S. K. CARD (1993), Bridging the paper and electronic worlds: the paper user interface. *Proceedings of CHI'93*, pp. 507 - 512.

JONES, W. P. and S. T. DUMAIS (1986), The spatial metaphor for user interfaces: experimental tests of reference by location versus name. ACM Trans. Inf. Syst., 1986. **4**(1): pp 42-63.

KARA BURAK, L. and F. T. STAHOVICH (2004), Hierarchical parsing and recognition of hand-sketched diagrams. *Proceedings of UIST'04*, pp. 13-22.

KHAN, F. (1993), A Survey of Note-Taking Practices, Tech Report HPL-93-107, Personal Systems Laboratory, HP Laboratory.

KIM, J., S. M. SEITZ and M. AGRAWALA (2004), Video-based document tracking: unifying your physical and electronic desktops. *Proceedings of UIST'04*, pp. 99-107.

KLEMMER, S. R., J. GRAHAM, G. J. WOLFF and J. A. LANDAY (2003), Books with voices: paper transcripts as a physical interface to oral histories. *Proceedings of CHI'03*, pp. 89-96.

KLEMMER, S. R., M. W. NEWMAN, R. FARRELL, M. BILEZIKJIAN and J. A. LANDAY (2001), The designers' outpost: a tangible interface for collaborative web site. *Proceedings of UIST'01*, pp. 1 - 10.

KOIKE, H., Y. SATO, Y. KOBAYASHI, H. TOBITA and M. KOBAYASHI (2000), Interactive textbook and interactive Venn diagram: natural and intuitive interfaces on augmented desk system. *Proceedings of CHI'00*, pp. 121 - 128.

KRISTOFFERSEN, S. and F. LJUNGBERG (1999), \“Making place\” to make IT work: empirical explorations of HCI for mobile CSCW. *Proceedings of ACM Group'99*, pp. 276-285.

KURTENBACH, G. (1993), The design and Evaluation of Marking Menus, PhD thesis, University of Toronto. 1993

KURTENBACH, G. and W. BUXTON (1991), Issues in combining marking and direct manipulation techniques. *Proceedings of UIST'91*, pp. 137 - 144.

KYUNG, K. and J. PARK (2007), Ubi-Pen: Development of a Compact Tactile Display Module and Its Application to a Haptic Stylus. *Proceedings of Eurohaptics'07*, pp. 109-114.

LEAPFROG (2005), Fly Pen, http://www.leapfrog.com.

LEE, C. J., H. P. DIETZ, D. LEIGH, S. W. YERAZUNIS and E. S. HUDSON (2004), Haptic pen: a tactile feedback stylus for touch screens. *Proceedings of UIST'04*, pp. 291-294.

LI, Y., K. HINCKLEY, Z. GUAN and J. A. LANDAY (2005), Experimental analysis of mode switching techniques in pen-based user interfaces. *Proceedings of CHI'05*, pp. 461-470.

LIAO, C., F. GUIMBRETIÈRE, R. ANDERSON, N. LINNELL, C. PRINCE and V. RAZMOV (2007), PaperCP: Exploring the integration of physical and digital affordances for active learning. *Proceedings of INTERACT'07*, pp. 15-28.

LIAO, C., F. GUIMBRETIÈRE and K. HINCKLEY (2005), PapierCraft: a command system for interactive paper. *Proceedings of UIST05*, pp. 241-244.

LIAO, C., F. GUIMBRETIÈRE, K. HINCKLEY and J. HOLLAN (2008), PapierCraft: A Gesture-Based Command System for Interactive Paper. ACM ToCHI, 2008. **14**(4): pp 1-27.

LIAO, C., F. GUIMBRETIÈRE and C. E. LOECKENHOFF (2006), Pentop feedback for paper-based interfaces. *Proceedings of UIST'06*, pp. 211-220.

LIGHTBLUEOPTICS (2005), Portable laser projector, http://www.lightblueoptics.com/.

LIVESCRIBE (2007), LiveScribe pen, http://www.livescribe.com.

LOWE, D. G. (2004), Distinctive image features from scale-invariant keypoints. International Journal of Computer Vision, 2004. **60**(2): pp 91-110.

LUFF, P., C. HEATH, M. NORRIE, B. SIGNER and P. HERDMAN (2004), Only Touching the Surface: Creating Affinities Between Digital Content and Paper. CSCW: ACM Conference on Computer-Supported Cooperative Work, 2004.

LUK, J., J. PASQUERO, S. LITTLE, K. MACLEAN, V. LEVESQUE and V. HAYWARD (2006), A role for haptics in mobile interaction: initial design using a handheld tactile display prototype. *Proceedings of CHI'06*, pp. 171-180.

MACKAY, W. and D. PAGANI (1994), Video mosaic: laying out time in a physical space. *Proceedings of MM'94*, pp. 165 - 172.

MACKAY, W. E., D. S. PAGANI, L. FABER, B. INWOOD, P. LAUNIAINEN, L. BRENTA and V. POUZOL (1995), Ariel: augmenting paper engineering drawings. *Proceedings of CHI'95*, pp. 421 - 422.

MACKAY, W. E., G. POTHIER, C. LETONDAL, K. BØEGH and H. E. SØRENSEN (2002), The missing link: augmenting biology laboratory notebooks. *Proceedings of UIST'02*, pp. 41 - 50.

MALONE, T. W. (1983), How do people organize their desks?: Implications for the design of office information systems. ACM Trans. Inf. Syst., 1983. **1**(1): pp 99-112.

MANDER, R., G. SALOMON and W. YIN YIN (1992), A 'pile' metaphor for supporting casual organization of information, in *CHI '92 Conference Proceedings. ACM Conference on Human Factors in Computing Systems. Striking a Balance*, Bauersbeld, P., J. Bennet and G. Lynch, Editor^Editors. 1992, ACM Press: New York, NY, USA. pp. 627-34.

MANSOURI-SAMANI, M. and M. SLOMAN (1997), GEM A Generalised Event Monitoring Language for Distributed Systems. IEE/IOP/BCS Distributed Systems Engineering Journal, 1997. **4**(25).

MARSHALL, C. C. (1997), Annotation: from paper books to the digital library. *Proceedings of DL'97*, pp. 131-140.

MCDONOUGH, W. and M. BRAUNGART (2002), *Cradle To Cradle*. 2002: North Point Press.

MICROSOFT (2003), OneNote, http://www.microsoft.com/onenote.

MICROSOFT (2005), Microsoft Windows XP Tablet PC Edition 2005 Recognizer Pack.

MILLER, R. C. and B. A. MYERS (1999), Synchronizing clipboards of multiple computers. *Proceedings of UIST'99*, pp. 65-66.

MILLER, T. and R. ZELEZNIK (1998), An insidious Haptic invasion: adding force feedback to the X desktop. *Proceedings of UIST 98*, pp. 59-64.

MORRIS, M. R., A. J. B. BRUSH and B. MEYERS (2007), Reading Revisited: Evaluating the Usability of Digital Display Surfaces for Active Reading Tasks. *Proceedings of IEEE Tabletop'07*, pp. 79-86.

MYERS, B., S. E. HUDSON and R. PAUSCH (2000), Past, Present, and Future of User Interface Software Tools. ACM Transactions on Computer-Human Interaction, 2000. **7**(1): pp 3–28.

MYERS, B. A. (2001), Using handhelds and PCs together. Commun. ACM, 2001. **44**(11): pp 34-41.

MYNATT, E. D. and G. WEBER (1994), Nonvisual presentation of graphical user interfaces: contrasting two approaches. *Proceedings of CHI'94*, pp. 166-172.

NAKAI, T., K. KISE and M. IWAMURA (2005), Camera-Based Document Image Retrieval as Voting for Partial Signatures of Projective Invariants. *Proceedings of International Conference on Document Analysis and Recognition*, pp. 379-383

NOKIA (2004), SU-1B Digital Pen. http://www.nokia.com.

NORRIE, M. C. and B. SIGNER (2003), Switching Over to Paper: A New Web Channel. *Proceedings of Web Information Systems Engineering'03*, pp. 209-218.

O'HARA, K. and A. SELLEN (1997), A comparison of reading paper and on-line documents. *Proceedings of CHI*, pp. 335 - 342.

OQO (2005), Model 01. http://www.oqo.com.

PIROLLI, P. and K. C. STUART (1995), Information Foraging in Information Access Environments. *Proceedings of CHI'95*, pp. 51-58.

POUPYREV, I. and S. MARUYAMA (2003), Tactile interfaces for small touch screens. *Proceedings of UIST'03*, pp. 217 - 220.

POUPYREV, I., S. MARUYAMA and J. REKIMOTO (2002), Ambient touch: designing tactile interfaces for handheld devices. *Proceedings of UIST'02*, pp. 51 - 60.

POUPYREV, I., M. OKABE and S. MARUYAMA (2004), Haptic feedback for pen computing: directions and strategies. *Proceedings of CHI'04 (extended abstracts)*, pp. 1309 - 1312.

PRICE, M. N., G. GOLOVCHINSKY and B. N. SCHILIT (1998), Linking by inking: trailblazing in a paper-like hypertext. *Proceedings of Conference on Hypertext and Hypermedia*, pp. 30 - 39.

RAMSTEIN, C., O. MARTIAL, A. DUFRESNE, M. CARIGNAN, P. CHASS and P. MABILLEAU (1996), Touching and hearing GUI's: design issues for the PC-Access system. *Proceedings of ASSETS'96*, pp. 2-9.

RAO, R., J. O. PEDERSEN, M. A. HEARST, J. D. MACKINLAY, S. K. CARD, L. MASINTER, P.-K. HALVORSEN and G. C. ROBERTSON (1995), Rich interaction in the digital library. Commun. ACM, 1995. **38**(4): pp 29-39.

RATTO, M., R. B. SHAPIRO, T. M. TRUONG and W. G. GRISWOLD (2003), The ActiveClass Project: Experiments in Encouraging Classroom Participation. *Proceedings of CSCL'03*, pp. 477-486.

RAZMOV, V. and R. ANDERSON (2006), Pedagogical techniques supported by the use of student devices in teaching software engineering. *Proceedings of SIGCSE'06*, pp. 344-348.

REKIMOTO, J. (1997), Pick-and-drop: a direct manipulation technique for multiple computer environments. *Proceedings of UIST'97*, pp. 31 - 39.

REKIMOTO, J. (1997), Pick-and-drop: a direct manipulation technique for multiple computer environments. *Proceedings of UIST '97*, pp. 31-9.

REKIMOTO, J. (1999), Time-machine computing: a time-centric approach for the information environment. *Proceedings of UIST'99*, pp. 45-54.

REKIMOTO, J. and M. SAITOH (1999), Augmented surfaces: a spatially continuous work space for hybrid computing environments. *Proceedings of CHI'99*, pp. 378 - 385.

ROHS, M. (2004), Real-world interaction with camera-phones. *Proceedings of UCS. IPSJ Press (2004)*.

SAUND, E., D. FLEET, D. LARNER and J. MAHONEY (2003), Perceptually-supported image editing of text and graphics. *Proceedings of UIST'03*, pp. 183-192.

SAUND, E. and E. LANK (2003), Stylus input and editing without prior selection of mode. *Proceedings of UIST'03*, pp. 213 - 216.

SAWHNEY, N. and C. SCHMANDT (2000), Nomadic radio: speech and audio interaction for contextual messaging in nomadic environments. ACM Transactions on Computer-Human Interaction, 2000. **7**(3): pp 353-383.

SCHILIT, B. N., G. GOLOVCHINSKY and M. N. PRICE (1998), Beyond paper: supporting active reading with free form digital ink annotations. *Proceedings of CHI'98*, pp. 249 - 256.

SELLEN, A. J. and R. H. R. HARPER (2001), *The Myth of the Paperless Office*. 1st ed. 2001: MIT press.

SELLEN, A. J. and R. H. R. HARPER (2003), *The Myth of the Paperless Office*. 1st ed. 2003: MIT Press.

SENSIVA (2005), http:// www.sensiva.com/.

SHEN, C., K. M. EVERITT and K. RYALL (2003), UbiTable: Impromptu Face-to-Face Collaboration on Horizontal Interactive Surfaces. *Proceedings of UbiComp'03*, pp. 281-288.

SIGNER, B. (2005), Fundamental Concepts for Interactive Paper and Cross-Media Information Spaces (ETH No. 16218), PhD thesis, Swiss Federal Institute of Technology, Zurich. 2005

SLAY, H., B. THOMAS and R. VERNIK (2005), A clipboard model for Ubiquitous Computing Environments. *Proceedings of Proceedings of the 4th international symposium on Information and communication technologies*, pp. 173-178.

SONG, H., F. GUIMBRETIÈRE, C. HU and H. LIPSON (2006), ModelCraft: capturing freehand annotations and edits on physical 3D models. *Proceedings of UIST'06*, pp. 13-22.

SONY (2006), Sony Operation Guid, PRS-500, Portable Reader System.

SOUSA, J. P. and D. GARLAN (2002), Aura: an Architectural Framework for User Mobility in Ubiquitous Computing Environments. *Proceedings of Proceedings of the IFIP 17th World Computer Congress - TC2 Stream / 3rd IEEE/IFIP Conference on Software Architecture: System Design, Development and Maintenance*, pp. 29-43.

STIFELMAN, L., B. ARONS and C. SCHMANDT (2001), The audio notebook: paper and pen interaction with structured speech. *Proceedings of CHI'01*, pp. 182 - 189.

SUN, L. and F. GUIMBRETIÈRE (2005), Flipper: a new method of digital document navigation. *Proceedings of CHI '05 extended abstracts*, pp. 2001-2004.

WASSON, G., P. SHETH, M. ALWAN, K. GRANATA, A. LEDOUX and C. HUANG (2003), User intent in a shared control framework for pedestrian mobility aids. *Proceedings of IEEE Intelligent Robots and Systems, 2003*, pp. 2962- 2967.

WEIBEL, N., A. ISPAS, B. SIGNER and M. C. NORRIE (2008), Paperproof: a paper-digital proof-editing system. *Proceedings of CHI '08* pp. 2349-2354.

WEISER, M. (1993), Some computer science issues in ubiquitous computing. Communications of the ACM, 1993. **36**(7): pp 74-84.

WELLNER, P. (1993), Interacting with paper on the DigitalDesk. Communications of the ACM, 1993. **36**(7): pp 87 - 96.

WHITTAKER, S. and C. SIDNER (1996), Email overload: exploring personal information management of email. *Proceedings of CHI'96*, pp. 276-283.

WILCOX, L. D., B. N. SCHILIT and N. SAWHNEY (1997), Dynomite: a dynamically organized ink and audio notebook. *Proceedings of CHI'97*, pp. 186-193.

WILKERSON, M., W. G. GRISWOLD and B. SIMON (2005), Ubiquitous presenter: increasing student access and control in a digital lecturing environment. *Proceedings of SIGCSE'05*, pp. 116-120.

WILLIAM POWERS (2007), Hamlet's Blackberry: Why Paper Is Eternal (http://www.hks.harvard.edu/presspol/research_publications/papers/discussion_papers/D39.pdf), in, Editor^Editors. p.

WILSON, A. D. (2005), PlayAnywhere: a compact interactive tabletop projection-vision system. *Proceedings of UIST'05*, pp. 83-92.

WIZCOM (1995), http://www.wizcomtech.com/.

WOBBROCK, J. O., A. D. WILSON and Y. LI (2007), Gestures without libraries, toolkits or training: a $1 recognizer for user interface prototypes, in *Proceedings of the 20th annual ACM symposium on User interface software and technology*, Editor^Editors. ACM: Newport, Rhode Island, USA. p.

YEH, R. B., C. LIAO, S. R. KLEMMER, F. GUIMBRETIÈRE, B. LEE, B. KAKARADOV, J. STAMBERGER and A. PAEPCKE (2006), ButterflyNet: A Mobile Capture and Access System for Field Biology Research. *Proceedings of CHI'06*, pp. 571-580.

YOUSAF, M. and M. LAZZOUNI (1995), Formulation of an invisible infrared printing ink. Dyes and Pigments, 1995. **27**(4): pp 297-303.

ZELEZNIK, R. and T. MILLER (2006), Fluid Inking : Augmenting the Medium of Free-Form Inking with Gestures. *Proceedings of Graphics Interface '06*, pp. 155-162.

ZHAO, S. and R. BALAKRISHNAN (2004), Simple vs. compound mark hierarchical marking menus. *Proceedings of UIST'04*, pp. 33-42.

ZHAO, S., P. DRAGICEVIC, M. CHIGNELL, R. BALAKRISHNAN and P. BAUDISCH (2007), Earpod: eyes-free menu selection using touch input and reactive audio feedback. *Proceedings of CHI'07*, pp. 1395-1404.