

A Comparison of Reading Paper and On-Line Documents

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ABSTRACT

We report on a laboratory study that compares reading from paper to reading on-line. Critical differences have to do with the major advantages paper offers in supporting annotation while reading, quick navigation, and flexibility of spatial layout. These, in turn, allow readers to deepen their understanding of the text, extract a sense of its structure, create a plan for writing, cross-refer to other documents, and interleave reading and writing. We discuss the design implications of these findings for the development of better reading technologies.

KEYWORDS

reading, paper, digital documents, hypertext, digital libraries, design, Web

INTRODUCTION

Jay Bolter, in his book "Writing Space" [2], heralded the computer as the fourth great document medium, next to the papyrus, the medieval codex, and the printed book. Implied in this is that the demise of the printed page is merely a matter of time. Certainly many of today's hot topics in human-computer interaction point to digital alternatives to paper documents: the Web, new hypertext applications, digital libraries, and digital document reading devices. Some have predicted that such advances will make books as we know them obsolete, will radically alter the relationship between authors and readers, and will change forever our concept of libraries as repositories of physical volumes of text, and of publishers as producers and sellers of paper books.

But the reality of day to day life shows that paper continues to be the preferred medium for much of our reading activity. This is despite the fact that screen technologies have vastly improved in recent years, that wireless, mobile computing technology is now widely available, and that new navigational and input techniques significantly improve the flexibility of our interaction with digital documents.

We describe a laboratory study aimed specifically at discovering how reading from paper compares to reading on-line documents so that we can design better on-line reading tools. This focus on design results in a study which differs

from typical laboratory comparisons of reading paper and on-line documents in three fundamental ways:

- We take a broadly descriptive approach rather than focusing on the measurement of one or two narrowly defined aspects of reading behaviour;
- We use an experimental task which we believe, based on our field studies of reading in organisations [23], is both naturalistic and representative of reading in real work settings;
- We ask subjects to comment on videotapes of their own behaviour to enrich our understanding of reading through the readers' perspective.

The Literature

A fairly substantial body of literature comparing the reading of paper versus on-line documents can be found in the psychological, human factors, and ergonomics literature (see [4, 10] for comprehensive reviews). The majority of studies focus on "outcome" measures of reading, such as speed [16, 25], proof-reading accuracy [3, 8, 25], and comprehension [6, 16]. A lesser effort has been devoted to looking at "process" differences between reading on paper and reading on screen such as how readers look at text in terms of eye movements [9], how they manipulate it [21], and how they navigate through it [5].

While some of these studies illustrate differences between paper-based reading and on-line reading they are generally either unremarkable or inconsistent. Even the reliable finding that reading from a screen is significantly slower than reading from paper [9, 16] has been challenged by recent experiments which demonstrate how improvements in screen technology lessen these differences, and may even eliminate them [17].

One reason sometimes cited for the failure to uncover significant differences between paper and on-line reading is the insensitivity of the measures used. For example, Dillon [4] has argued that this may account for the fact that the literature has generally suggested no negative effects of electronic text on comprehension. An important question this raises is: If the differences in performance between paper-based reading and on-line reading are that subtle, is it the case that even the reader fails to detect them, let alone the experimental method? Such a question is not so important for theoretical purposes, but is critical from a design perspective.

Perhaps a more fundamental problem with many of the studies has to do with the approach itself. After reviewing this literature, Dillon [4, p. 1322] remarked on the distorted view many researchers appeared to have of reading: "Most [ergonomists] seem to concern themselves with the control

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of so many variables that the resulting experimental task bears little resemblance to the activities most of us routinely perform as 'reading'."

Taken together, a review of the experimental literature suggests a need to establish a view of reading from the reader's own perspective as a more direct way of assessing perceived differences in paper and on-line conditions. Second, it suggests that, if our findings are to be extrapolated to real reading situations, one must be quite careful about designing the experimental method. It must involve a task which is representative of real world tasks and it must employ analytic methods which capture issues of relevance to design. One might argue that laboratory methods are simply inappropriate for these reasons. While there are many issues laboratory investigations of reading cannot address, we will demonstrate that there are nonetheless many lessons for design which can be produced systematically within such an approach.

METHOD

Choice of Experimental Task

Reading is a highly practised activity which forms a component of a wide range of different activities, and which serves many different purposes [13, 19, 20]. For example, text may be read by skimming it rapidly, scanning for a specific piece of information, reading it for comprehension, or reading it reflectively. Why a text is read, and the broader context within which the reading activity is embedded, shape these reading processes [20].

In choosing a task for the study, we wanted one that was both ecologically valid and required a comprehensive level of reading that would be rich in the demands made on the document presentation medium. We chose the task of text summarisation as fulfilling these criteria. Reading in order to write a summary is a task which requires a deep understanding of the text. Indeed, Winograd [24] has pointed out that some of the strategies used in summarisation may also relate to the more general process of text comprehension.

Also, because text summarisation involves reading in order to write, it has a strong connection with many of the kinds of reading tasks we have observed "knowledge workers" carrying out. For example, we found at the IMF that economists spend a great deal of their time reading and condensing information, whether it be from their own notes, or the notes and documents of other people. In more general terms, we found that, while editing documents on-line, 89% of the time they read and refer to other documents. Thus it seems that reading for the purpose of writing is a fundamental part of this kind of professional work. As such, this task seemed a good candidate for our purposes.

Choice of On-Line Condition

In choosing both the software and hardware for the on-line condition, we had at least two alternative approaches. We could attempt to optimise the configuration used in the on-line condition by choosing the "best" available software and hardware, or we could opt for a set-up which aimed to emulate a more conventional situation — a typical workstation running a commonly used word processing application. The former approach would be, in a sense, second-guessing what aspects of hardware and software best support reading, which is antithetical to our approach. We therefore chose the latter approach recognising that better

systems and better interfaces may significantly alter the reading process. Nonetheless such an approach gives us insights into the benefits and drawbacks in a typical on-line reading situation.

Procedure

Subjects were 10 volunteers from the research and administration staff of our laboratory. All used computers on a daily basis and were experienced with the application used in the study. The subjects were asked to summarise a 4 page article from a general science magazine. Five subjects were randomly assigned to the "Paper" condition, and 5 to the "On-line" condition. In the Paper condition, subjects were to read the document on paper and summarise it on paper; in the On-line condition, subjects were to read the document on-line and write the summary on-line.

The paper article was presented in three-column format and was black on a white background with some colour pictures. In the Paper condition, subjects were presented with 3 documents in a pile: the article to be summarised, some paper for note-making, and a blank sheet of paper on which the summary was to be written.

The On-line condition used a similar format for the article, and was run on an Apple Macintosh Quadra 950 with a ProNitron 80.19 colour screen 1152 pixels wide by 870 pixels high, and with a refresh rate of 75 Hz. Three open documents were displayed in Microsoft Word 6.0. The first was the article itself which was presented in page layout mode so that, although each page was scrollable, it visually resembled a single sheet of paper. On top of this was a blank word document (in Normal view mode) with the title "Notes" on the title bar. On top of this was another blank word document (in Normal view mode) with the title "Summary" on the title bar.

Subjects in both conditions were asked to create a 200-300 word summary of the source article, and were told it should provide a clear indication of the main points and ideas of the document. It was made clear that they could mark the article in any way they saw fit and that they could make as many notes as they wished. Subjects were told that they could refer back to the source article at any point during the task.

Each session was video recorded. On completion, the experimenter interviewed each subject extensively about the nature of their reading and support activities. In addition to these questions, each subject was shown, and asked to comment on and explain, various clips of their behaviour which the experimenter had noted as being interesting during the course of the task. The clips were used to cue subjects' recall as to what they were doing at these points and why.

SELECTED FINDINGS

Given the objectives of the study and the sample size, a quantitative analysis of the data was deemed inappropriate. Rather, the emphasis in the analysis was on describing subjects' strategies and activities with the aim of uncovering similarities and differences among subjects and across conditions. These descriptions were constructed by watching the tapes and transcribing subjects' comments during these key activities. Notes taken during the interviews were then used to enrich our understanding of the activities we observed. Only a selection of the findings are presented—those which we feel have the most important implications for design.

Annotation While Reading

Subjects' comments in both conditions indicated that annotating and note-taking while reading was important in deepening their comprehension of the text, and in helping them to form a plan for writing the summary. Essentially, it did this by drawing attention to important points and making explicit the structure between them.

Paper. The majority of subjects (4 of 5), during the first pass through the document, undertook some form of note-taking activity while reading. In general such markings were made quickly and interwoven with the ongoing reading.

Two subjects relied heavily on annotation of the source document itself. Their markings included underlining, the use of asterisks, and making notes in the margin. Marking was idiosyncratic both in the choice of marks and in the ways in which subtle style changes were used to different effect. For example, the thickness of a line was used to indicate the degree of importance of some piece of text for later reference, while asterisks were used to link disparate sections of text.

One reason for this kind of annotation was to provide a set of markings for later reference. In effect, such markings helped the subjects extract structure from the text on re-reading the article. One feature of such marks was that they relied heavily on the context of the original document, or as one subject put it:

"The first reading was quite slow and the second reading was skimming. The annotations helped me when I was skimming in the second reading...Whenever I finished writing about some point I skimmed forward - I looked for the next annotated bit and then I just read around it a little bit if I needed to remind myself of what they were trying to say."

Quite apart from the way these marks supported re-reading, at least one subject who marked up the source document suggested that the very act of making such marks is a process which aids understanding and facilitates the building of an internal representation of the text. This subject believed that *"as you underline something you re-read the words, and this enforces it more."* Previous research [1] offers confirmation of this finding.

Notes written separately were also used as a resource for later reference, and three of the subjects relied on this strategy. However, this was different from annotating the source document, in that it helped in re-structuring and collating information from diverse locations. As one subject put it, it provided *"a pool of text and ideas that I can dip into to write real sentences"*. But the notes were more than this, because they were also in the form of plans or outlines which were enriched and modified iteratively during the course of reading. A key feature of this kind of note-taking mentioned was that it needed to be done without disrupting the main reading task:

"The notes aren't in full sentences or anything, they are deliberately shortened so as not to interfere with reading and thinking and things, they are just jotting."

Indeed, a more general characteristic of this kind of note-taking on a separate piece of paper was its smooth integration with reading. Note-taking was both frequent and interleaved with reading the source document. Reasons why

this was possible are elaborated when we discuss navigation and spatial layout issues.

On-line. In the On-line condition, 4 of the subjects expressed that, had the document been on paper, their natural tendency would have been to annotate the document in some way or another. However only one of the subjects attempted to do this on-line, using a complex customisation of the tool bar to allow him to draw boxes around relevant sections of text or to draw a line down the side of the text. In doing so, this subject experienced a number of difficulties which interfered with the smooth flow of reading:

"So the annotation was not as easy as all that... I think the whole process would have been a lot quicker on paper. Annotations are that much more flexible because you can write in the margins which you can't very easily do here. You have to establish a new text block and then have to write."

This comment emphasises the difficulty of making marks within the context of the article due to the inflexibility of interaction techniques via mouse and keyboard.

Another reason for the general reluctance to annotate the document was that annotating on-line results in making changes to the original document: boldening, italicising or underlining all alter the original document. Subjects indicated that they wanted to regard annotations as a separate layer of the document, and felt uncomfortable not maintaining this distinction. But it was not just the fact that the methods interfered with the base document. They also expressed dissatisfaction at the fact that they could not easily make annotations that were perceptually distinct from the underlying text. This distinctiveness is, in part, what supports quick re-reading by drawing attention to points of interest.

It seems, then, that note-taking separate from the source document was more appropriate with these on-line tools. Four subjects did do this. Two of them took notes using the copy and paste function to transfer information from the source text directly into a separate document. For one of these subjects this was fundamentally different from the note-taking activity observed in the Paper condition in that the transfer of verbatim information was followed by extensive editing on the copied text. This text then became the basis of the final written summary. The other two subjects took most of their notes only after reading the whole source document, producing a plan almost entirely from memory with very little reference back to the source document. In all cases, none of the frequent back and forth movement between notes and reading was observed as in the Paper condition.

Summary. To summarise, we found that the ability to annotate while reading was important in enforcing an understanding of the source document, and helped in planning for writing. Three major differences between conditions were noted:

- (1) Annotation on paper was relatively effortless and smoothly integrated with reading compared to on-line annotation which was cumbersome and detracted from the reading task.
- (2) Paper supported annotation of the source document itself which many subjects felt was important. The On-line condition did not provide enough flexibility to do this, nor did it support the richness and variation of annotations on paper. In addition, subjects were

reluctant to tamper with the original text and wanted their marks perceptually distinct from the original document.

- (3) Subjects in both conditions also took notes on separate documents. Note-taking in the Paper condition was frequent and was interleaved with reading. In the On-line condition, reading was interspersed with long periods of editing, or note-taking was done after reading with little reference back to the source document.

Movement Within and Between Documents

Subjects spent a good deal of time moving through their documents in both conditions. It emerged from the interviews that this served at least three important functions:

Planning. Subjects talked about the need to make connections between different parts of a document to create a plan and develop an overall sense of its structure [cf. 10]—a process supported by skim reading though the text.

"Here you seem to flick through some pages." (Exp.)

"I get the 1st and 2nd pages and then look at the third...[I'm] trying to connect bits of information to write on my plan - areas that I want included in the same paragraph - or topics I want included in my paragraph." (Subject, Paper condition)

For Reference. Subjects were also seen scanning the source article to check on facts, particular expressions, and spellings:

"I was looking for the 'dragon's blood tree'. I was trying to find that name...I couldn't remember exactly what they called it." (Subject, On-line condition)

For Checking Understanding. There were several times when subjects needed to re-read sections of the document to confirm or clarify their understanding:

"You refer back to it after reading something up here." (Exp.)

"Yes it was because of the name of the tree - Cinnabar. And I needed to know if it was the same tree as they talked about over here." (Subject, Paper condition)

Paper. Movement through paper documents was characterised by its speed and automaticity. For example, page turning in the Paper condition was often anticipatory, with one hand often lifting a page even before it was read, minimising disruption between reading the text at the end of one page and the beginning of another. That it was so automatic is highlighted by the fact that sometimes pages were turned prematurely

Partly what speeded this movement through paper was the use of two hands in combination with the tangibility afforded by the paper, enabling the effective interleaving and overlapping of activities. For example, subjects used one hand to keep hold of a page while searching through the document, or referring to another page, with the other. By marking one's place with one hand, subjects could quickly return to their prior activity. Two handed manipulation also offered opportunities for other types of interactions such as writing while moving a page closer to read, or turning over a page with one hand while the other was used to feel how many pages were left. The quick flicking through pages when searching and skimming was also quite clearly a two-handed action using one hand as an anchor for the actions of the other. Aside from issues of speed, physical cues such as

thickness provided important implicit information about where in the document a subject was, as well as its overall length.

A final feature of paper that showed itself to be important in navigation was the fixity of information with respect to the physical page. Consistent with previous research [10, 14, 22], subjects in the Paper condition showed that they had acquired incidental knowledge of the location of information by reference to its physical place on the page:

"I knew it was on the 3rd page 'cause I could remember that it was in the middle [column] 'cause it was this botanic bit so I knew it was on this page."

This incidental memory meant that subjects could flick through the document quickly using only surface visual features.

On-line. In the On-line condition, whether scrolling or paging through the document, navigation was found to be irritatingly slow and distracting — the rendering of the pictures exacerbating the problem:

"I was getting very annoyed and clicking on those things and shouting at it...I just found that it took ages and ages. I was losing interest. It was distracting me from the point."

However, the sheer length of response time was only one drawback. Another feature which limited quick movement was the fact that one handed input meant that navigation activities had to be performed serially with other activities. Combining a single source of input with a significant system response time meant that interleaving any two activities was cumbersome, as well as making it impossible to perform anything concurrently.

All of this was made worse by the lack of feedback in response to many actions which meant that subjects were not supported in temporarily committing to various actions. For example, one subject tried to get to a particular location in the document using the drag function on the scroll bar, but the document contents did not move concurrently in response to the dragging. As a result, the subject had to release the page icon and then wait to find out if she was in the right place. This kind of scrolling can make finding exact locations extremely time-consuming.

Spatial constraints on the interface also interfered with quick, flexible movement. For example, in order to move an electronic window, subjects were required to access the title bar which was often obscured by another window. Similar problems were encountered by subjects attempting to resize windows or scroll — actions which were also restricted to limited active areas. The overall result of this was that subjects' attention was drawn away from reading, as they attended to the often complicated task of dealing with the mechanics of moving in these spatially constrained ways.

Unlike with the paper documents, assessing document length was difficult to do in any incidental or implicit way. For many of the reasons just discussed, subjects complained about having to scroll through to assess a document's length. Further, while information about document length and page number was available at the bottom of the active document, none of the subjects remembered using this information when asked.

Finally, whilst subjects in the Paper condition used the fixity of information with respect to the physical page to support search, it was an interesting question whether the

use of Page Layout mode was used in the On-line condition for similar purposes. This mode fixes the contents of the document with respect to its electronic page. When asked, subjects said that the fact that it was difficult to view a whole page meant that they had little sense of the location of information with respect to its page. However, comments by subjects in both conditions suggested that some did use the fixed relationship between pictures and text to support navigation.

Summary. Movement through documents in both conditions was found to be important for information organisation, for reference, and for checking understanding. However, there were four ways in which this movement differed:

- (1) Navigation through paper was quick, automatic, and interwoven with reading. In the On-line condition it was slow, laborious, and detracted from reading.
- (2) Two handed movement through paper allowed readers to interleave and overlap navigation with other activities, and allowed temporary commitment to interim activities. Movement through the on-line documents required breaking away from ongoing activity and committing to navigation activities because it was: one-handed, not always accompanied by immediate feedback, and spatially constrained to active areas on the screen.
- (3) Subjects reading from paper used its tactile qualities to support navigation and to implicitly assess document length. Subjects in the On-line condition failed to make use of explicit cues such as page length to assess document length.
- (4) The fixity of information with respect to physical paper pages supported incidental memory for where things were, which in turn supported search and re-reading activities. The inability to see a complete page may undermine use of this feature on-line, but it appears pictures were used as anchor points.

Spatial Layout

Finally, we consider differences in the way subjects in both conditions laid out their documents in space. The reasons why the spatial arrangement was important can be summarised as follows:

To Gain a Sense of Overall Structure. Subjects talked of the need to lay pages out in order to form a mental picture or overview of the document:

"I did put it into two page mode at one point just to get a sense of the how the article was structured and that was actually very helpful." (Subject, On-line cond.)

To Cross Reference. They also commented on the need to lay pages close to each other in order to check on or to relate specific pieces of information across pages.

"When I was referring back to it I didn't like the paper clip being on it...I could lay out the pages and have two pages at once or even so that I could lay them out like that...so that I could find whatever bit I was looking for and also so that I could join things together." (Subject, Paper cond.)

To Interleave Reading and Writing. Juxtaposing the article to be read with the document being written also appeared to be important in the writing process:

"I always [overlap the source document with the plan/summary page] so that you can see it and write it at the same time so you are not looking here and then writing over there You have them together and you just write from one to the other don't you..." (Subject, Paper cond.)

Paper. The ability to unclip the documents in this experiment meant it was possible to lay out individual pages in space. All 5 subjects exploited this fact. Visualising more than one page in order to see its structure was one reason for this. In addition, pages were often arranged such that they were within easy reach for quick reference:

"You have got p1 and next to it p2 and then you have got your notes. Any reason for that?" (Exp.)

"It will be there in case I need to refer back to it but also to the side so that I am concentrating on p2." (Subject)

Spatial arrangement was also dynamic. Pages would be moved in and out of the centre of attention as different parts of the document became more or less important. Hidden pages would be brought to the front, while others would be covered up or if needed for quick reference later, moved to a more peripheral region of the workspace.

The ability to quickly refer to other documents while writing was also important. Most subjects made constant shifts back and forth between reading the source document and writing during planning. The source document and the plan/summary document would be positioned close together, often overlapping, during the planning phase of writing so that sections of the source text could be close what was currently being written.

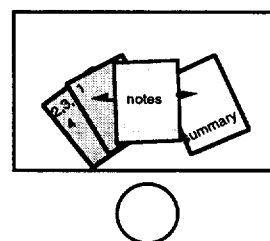


Figure 1. An example of document placement layout during the planning phase of writing (pages 1-4 being the source article).

One example of how documents were arranged during this planning stage is shown in Figure 1. The subject, when writing the summary, needed to refer to three documents at once — the source document, the notes, and the summary itself. By positioning and overlapping the documents this way, it was possible to make the desired information available in a compact space. At one point the notes were moved several times within the space of seconds as the need to refer to the source document several times in quick succession was demanded by the creation of a single sentence. This points to the need to be able to access other documents quite quickly so that reading can be effectively integrated with the process of writing.

Another important characteristic of the interplay of reading and writing was the way in which the paper could be quickly and even simultaneously accessed while reading and referring to other documents. Aside from its concurrent accessibility, another feature of separate reading and writing

"spaces" is it allows independent manipulation. This is important when one considers that the optimal angles for reading and writing may be quite different from one another. Subjects placed the paper at a greater angle away from the perpendicular (approx. 30 - 45 degrees) while writing than while reading (0-20 degrees). Additionally, the ergonomics for writing with a pen required continuous minor adjustments to the paper over time, using one hand as an anchor.

On-line. The most obvious constraint on spatial layout is the restricted field of view offered by the screen. Subjects did make use of multiple page view mode, however, even when only two pages were displayed, the resolution was essentially unreadable. At readable resolution, subjects could never see even one whole page at a time. Subjects expressed a great deal of concern over this trade-off, and talked of feeling lost in that much of the necessary contextual information for developing a sense of text and location [cf. 10] lay beyond the window boundaries.

By resizing and overlapping windows, however, subjects were able to do some cross-referencing of documents. But again, limitations on the space available and the lack of flexibility in the ways they could be laid out caused problems for quick access across documents. For example, there were occasions when subjects wanted to use all 3 documents for various parts of the task but this called for very small window sizes or obscured windows. While Page view allowed the display of multiple pages, it displayed them in a fixed order.

The lack of any real periphery also meant that subjects had to give some thought to selecting and displaying documents. Generally speaking the task was divided into discrete phases: first pass, note-taking, and summary writing. Window positioning and sizing tended to occur at the boundary between these different phases and not during the phases. Thus subjects were having to anticipate what they would need rather than reacting to the requirements of the task as they arose.

A commonly used arrangement, especially in the note-taking or writing phase, was placing two documents side by side with minimal overlap. This avoided problems with the currently active window being sent to the foreground which was not only time-consuming, but was sometimes undesired, such as in the case of this subject trying to alternate between taking notes in one document and navigating in another:

"It was annoying that its got to be the current window in order to be able to move, and the current window is always the one in front. So I can't hide the one I was typing into behind there and simply move the pointer into it and start typing or pasting or whatever."

This foreground/background distinction constrained the extent to which a page was accessible for writing concurrently with reading — something which was clearly important for these subjects.

Summary. Laying out pages in space was found to be important for gaining an overall sense of the structure of a document, for referring to other documents, and for integrating reading with writing. There were three main differences in the two conditions:

- (1) Laying out paper in space allowed the visualisation of a great deal of information, and provided a holding space for quick reference to other documents. The

restrictions on field of view for on-line documents meant that subjects either lost resolution through shrinking the documents, or had to use overlapping windows.

- (2) The layout of paper documents was flexible and dynamic, providing quick access for cross-referencing, and supporting the juxtaposition of documents for reading and writing. In the On-line condition, subjects had to plan in advance how to position and size the windows in anticipation of their future requirements.
- (3) Paper supported the use of independent reading and writing spaces which could be accessed concurrently and manipulated independently. Because only one window could accept input at a time, subjects in the on-line condition experienced difficulties integrating reading and writing.

DISCUSSION AND DESIGN IMPLICATIONS

On-line tools clearly offer valuable benefits for the writing process: They support fast keyboard entry, information re-use, easy modifiability of text, and provide specialised tools such as spell-checkers and word count facilities. But in the support of reading, and more specifically in support of reading *for the purpose of* writing, this study has shown that the benefits of paper far outweigh those of on-line tools. Further, unlike much of the existing literature comparing paper to screen, none of these benefits have to do with issues of screen resolution, contrast or viewing angle. Rather, the critical differences have to do with the major advantages that paper offers in supporting annotation while reading, quick navigation, and flexibility of spatial layout. These, in turn, allow readers to deepen their understanding of the text, extract a sense of its structure, plan for writing, cross-refer to other documents, and interleave reading and writing.

In terms of design, one could make the decision not to attempt to supplant paper for reading but rather to develop scanning technologies to ease the transition of paper-based information into the digital realm for the purpose of writing. Many such technologies developed in our own laboratory [18] as well as others [e.g., 12] could well be applied in this way. This approach accepts that paper is, and is likely to remain, the best medium in support of reading.

But one could also choose to look to paper for improving the design of digital reading technologies, both in terms of the development of better hardware and software. This is not to say that such technologies must become more "paper-like" or support reading in the same way as paper. Rather, the use of paper can be used to help draw attention to the kinds of processes that are important to support within reading, and to suggest alternative ways in which that support could be offered. On the basis of the findings of this experiment, some examples are as follows:

Recognise that annotation can be an integral part of reading and build support for these processes. For many reasons which this experiment has pointed out, on-line tools simply did not support the seamless integration of note-taking while reading. Whether annotating the source document itself, or annotating within a separate document, the process was effortful and distracting.

Part of the problem is the lack of support for free text annotation. Not only does stylus input support variegated, idiosyncratic marks, but it also supports the making of marks in context, and as a distinct layer on top of typed

text. It is clear that, for this purpose, OCR is unnecessary, since it is not so important that these notes be used verbatim for writing as it is that they support the process of helping to extract structure from a document and to speed re-reading. For this purpose, it is more important to concentrate on input techniques which maximise richness and variation in marking, such as the use of pressure-sensitivity to vary line thickness, and the use of texture and colour. Careful consideration will then need to be given to how the input technology and display device interact. For example, if emulating direct pen input onto the document through a touch-sensitive screen, then the screen will need to be quite mobile to be placed at the correct ergonomic angle for writing.

This experiment has also found that there is a clear need for markings to be functionally distinct from the "base" document so that changes to the underlying text are not actually implemented unless the reader explicitly allows it. The use of hand-written markings is a way of enforcing the idea of markings as a layer on top of a document. However, digital technologies can offer interesting advantages over paper by allowing readers to choose whether the annotations are to be permanent or temporary, by offering selective viewing capabilities according to who wrote the marks or when, or by allowing marks to actually effect changes in the underlying text if desired. Many such features can be found in a prototype collaborative writing system called "MATE" [11]. While there are systems such as TkMan which offer the ability to highlight text, and while there are features such as "Revisions" in Microsoft Word that support collaborative authoring, commercial systems tend to offer limited support for annotation during reading, or for the purpose of re-reading.

The need to support quicker, more effortless navigation techniques. Improvements in system response times clearly will benefit on-line navigation, but a range of other issues need to be addressed if it is to be quick and non-disruptive to ongoing reading activities. Improved input techniques could have significant impact here. Multiple input, or at least two-handed input could support a whole range of new navigation techniques, such as using one hand to mark one's place in a document while scrolling or page turning with the other. This would also allow for the support of concurrent activities like writing on one document while navigating in another.

Multiple input raises another design possibility which is that kind of input can depend on the device used. For example, drawing directly from the paper case, direct input through touch could correspond to navigation activities whereas stylus input could produce markings.

Another major design issue that the findings help make clear is the need for better feedback to aid navigation. Not only does it need to be immediate, but, if it is to support quick interim actions, it needs to be continuous during the course of an action, and not simply delivered on its completion (e.g., releasing the mouse button after dragging). Further, other modes of feedback such as audio or even tactile feedback could provide more implicit cues as to where in a document one is, and how much information there is. For example, one could imagine using non-speech audio cues [7] to indicate the thickness of a document, or number of pages left. This feedback could be provided in the natural course of navigation so that the cues are picked up incidentally. This is not to say that visual cues have already been exploited as much as they could be. The use of

perspective and stereoscopic displays may offer a "third" dimension to better represent features such as document thickness, for example.

Of additional consideration for the support of navigation is heavier reliance on a mode which fixes information with respect to a page. However, this study suggests that this will only be of benefit provided a whole page can be viewed at once (and indeed previous research suggests that even that may not be enough [10]). Designers might also consider emphasising endemic reference points such as page corners and edges for use in information search.

The need to support more flexibility and control in spatial layout. With regard to the issue of spatial layout, the study points out many benefits of a larger screen size. Improvements in display technology will mean cheaper and larger display areas with increased resolution. This will improve readers' ability to gain quick access to other documents, which was shown to be crucial to this kind of reading task. However, even a large screen is not sufficient to offer the reader the same level of flexibility as paper in terms of document positioning or the number of documents displayed.

One approach is to create virtual space whereby the visible screen space forms only a part of the workspace available, such as in *fvwm* in UNIX, and in Hypercard. In these applications, documents can be moved around this larger, virtual workspace through a separate, miniaturised overview. This offers an advantage over paper in that it can potentially help to manage extremely large workspaces not practically possible in the paper domain. However, it is fundamentally different in that, in the paper case, what is at the focus of attention and what is at the periphery exists in a spatial continuum. In these electronic cases, peripheral documents and documents at the focus of attention exist in separate virtual spaces. Thus, drawing a new document into focus, or setting them aside, requires a shift of attention to a different representational space, and the dynamics of this will necessarily take more time and effort.

The spontaneous dynamics of spatial layout may also be facilitated by improvements in interaction techniques. For example, designers could consider doing away with the idea of constraining document movement to "active" areas such as title bars. There are various window managers in current systems that allow the whole document to be made "active" (e.g. Motif Window Manager in UNIX). However, this is done by requiring users to enter a navigation mode. Consistent with a previous suggestion, the need for these temporal modes might be handled by the use of multiple, specialist input devices such as hand versus stylus.

Another implication which arises from the experiment is the need for increased flexibility in the way that readers can arrange on-line documents in the space available. This ranges from simple suggestions like removing constraints on readers' ability to lay any two pages side-by-side, to the possibility of placing documents and pages at angles to each other. Allowing readers to make virtual "piles" is also an interesting idea, and one that interface designers have tried elsewhere [15].

An alternative approach to increasing the flexibility of spatial layout is to treat portable, wireless displays as a way of providing a physical embodiment for documents. As with paper, documents can be placed by moving the display itself, rather than moving documents within a display. However, unless one has many of such displays, this

approach does not address the requirement of providing concurrent access to multiple documents or pages. However, the experiment has pointed to the effectiveness of independent reading and writing spaces in the paper domain. Thus, two such displays—one for reading and one for writing—might deliver valuable benefits.

CONCLUSIONS

Using a broadly descriptive approach, we have carried out a laboratory study which draws attention to a number of important implications for the design of better interfaces for reading digital documents. Not only was this study motivated by our own field studies of reading in real work settings, but the design of the experiment was grounded in and guided by these observations. In turn, the findings help us to understand much of what we observed in the reading practices of these organisations. For example, it gives us a better understanding of why economists at the IMF always mark up and review their colleagues documents on paper, why they choose to read important documents from paper, and why paper documents surround their workstations as they do their authoring work [23].

What we hope to have demonstrated is the value of contrasting paper-based and on-line reading specifically with an eye to design. By doing so, we can begin to unravel the complexity of the design challenge, and begin to make some better informed predictions about when and if we can ever expect a paperless future.

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