University of Glasgow
Department of Computing Science
Lilybank Gardens
Glasgow G12 8QQ

University of St. Andrews
Department of Computational Science
North Haugh
St Andrews KY16 9SS

Factors That Affect Reading and Writing with Personal Computers and Workstations

Wilfred J. Hansen and Christina Haas

Persistent Programming
Research Report 41
June 1987

Alan Dearle.

Factors That Affect Reading and Writing with Personal Computers and Workstations

Wilfred J. Hansen
Computing Science Deptartment
University of Glasgow
and
Information Technology Center
Carnegie-Mellon University

Christina Haas
Information Technology Center
and Department of English
Carnegie-Mellon University

March, 1986

Abstract: To study the factors that affect reading and writing with computers we have conducted a series of experiments comparing behavior using paper, personal computer, and advanced workstation. Subjects were given tasks of recall, reordering scrambled lines, proofreading, and writing a letter. For reading tasks, subjects seemed to perform about the same on both paper and the workstation, which featured a large screen bit-mapped display; but they performed more slowly on the personal computer, which had a small, single-font display. For writing, subjects did more and better work with workstations than with either paper or the personal computer. As we examined our results, it seemed that a number of factors explained the observed differences in behavior. To describe them we have distinguished five primary factors: Page Size, Legibility, Responsiveness, Interaction Design, and Graphic Imagery. These then induce in users three secondary factors: Directness, Fascination, and Sense of Text. Our results are presented as illustrations of these factors.

1. Introduction

The fundamental questions of user interface design are *Does the user interface make a difference?* and, if so, *How?* In this paper we demonstrate that system characteristics, including user interface design, can make a difference in user performance; in our experiments, users did better work on the workstations with large screens and graphical, mouse-driven user interfaces. To approach the second question we speculate on some factors that may account for the differences; we have called the primary factors Page Size, Legibility, Responsiveness, Interaction Design, and Graphic Imagery. If these or other factors are carefully identified, experiments on each separately may eventually make possible answers to the practical question of interface design, "How can we avoid trial and error in designing interactive systems?" However, we do not try to answer this latter question below.

The opportunity to study these questions arose with the development of the Andrew system [Morris, 1986]. It was our hope and that of other system designers that a better system could be deployed if we paid careful attention to the user interface, including the conduct of controlled experiments to explore alternatives. At the same time, one of the co-authors was exploring paper versus computer as a medium for reading and writing These experiments seemed an ideal vehicle for exploring the emerging user interface for the Andrew text editor, EditText. The full details of each of the experiments have been reported elsewhere [Haas and Hayes, 1985, 1985b, 1986; Haas, 1986]. They cover both reading tasks and writing tasks; complex cognitive skills that are an intrinsic part of many tasks performed in educational and business settings.

As a study of reading and writing, these experiments were designed to pursue two further questions. The first of these, *Is using a computer to read and write different than using paper?* was suggested by prior research and by conflicting reports from users that reading and writing with computers is incredibly difficult and not worth the effort, or that it is cost-effective, faster, and easier [Haas and Hayes, 1986]. Our own experience has been that, at least for writing, computers have increased our productivity and our motivation and made writing seem less of a "chore."

However, the machine we use for our daily reading and writing tasks is not a typical personal computer; it is a high-resolution, high-speed workstation with software under development at Carnegie-Mellon University. Thus we ask our second question: *Is using a more advanced* *workstation for reading and writing different than using a typical personal computer?*

Several studies of similar issues have been reported in the literature. Muter, et al. [1982] studied reading from TV screens, which have a low quality image. They found that comprehension was comparable to that of paper, but reading speeds were more than 25% slower from the TV. Wright and Lickorish [1983] compared paper with personal computers and found that paper was faster. Gould and Grischkowsky [1984] studied subjects performing an eight hour proof reading task. They found that work was more rapid on paper, with slightly higher quality than on personal computers. In a summary of this and other work, Gould [1986] concluded that image quality—we call it Legibility—is the principal factor in the advantage of paper over computers. This quality is not indivisible; it is composed of numerous items like resolution, contrast, type design, page layout, and spacing.

Other studies have considered writing tasks. Gould [1981] found that expert writers using personal computers required 50% more time to compose than on paper, while producing results of no greater quality. Hansen, Doring, and Whitlock [1978] showed that students took considerably longer to answer an examination on-line rather than on paper, though a large portion of the difference could be attributed to poor design of the interactive interface.

Each of our experiments used a different combination of hardware and software conditions, but each included a control condition using paper. In this way we explored our question about whether using a computer to read and write differs from using paper. To explore our question of whether there are differences in behavior with different computers, we examined a variety of computer conditions: two on personal computers and two on workstations. We use the term *personal computer* to refer to systems typified by the IBM PC; especially one with a "green-screen" monochrome adapter. The term *workstation* refers to the more recent advanced systems typified by the IBM RT/PC, with mouse and large-screen, black-on-white display.

The personal computer was used as both a terminal and a local computer. As a terminal, it ran Emacs [Stallman, 1981] on a mainframe computer (TOPS-20), connected at 4800 baud. As a local computer, subjects had a choice of two editors—Mince and Epsilon—both similar to Emacs. In the discussions below we will contrast these editors with the Personal Editor [Wylie, 1982], a system which was not used in the experiments because our subjects were unfamiliar with it. The two workstation conditions utilized EditText on Andrew, one with a large screen window and the other with a small window. See Figure 1 for examples of both screen layouts.

Figure 1. Andrew screen images. (a) With small window. (b) With large window.

We can summarize the results of our experiments by noting that subjects' reading performance with paper was slightly better than with workstations, but both were considerably better than with personal computers. For writing, the quality of the work produced was highest with the workstation and lowest with the personal computer, with paper in between.

2. Factors

Many factors may account for the fact that users do not perform with the same speed and quality in reading and writing with a computer as they do on paper. In this section we describe eight clusters of factors—five primary and three secondary—which we believe serve together to explain our results. Several caveats are in order: These factors are not original discoveries; most have been at least mentioned elsewhere. They are not the outcome of a factor analysis or other statistical process, but are empirically derived. Moreover, it is unlikely that these factors were the only ones affecting our subjects. Despite these limitations, we present these factors as a convenient framework to organize discussion of the multitude of influences at work.

The five primary factors are Page Size, Legibility, Responsiveness, Interaction Design, and Graphic Imagery. All are directly observable attributes of hardware and software design each of which can be individually varied to alter subjects' performance. Rather than single numeric parameters, all but the first factor are clusters of related parameters. These groupings seem appropriate, however, because each is a distinct dimension suitable for further research. For each factor the following sections define it, explain why it might be expected to affect performance, and detail the variations employed in the experiments.

A. Page Size measures the amount of text visible at one time. It can affect reading and review tasks by limiting the context that can be mentally associated with the current text. It can affect writing by preventing referral to recently written text; one common result is repetition. If the Page Size is small, the user will also have to perform more scrolling operations to view the entire text. In addition to the time for the operation itself each scroll movement can slow the reader by interfering with concentration. For example, one study estimated that there was a three second pause for a subject to reestablish contact with the work when the screen was repainted [Hansen, 1978].

In our experiments the Page Size for the small window condition was chosen to be about the size of the PC screen, with room for between a half and a third the contents of a sheet of paper. The small window was 5 1/2 inches high and 8 inches wide and held 22 lines of text. The full screen of a workstation typically has enough room for as many words as two paper pages. This can be used to display two pages of a manuscript, but is often exploited for writing by displaying one page of the manuscript and several partial pages of supporting material. In the large window conditions on workstations, our experiments displayed about one full page of text, leaving the rest of the display grey. The window was about 10 inches square and held 46 lines of about 80 characters each.

B. Legibility is the ease with which letters and words can be correctly recognized. Many characteristics of a text image contribute to greater legibility: size of character, spacing between characters and lines, font design, contrast, brightness, color and background color, resolution in pixels per inch, edge sharpness of pixels, anti-aliasing, page layout, heading styles, and more. Legibility is an important factor in the speed at which text can be read, as discovered by J. Gould [1986]. He devoted many experiments to the above characteristics of computer displays hoping to find one which explained slower rates of reading with computers. After considerable effort, he concluded that it was not one characteristic, but the resulting overall "quality" of the text that made the difference. It is this quality we have called Legibility.

Text printed on paper is typically of higher legibility than computers, and was so for our experiments. The workstation conditions offered higher quality text than the personal computers, even though resolution was about the same on both. The workstation offered a black-on-white image, proportionally spaced and seriffed fonts, and headings in boldface, larger type, or both. Resolution was 72 pixels to the inch, with a typical twelve point font having characters in a maximum box of 13×15 pixels and a "X" sized at 10×10 pixels. Characters on the personal computer are displayed in a box of 8×14 pixels, with the "X" occupying a 7×9 subrectangle. Resolution is 70 pixels per inch vertically and 80 horizontally.

C. Responsiveness measures the speed of system response to a user's action and has two components: the speed with which the system begins to respond to a user's action and the speed with which it completes that response. These speeds can vary through a wide range. The response to typing a text key is usually the instantaneous display of the character.

The response to a scroll operation begins immediately, but may take one or more seconds to complete. The response to a Print command may take minutes as the document is formatted for the printer.

In analyzing the impact of Responsiveness to a user action, we must consider the state of "completion" the user attains with the action. *Completion* is a measure of the degree to which the user feels finished with a phase of an operation. A text key is likely to have a low degree of completion because the user is thinking about further text. An operation to print a document has a much higher degree of completion because the user has committed the work to paper and has presumably completed the current phase of creative work. Scrolling operations generally have a quite low degree of completion because the user is anticipating new information and must remain in a state of suspension until it appears. Poor Responsiveness when the user has a low degree of completion can be frustrating and can induce errors.

A highly Responsive system can improve the users performance beyond the mere saving in time. Rapid response to requests reinforces the user's confidence in his or her ability to understand the system and control it. There is then less mental concentration on the commands and more on the work at hand. This contrasts with a less Responsive system which slows the user in two ways: first, by simply requiring more waiting from the user, and second by causing the user to pay more attention to the mechanics of the work and less to the actual work itself.

The Responsiveness of paper is excellent for scrolling, though rather poor for constructing individual characters. That of a personal computer for local editing is generally good, depending on the editor in use. As a terminal, a personal computer is no better than the host system and is limited by the speed of the communication line. At 4800 baud, the repaint time for a screen-full is four seconds. In contrast, the workstations using Andrew required less than a second to repaint even the large window.

The most Responsive editor we know of is the Personal Editor for the IBM PC. It repaints the entire screen faster than the function keys can be pressed to scroll pages. Indeed, the Responsiveness of the Personal Editor is so high that it was chosen as the tool for drafting this paper. Unfortunately, the Page Size is small so hard copy was essential in making revisions.

D. Interaction Design is the choice of how each system action is requested by a sequence of one or more user actions: key press, mouse movement, or mouse button. If a design is well done, users will be able to learn it, remember it, and use it effectively and efficiently. Some of the components of good Interaction Design seem to be consistency of behavior, mnemonic commands or other memory aids, fewer keystrokes for the more common operations, and careful choice in the tradeoff between having many commands with few operands or few commands with many operands. The first decision in designing the interactions of a system is whether to have a mouse or not (or whether to use it if it is there). Experience has shown that very different forms of design arise with and without a mouse. The difference is so remarkable that the Interaction Design parameter can be quantified at a crude level just by stating whether or not a mouse is used.

Without a mouse, editors are either *moded* or *modeless*. In the former, text can only be entered in the document when the editor is in an "insert" mode; at other times key presses cause commands to be performed. With a modeless editor text keys are always inserted at the cursor position; to issue commands the control-shift key must be held down while a text key is typed. With a mouse this dichotomy is not necessary; or rather, a modeless editor is much easier to design. The mouse is used to position the cursor, give scroll commands through the scrollbar, and give other commands through a menu.

Poor Interaction Design can reduce user performance in a number of ways. If the number of user actions needed for common operations is higher than that of less common operations the user will be slowed unnecessarily; the user action sequences could be reassigned so the user would need fewer total actions to complete a task. If commands are sufficiently inconsistent or immemorable that users make errors, time will be wasted correcting them. And more delay can arise if the interruption for an error causes a loss of the user's train of thought. Finally, the use of keyboard for both text and commands may be confusing; but this must be balanced against the longer time required to move the hand between mouse and keyboard.

In our experiments the Interaction Design for personal computer—both local and as a terminal—utilized solely the keyboard; the editors were modeless. For the reading experiments, the only commands were to change the screen image to display a different portion of the document. These *scrolling* operations were performed by striking keys, one combination to move forward in the document and another for backwards. For writing, other key sequences were necessary to position the cursor for additions or corrections.

The Interaction Design for the workstation software exploited a mouse. It was used for scrolling for both reading and writing and for positioning the cursor in writing tasks. Scrolling was done by pointing into a *scrollbar*. With Andrew, the scrollbar is a vertical rectangle at the left of the text which represents the entire length of the text. An "elevator" image within the scrollbar shows the position and extent of the visible

text. Mouse clicks in the scrollbar change the view to show an adjacent portion of the text. The elevator can be "dragged" with the mouse to change the view to any arbitrary portion of the text. When text is scrolled to the next "page" on the computer, a few lines of the previous page are left on the top of the screen to provide continuity. Thus the number of scrolling operations required to move through the entire document are larger than the number of screen-fulls required to display the document.

E. Graphic Imagery in the design of a system is the choice of using non-text images to expose portions of the state of the system. A scrollbar, for example, represents the relation of the visible text to the entire text. In *passive* imagery the user can only observe the system state, while in *active* systems the user can interactively manipulate the image to control the state of the system. A scrollbar is active imagery because the elevator can be dragged to move the view to another portion of the text.

The importance of good Graphic Imagery is that it provides information in forms that are easier to assimilate than reading text. The expression "a picture is worth a thousand words" applies not only to photographs, but to all well-chosen forms of non-textual information. (Of course, poorly chosen images can detract from comprehensibility.) Active Graphic Imagery is important because it avoids proliferation of commands, each of which must be designed, documented, taught, and remembered.

Text on paper, even without graphics, has both active and passive Graphic Imagery: the text is laid out in particular places on each sheet of paper, the sheets are stacked together, and the user can move sheets from the unread stack to the finished stack. As the user reads, the shifting stack gives gives tactile position cues as well. This contrasts with the editors used on mainframes and personal computers in our experiments. At best the text of each file is accompanied by a title bar in which an integer indicates the position of the cursor within the document. Much more than this is shown by the Graphic Imagery of Andrew's scrollbar.

Secondary factors

The primary factors described above are all observable characteristics of interactive systems, present to a greater or lesser extent in each system. It is unlikely that these factors themselves are immediately responsible for the behavior of users. Rather, we suggest, a number of intervening variables that describe states induced in users are more directly responsible for user behavior. That we cannot measure these variables does not mean they do not exist. Indeed, positing their presence may simplify explanation of user behavior when changes to diverse observable variables all produce similar observable results.

With each description below we speculate as to how the factor may affect the user, the extent to which the factor is generated by the primary factors, and the degree to which the factor is engendered by each of the media used in the experiments. The interactions of primary and secondary factors and their possible influence on users is diagrammed in Figure 2.

Figure 2. Relationships among the primary and secondary factors.

A. Directness. Shneiderman [1983] has described Direct Manipulation as an important characteristic of modern user interfaces. In such an interface—we have called it Active Graphic Imagery above—the user directly modifies an image on the screen to cause a change in the state of the system. By the term "Directness" we refer not to a characteristic of the system, but to the opinion of the system which it creates. At the extreme of the feeling of Directness, the user has an "illusion of mechanical linkage," a feeling that the displayed image is a physical object which the user can manipulate as easily as turning the pages of a book.

One important advantage of a system with good directness is that the user learns its commands more quickly; each response of the system to a user's command is a reinforcement of the user's understanding. Even more subtly, we speculate, good Directness changes the way a user interacts. With an indirect system the user thinks about a problem, decides on a change, enters a command, observes the response, and repeats. With a Direct system the cycle reduces to: think about problem, make a change, repeat. The interaction is so natural that the user ceases to think about it, just as a user seldom pays any attention to paper and pencil. (In terms of Hansen [1971], the user utilizes "muscle memory" rather than conscious control.)

Of the media used in the experiments, paper is quintessentially Direct. Users have spent almost their entire lives making images on paper and turning pages. The editors used with the personal computer, both local and as a terminal, are direct enough to not require RETURN at the ends of commands. Since no mouse was used, however, they did require the indirectness of a sequence of cursor movement commands to get the cursor to any particular place on the screen. Such commands are unnecessary with the editor used on the workstation: the cursor can be moved directly to any point in the text with the mouse; and the elevator in the scrollbar can be dragged directly to a desired position.

B. Fascination is the state of mind in the user where he or she feels drawn to use or continue using an interactive system. This feeling can reach its heights with video arcade games, where the vendor relies on it to attract enough play to recoup the cost and provide a profit. The Fascination with systems may arise from the fun of seeing the system react or from some other source, possibly similar to the fascination exhibited by subjects in stimulus-response experiments. The instant response of the computer provides a reward which reinforces the users behavior. Sometimes Fascination is akin to a hypnosis, even a narcosis to the extent that intense concentration on the system can blot out external concerns.

A good interactive system can harness this fascination and keep the user interested in his or her task for longer periods than other systems might. This may result in more work, though if the work continues too long its quality may decline unnoticed due to fatigue. It is not clear that Fascination is a desirable response to an editor. Not only may quality decline, but the catchy graphics used in arcade games to generate Fascination may distract the user from the task at hand.

Two primary factors that contribute somewhat to Fascination are Graphic Imagery and Interaction Design, especially those combinations that lead to a system with good Directness. However, the primary factor that is probably most responsible for Fascination is Responsiveness. Fast reaction by the system seems to encourage the user to respond rapidly in turn, setting up a rhythm of intense interaction. Slow response gives the user time to be distracted and lose concentration. Systems with variable Responsiveness, perhaps due to multi-processing, not only interfere with concentration, but may even cause frustration. Possibly they are harder to learn to use, just as subjects in stimulus-response experiments exhibit longer learning times when treated with variable reinforcement schedules.

For our experiments we consider that paper had low Fascination because users are so familiar with it and it is completely passive. Personal computers used as terminals probably had negative Fascination because of slow and variable response. Personal computers for local editing can have very good Fascination because the response can be instantaneous and unvariable. The workstation editor is not yet quite Responsive enough to have Fascination as high as the personal computer when the keyboard alone is used. However, use of the mouse to position the cursor seem to have a novelty and Directness that generate considerable Fascination.

C. Sense of Text. One difficulty users have dealing with documents on computers is in getting a "sense of the text" [Haas and Hayes, 1985]. By this phrase we mean the feeling that a user may have that he or she has a good grasp of the physical arrangement of the text—the absolute and relative location of each topic and the amount of space devoted to each. Good Sense of Text is invaluable to a reader in finding parts of the text, following the thread of an argument, and gaining a confident grasp on the material. For a writer, Sense of Text has all these merits and is necessary in order to organize the work, avoid duplication, and achieve balance among the sections.

Rothkopf [1971] has shown that readers can recall the position of text on paper pages. This may aid Sense of Text by tying the text to a physical entity which, as we have already mentioned, provides visual and tactile cues to further fix the text within a physical space.

Many factors may detract from a Sense of Text with computers. The position of lines within pages cannot be known if the computer system displays text with a different line at the top of the window each time. A small Page Size reduces the context for each piece of text. Limited Legibility may cause the reader to spend more mental effort on recognizing individual words and comparatively less on getting an impression of the entire page. Even poor Responsiveness may distract the reader with delays while scrolling. However, the Sense of Text could be enhanced by the Graphical Imagery of a scrollbar.

Since most of the factors we have discussed seem likely to impact the reader's Sense of Text, we chose to study this factor with our first three experiments.

3. Experiments and Results

In this section we review five experiments we have conducted over the last two years to study various aspects of the factors affecting use of computer for reading and writing. For each experiment we first describe the method and results and then discuss the relation of these results to the factors described in Section 2.

The first four experiments required subjects only to read material from whatever media they were using. Responses were given verbally or by pointing with a finger. Interaction with the computer was limited to scrolling the text, which used two keystroke combinations on the personal computer and mouse presses in the scrollbar on the workstation. Section 2 has already discussed the impact on scrolling of Interaction Design and Graphic Imagery. These factors--along with Directness and Fascination--are more crucial for creative, as in the letter writing task of the fifth experiment. Thus the important factors for the first four experiments are Page Size, Legibility, Responsiveness, and Sense of Text.

A. Spatial Recall

Spatial recall is the ability to remember the page and line of specific items. Rothkopf [1971] found that subjects reading from printed text showed significant spatial recall. Since this ability may be an important component of Sense of Text, this experiment was designed to study how spatial recall is affected by viewing the text through a computer.

Subjects read a text of 1000 words (9 pages) and were subsequently shown eight particular sentences from that text and asked to mark their location on a blank image of the text (empty paper in a folder or blank lines in a text file). The responses were compared with the correct page, line, and position in line and the scores assigned as the sum of the absolute values of the difference between the response and the correct answer.

The ten participants in this experiment were graduate students in English and were familiar with the text editor used. Five subjects performed the task on paper and five on the personal computer used as a terminal. The text size on the paper pages was restricted so pages could be (and were) presented on the computer at the same size as the paper pages. The results, Table 1, showed that paper was superior on all measures, but the differences are statistically significant only for the line-on-page variable, where the error is fifty percent larger with the personal computer.

	Page Number	Line Number*	Position in Line
Paper	11.8	30.0	92.0
Personal computer as a terminal	13.6	45.0	117.6

Table 1. Mean Error of Spatial Recall. N=10. The difference in the starred (*) column is significant at the .05 level.

Of the five primary factors, Page Size cannot explain the observed differences because pages were the same size in both conditions. The difference in Responsiveness was large--two or three seconds per page on the computer--and may have been a major cause of the disparity in performance. However, the computer also had lower Legibility and lacked the rudimentary Graphic Imagery afforded by the thickness of paper as pages are turned from one pile to another. In any case, the subjects' Sense of Text seems to have been impaired by the computer condition.

B. Content Retrieval

The first experiment demonstrated that readers can recall the location of information more accurately from paper than from a personal computer. This result suggests that readers would find it easier to retrieve information to answer questions from paper than from computer screen. The second experiment was designed to test this possibility. It seemed likely that the results would further explore the question of Sense of Text and this experiment also was the first to use the advanced workstation with Andrew. The personal computer was again used as a terminal to a mainframe.

In this experiment, subjects read an 1800 word text and subsequently retrieved answers to twelve questions, half of which required inferences, by finding the place in the text that gave or implied the answer. The paper version of the experiment was printed in twelve point TimesRoman, the personal computer version utilized the green monochrome display, and the workstation version was the large screen condition with twelve point TimesRoman text, but with bold text to highlight headings instead of all-capitals as used in the other two conditions. As formatted, the text occupied 3 1/2 pages on paper, 12 scroll operations on the personal computer, and 5 1/2 scroll operations on the workstation.

Subjects were students familiar with using the personal computer as a terminal, although unfamiliar with Andrew. Each subject did the experiment with only one of the media. Almost all responses were correct so the performance measure was not accuracy, but total time to complete the retrieval portion of the experiment, as shown in Table 2.

	Mean Time (minutes)
Paper	13.0
Personal computer as a terminal	32.7*
Workstation, large window	15.9

Table 2. Mean Time for Content Retrieval. N = 15. The difference between the starred (*) value and the other two is statistically significant at the .01 level.

Most of the factors differed between the personal computer and the workstation, so it is not surprising that there should be such a difference in performance with the two systems. The Page Size differed by a factor of more than two; the Legibility of the workstation text was enhanced by a seriffed font and bold headings; Andrew was more Responsive both in beginning to respond to a command and displaying a page three to four times faster; and Andrew offered the Graphic Imagery and Interaction Design of the scrollbar for moving through the document. If Sense of Text were indeed the more proximate determinant of performance, then subjects clearly had lowered Sense of Text with the personal computer.

C. Reordering a Scrambled Text

Given the number of differences between editing text on Andrew and with a personal computer used as a terminal, there is no good way to say which of the factors contributed most to the results of the second experiment. Since the size of screen would seem to be a significant factor in Sense of Text, the next experiment was designed to determine if size of screen alone could account for differences in performance. This experiment also tested a difference in Interaction Design by varying between two methods to control scrolling.

The experimental task tested the ability of subjects to read critically in order to determine the correct arrangement of a collection of text lines. Critical reading requires forming a mental representation of a text's content and is a more sophisticated skill than Spatial Recall or Content Retrieval. This kind of reading is necessary when revising or reorganizing text and requires an understanding of the whole text, rather than just local interpretation.

In each condition of the experiment, subjects read a 1200 word text whose lines were scrambled and numbered. To reduce interference from motor variables, subjects responded orally; they gave instructions (by line number) as to how the text should be resequenced to produce a meaningful whole.

Five conditions were tested: paper and four workstation conditions which crossed the variables of window size and method of scrolling. On paper and with the large windows, the texts occupied about two pages; with the small window the texts were about 4 1/2 pages. For scrolling, one method was the Andrew scrollbar and the other was four function keys: two scrolled the image forward or backward by a fixed amount when pressed and the other two moved directly to the beginning or end of the document.

A counter-balanced design was selected for the experiment, so each subject performed the task five times, once for each condition.* The subjects, all incoming freshmen at Carnegie-Mellon, were each given three hours of individual training on the workstation to become familiar with the system and the two scrolling methods. As with the other experiments, observed error rates were uniform and low, so the results, Table 3, are shown as the mean time to complete the task. Subjects did best on paper, less well with large windows, and poorly with the small window. Method of scrolling made no difference.

- - - - - - - - - - - -

{{{Footnote}}}

* With a counter-balanced design, each subject serves as a control for his or her own performance, thus eliminating the impact of individual characteristics like reading and typing speeds. The observed differences in performance can be statistically analyzed to determine the difference due entirely to the experimental conditions.

- - - - - - - - - - - -

Mean Time (minutes)

	Scrollbar	Keys
Large Window	15.7	14.4
Small Window	20.6	20.7
Paper	13.5	

Table 3. Mean time to reorder text. N = 10. The difference between large and small windows was statistically significant at the .01 level. The difference between paper and small windows was significant at the .05 level.

In this experiment the task of rearranging lines was made more difficult in the small window because subjects had to scroll back and forth more to understand the relations among the lines. Page Size would thus seem the most important factor. Legibility was identical for all computer conditions. Response time was identical as well, but may have contributed to the difference in times for large and small windows. Each scroll operation required a second or two, so the larger number of scroll operations for the small windows increased the total time. An extra five minutes, however, would require at least twice as many scroll operations as subjects actually made. The additional time with the small windows

may be due to decreased Sense of Text in that condition.

Graphic Imagery and Interaction Design are the factors most affected by the method of scrolling. In the event, however, the experiment revealed no difference in performance between mouse and function keys. This is probably because neither device was used for anything other than scrolling so once the subject's hand was positioned over the scrolling device any scrolling could be done solely by pressing down with a finger.

D. Proofreading

As a further test of the efficacy of computers as a tool for reading, the subjects from the Reordering experiment were given a Proofreading task. Extracts of 500 words were taken from the texts used in the previous experiment; they were presented in correct order but with simple mechanical errors: missing spaces, faulty mid-word capitals, repeated letters, and repeated words. Such blatant errors were utilized so any observed differences would be more likely the result of reading rather than knowledge of grammar or usage rules.

Accuracy in finding errors was high for all subjects and conditions, so it was not analyzed. The mean times, Table 4, showed no significant difference between the conditions, though the means were in the order we would predict from our other experiments, with paper doing better than large windows which did better than small windows. Since the task required only local examination of the text, it is not surprising that the two window sizes gave similar results.

	Mean Time (minutes)
Paper	5.10
Large Window	5.36
Small Window	5.44

Table 4. Mean time for Proofreading Task. N = 10. There are no statistically significant differences among these values.

Subjects were permitted to choose between scrollbar and function keys for scrolling. Almost without exception, they chose the scrollbar, which argues strongly that users, consciously or not, prefer the Graphic Imagery and Interaction Design of a scrollbar, even if it is not actually faster than function keys.

Although these results show no significant difference between paper and workstation, Gould's earlier results did show differences. In view of his general result it seems likely that this experiment showed no difference because Legibility on the computer was close to that of paper. None of the other factors would seem likely to have had an effect.

E. Letter Writing

After four studies of reading, our fifth study examined writing, which exercises more aspects of interactive behavior. Writing is more difficult than reading in part because the author must not only review the text, but must simultaneously revise it and create new material. To begin to learn about writing behavior, we chose as a paradigm Gould's 1981 study comparing writers' performance with text editors and paper. In this paradigm, subjects are directed to write a persuasive letter to a particular audience and to "produce a letter of quality as quickly as possible."

For this experiment three conditions were chosen: paper, a local editor on a personal computer, and the Andrew editor on a workstation. Gould's study had employed line editors; we hypothesized that hardware and software advances might lead to different results. (Both large and small screen conditions were examined on the workstation, but the subjects wrote letters short enough that no differences emerged; the results for the two window sizes have been combined for this analysis.) The fifteen subjects were experienced writers—faculty, administrators, and systems designers. Results are summarized in Table 5.

Two quantitative measures were collected and analyzed: time to completion and number of words. These measures showed that—unlike the other experiments—subjects performed similarly with personal computer and paper, and differently on the workstation. In all conditions the words per minute were about the same, but subjects worked longer and wrote more words on the workstation.

Two qualitative measures were also collected: Content Quality and Mechanics Quality. For both, Quality was evaluated by a forced quartile scheme. Two independent readers with at least five years experience teaching English rated each set of letters and were instructed to place each letter into one of four quartiles. The quality score was the sum of the two quartile scores and ranged from 2 to 8. (Agreement between the raters was eighty percent.) Quality of Content and Quality of Mechanics were measured separately and later summed to produce a Total Quality score. Quality was found to be highest for the workstation and lowest for the personal computer, with paper in between.

Our results show a statistically significant difference in quality among

letters while the results of Gould's earlier study did not. Our finding of a difference may have been affected by the grading method. Gould's evaluators gave an independent grade to each letter; while ours used the more discriminating quartile split.

	Time* (minutes)	Words*	WPM
Paper	13.4	264	21
Personal computer	15.1	292	21
Workstation	17.4	353	20

	Quality		
	Content*	Mechanics	Total*
Paper	5.1	5.7	10.8
Personal computer	4.0	4.3	8.3
Workstation	6.0	5.2	11.2

Table 5. Results of Letter Writing Experiment. N= 15. Analysis of variance shows a statistical significance of .02 for each starred (*) column. In each, a Neuman-Keuls analysis shows that the largest value differs from the smallest at a probability level of .05.

The results of this experiment raise several questions:

Why the disagreement with Gould's results? Gould's subjects were 50% slower with computers while our subjects had the same or better speed on computer than on paper. The difference is probably because Gould's subjects used a line editor rather than a full-screen editor.

Why did no subject use a mouse on the personal computer? Probably because mice are not common on personal computers so our subjects had not become accustomed to them. It is possible that use of a mouse might have improved performance with personal computers, but it should be noted that there are no scroll bars so the mouse can only be used as a faster means of positioning the cursor.

Why did subjects work longer and produce more words with the workstation? Each of our factors can be used as part of an explanation of this phenomenon. Perhaps Page Size was a factor and subjects simply worked long enough to fill the space available. This seems incorrect, however, because results were similar with both large and small windows. Perhaps the high Responsiveness of the workstation produced Fascination in the subjects. Certainly not "hypnotic" Fascination since these were experienced writers with computers, but it may be that the work was more enjoyable or less frustrating with the workstation than with the other media. Perhaps the work was physically easier because of better Interaction Design. The movements to type keys are less precise than those needed to form letters and the workstation does not require physical movement of pen or paper. However, the personal computer shares the same physical ease.

We are forced then to consider the possibility that use of the workstation is mentally easier than with paper and the personal computer. We may speculate as follows: Legibility makes it easier to review the work than on the personal computer. The Interaction Design and Graphic Imagery reduce the number of commands that must be typed, reducing confusion with the text that must also be typed. In conjunction with Responsiveness these factors make the system more Direct and all together contribute to a heightened Sense of Text. All conjoin to reduce the non-productive efforts, freeing the subject to think about the actual work.

Finally, *Why was the quality of work higher on the workstation?* Possibly the graders were biased toward longer letters, or perhaps the greater length gave more room for better arguments supporting the argument. Possibly the reduced mental effort postulated above to explain the length of the letters also allowed subjects to concentrate more on the quality of the letters without concern for the physical aspects of transcribing them. Possibly an increased Sense of Text made it easier for subjects to imagine and carry through a cogent argument.

4. Summary

The results of the five experiments can be summarized as in Table 6. On the left of this table, the various computer conditions are compared with respect to the five primary factors, assuming for each that paper is the norm. The computer conditions are graded as greatly inferior (- -), inferior(-), slightly inferior (= -), or just about the same (=) as paper. For page size, the size of a page on the screen is given as a fraction of that on paper. On the right of the table, the results are similarly compared against the results on paper. An exclamation mark (!) indicates that the result differs with statistical significance from one of the other results on that experiment. The last column contains the one result, marked plus (+), where paper was inferior to computer—the quality of written work produced with the workstation.

	Page Size	Legi-bility	Respon-siveness	Inter-action[1]	Graphic Imagery	Task Time	Quality of work
paper	=	=	=	=	=	=	=
A. Spatial Recall							
PC as terminal	=	-	- -[2]	-	-		- !
B. Retrieval							
PC as terminal	< 1/2	-	- -[2]	-	-	2.5 !	════
W/S, large window	=	=-	-	=-	=-	=-	=
C. Reorder Lines							
W/S, large window	=	=-	-	=-/-[3]	=-	=-	════
W/S, small window	< 1/2	=-	-	=-/-[3]	=-	1.3 !	=
D. Proofreading							
W/S, large window	=	=-	-	=-[4]	=-	=-	════
W/S, small window	< 1/2	=-	-	=-[4]	=-	=-	=
E. Writing Letters							
PC with editor	< 1/2	-	-	-	-	=	- ![5]
'ps 10							
W/S	&[6]	=-	-	=-	=-	=[7]	+ ![5]

Table 6. Summary of experiments and results Each computer condition is graded on each of the factors as to whether it is about the same as paper (=), slightly inferior (=-), inferior (-), or very inferior (- -). An exclamation mark (!) indicates a result that is statistically significant at the .05 level or better.

1. Mouse availability: =- means yes; - means no.
2. Display took four seconds a page.
3. The tasks were performed with both mouse and keys for scrolling. Results were similar for both methods.
4. Subjects were allowed to choose between mouse and keys. Results were similar for both methods.
5. The personal computer differed statistically in quality from the workstation, but the difference of each from paper was not statistically significant.
6. Windows of large and small size were tried. Results were similar for both methods.
7. Subjects worked at the same rate in words per minute, but worked longer on the workstation than on the other two media.

At the beginning we asked four questions, two about user interface design and two about interactions of the computer with reading and writing. We can now answer them all:

Does the user interface make a difference? Indeed it does. Significant differences in user performance were observed in four out of the five experiments.

How? We have not answered the question of how differences affect performance, but have speculated on a number of possible answers. The primitive factors at work can be organized in the categories of Page Size, Legibility, Response Time, Interaction Design, and Graphic Imagery. The first three were shown to be plausible explanations of the differences in performance observed in the reading experiments. They also contributed to writing performance, where they were joined by the fourth and fifth factors. Second level factors of Sense of Text, Directness, and Fascination can also help explain our results. Only future work will show the extent to which these factors can be isolated, studied, and exploited in the creation of better systems.

Is using a computer to read and write different than using paper? Is using a more advanced workstation for reading and writing different than using a typical personal computer? Both of these questions must be answered in the affirmative. Every experiment showed that paper was superior for reading to any computer condition, although the workstation results were closer to those of paper than those of the personal computer. On the writing task, paper differed from the personal computer chiefly in that subjects produced higher quality letters. The most surprising results were in the writing task where subjects worked longer and wrote more with workstation than with the other media. Moreover, the letters produced had higher quality than even those produced on paper.

It would not be fair to claim that workstations are universally superior to personal computers. With both available, this text was drafted on a personal computer because of the advantages of the Personal Editor. Its Responsiveness and the resulting feelings of Directness and Fascination outweigh the disadvantages of reduced Page Size and lack of Graphic Imagery. Even the Interaction Design is not ideal since the lack of a mouse sometimes means it takes too long to move the cursor to the correct place. There is a considerable feeling of loss of Sense of Text, which must be offset by producing a paper copy of the text for review and markup.

The final test of the work for the Andrew project as a whole must be whether the studies reported here had a favorable influence on the user interface finally deployed. In fact, they did. Numerous changes to the system were made in response to observations made during the conduct of these studies as well as other studies. It may well be that the most important result of user interface studies are not the results of specific experiments, but the general attitude of adapting the system to the users engendered by having the studies at all.

Acknowledgements: We are grateful for the help and guidance of John R. Hayes of the CMU Psychology Department who collaborated on the experiments reported here. Christine M. Neuwirth of the CMU English Department helped in both design and analysis of several of the experiments. James Gosling built the first version of the Andrew editor, with contributions from W. J. Hansen and A. J. Palay. We are grateful for their help and for the help of all other members of the Information Technology Center and its director, James H. Morris.

References

Gould, J. Composing Letters with Computer-Based Text Editors. *Human Factors* 23(5), 1981, 593-606.

Gould, J., and Grischkowsky, N. Doing the same work with hardcopy and with CRT terminals. *Human Factors* 26(3), 1984, 323-337.

Gould, J. Seminar presented at Psychology Department, Carnegie-Mellon, February 7, 1986.

Haas, C., and Hayes, J. *Effects of text display variables on reading tasks: computer screen vs. hard copy.* Pittsburgh: CDC Technical Report #3, 1985.

Haas, C. and Hayes, J. *Reading on the computer: a comparison of standard and advanced computer display and hard copy.* Pittsburgh: C-MU, CDC Technical Report #3, 1985b.

Haas, C. and Hayes, J. What did I just say? Reading problems in writing with the machine. *Research in the Teaching of English*, February, 1986.

Haas, C. *Technology in the classroom: Do computers change the way* *we write?* American Educational Research Association, San Francisco, April, 1986.

Hansen, W. J. User Engineering Principles for Interactive Systems, Fall Joint Computer Conference, AFIPS Press (Mondale, NJ, 1971), 523-532.

Hansen, W. J., Doring, R., and Whitlock, L. R. Why an examination was slower on-line than on paper. *Int. J. of Man-Machine Studies, 10,* 1978, 507-519.

Morris, J., Satyarayanah, M., Conner, M. H., Howard, J. H., Rosenthal, D. S. H., Smith, F. D. Andrew: A distributed Personal Computing Environment. *Comm. ACM*, V. 29, 3 (March, 1986) 184-201.

Muter, P., Latremouille, S. A., Treuniet, W. C., and Beam, P. Extended reading of continuous text on television screens. *Human Factors, 24* (1982), 501-08.

Rothkopf, E. Z. Incidental memory for location of information in text. *Journal of Verbal Learning and Verbal Behavior 10*, 1971, 608-613.

Shneiderman, B. Direct Manipulation: A Step Beyond Programming Languages, *Computer* V 16, 8 (Aug, 1983), 57-69.

Stallman, R. M. *EMACS: The Extensible, Customizable Self-Documenting Display Editor.* ACM SIGPLAN/SIGOA Symposium on Text Manipulation, 1981.

West, M., Nichols, D., Howard, J., Satyarayanan, M., Sidebotham, R. The ITC Distributed File System: Prototype and Experience. *SIGOPS Proceedings*, 1985.

Wright, P. and Lickorish, A. Proof-reading texts on screen and paper. *Behavior and Information Technology*, 2 (1983), 227-235.

Wylie, J., Personal Editor, IBM Corp. 6936760, 1982.

Figure 1 (a). Andrew small screen image. The examples are taken from the Proofreading experiment, which accounts for the plenitude of errors. These figures were created on a slightly larger screen than that used for the original experiments.

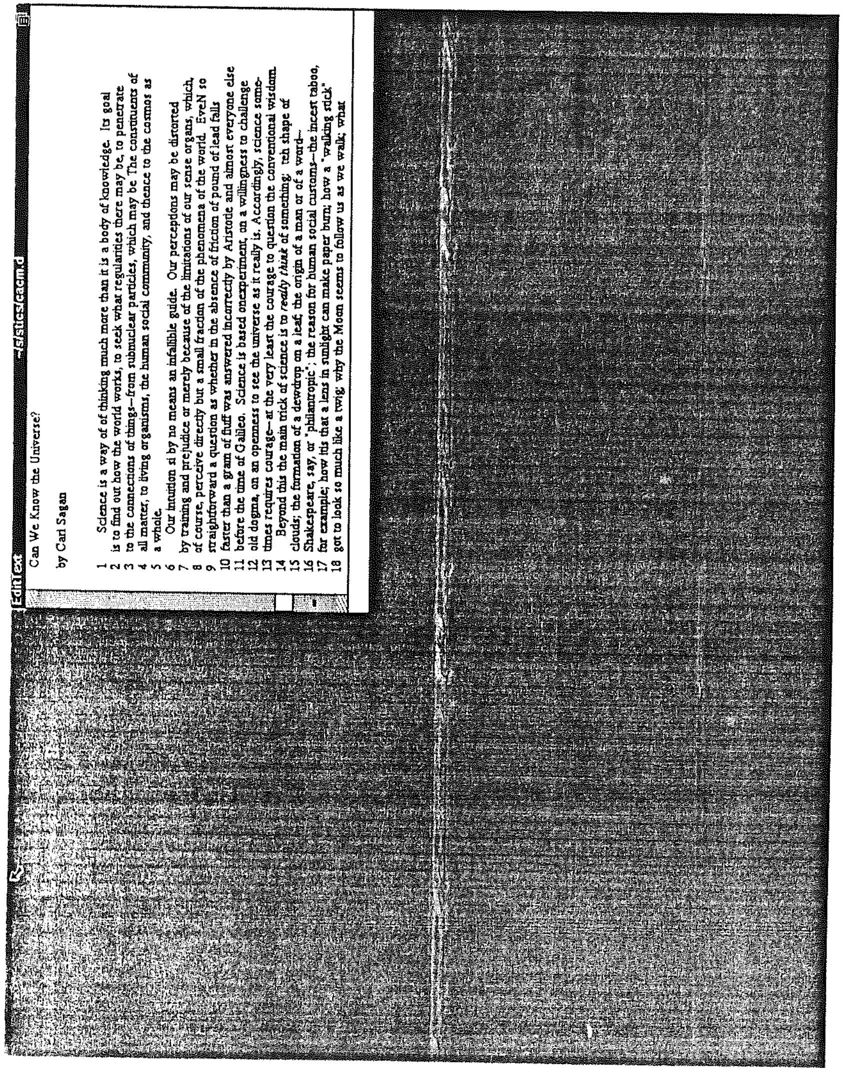
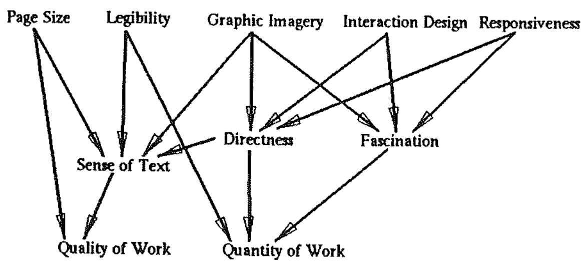


Figure 2. Relationships among the primary and secondary factors. An arrow indicates our belief that a change in the variable at the tail will affect the parameter at the head.



Bibliography

Copies of documents in this list may be obtained by writing to:

The Secretary,
Persistent Programming Research Group,
Department of Computing Science,
University of Glasgow,
Glasgow G12 8QQ
Scotland.

or

The Secretary,
Persistent Programming Research Group,
Department of Computational Science,
University of St. Andrews,
North Haugh,
St. Andrews KY16 9SS
Scotland.

Books

Davie, A.J.T. & Morrison, R.
"Recursive Descent Compiling", Ellis-Horwood Press (1981).

Atkinson, M.P. (ed.)
"Databases", Pergammon Infotech State of the Art Report, Series 9, No.8, January 1982. (535 pages).

Cole, A.J. & Morrison, R.
"An introduction to programming with S-algol", Cambridge University Press, Cambridge, England, 1982.

Stocker, P.M., Atkinson, M.P. & Grey, P.M.D. (eds.)
"Databases - Role and Structure", Cambridge University Press, Cambridge, England, 1984.

Published Papers

Morrison, R.
"A method of implementing procedure entry and exit in block structured high level languages". Software, Practice and Experience 7, 5 (July 1977), 535-537.

Morrison, R. & Podolski, Z.
"The Graffiti graphics system", Proc. of the DECUS conference, Bath (April 1978), 5-10.

Atkinson, M.P.
"A note on the application of differential files to computer aided design", ACM SIGDA newsletter Summer 1978.

Atkinson, M.P.
"Programming Languages and Databases", Proceedings of the 4th International Conference on Very Large Data Bases, Berlin, (Ed. S.P. Yao), IEEE, Sept. 78, 408-419. (A revised version of this is available from the University of Edinburgh Department of Computer Science (EUCS) as CSR-26-78).

Atkinson, M.P.
"Progress in documentation: Database management systems in library automation and information retrieval", Journal of Documentation Vol.35, No.1, March 1979, 49-91. Available as EUCS departmental report CSR-43-79.

Gunn, H.I.E. & Morrison, R.
"On the implementation of constants", Information Processing Letters 9, 1 (July 1979), 1-4.

Atkinson, M.P.
"Data management for interactive graphics", Proceedings of the Infotech State of the Art Conference, October 1979. Available as EUCS departmental report CSR-51-80.

Atkinson, M.P. (ed.)
"Data design", Infotech State of the Art Report, Series 7, No.4, May 1980.

Morrison, R.
"Low cost computer graphics for micro computers", Software Practice and Experience, 12, 1981, 767-776.

Atkinson, M.P., Chisholm, K.J. & Cockshott, W.P.
"PS-algol: An Algol with a Persistent Heap", ACM SIGPLAN Notices Vol.17, No. 7, (July 1981) 24-31. Also as EUCS Departmental Report CSR-94-81.

Atkinson, M.P., Chisholm, K.J. & Cockshott, W.P.
"Nepal - the New Edinburgh Persistent Algorithmic Language", in Database, Pergammon Infotech State of the Art Report, Series 9, No.8, 299-318 (January 1982) - also as EUCS Departmental Report CSR-90-81.

Morrison, R.
"S-algol: a simple algol", Computer Bulletin II/31 (March 1982).

Morrison, R.
"The string as a simple data type", Sigplan Notices, Vol.17,3, 46-52, 1982.

Atkinson, M.P., Bailey, P.J., Chisholm, K.J., Cockshott, W.P. & Morrison, R.
"Progress with Persistent Programming", presented at CREST course UEA, September 1982, revised in "Databases - Role and Structure", see PPRR-8-84.

Morrison, R.
"Towards simpler programming languages: S-algol", IUCC Bulletin 4, 3 (October 1982), 130-133.

Atkinson, M.P., Chisholm, K.J. & Cockshott, W.P.
"Problems with persistent programming languages", presented at the Workshop on programming languages and database systems, University of Pennsylvania. October 1982. Circulated (revised) in the Workshop proceedings 1983, see PPRR-2-83.

Atkinson, M.P.
"Data management", in Encyclopedia of Computer Science and Engineering 2nd Edition, Ralston & Meek (editors) January 1983. van Nostrand Reinhold.

Atkinson, M.P., Chisholm, K.J. & Cockshott, W.P.
"Algorithms for a Persistent Heap", Software Practice and Experience, Vol.13, No.3, 259-272 (March 1983). Also as EUCS Departmental Report CSR-109-82.

Atkinson, M.P., Chisholm, K.J. & Cockshott, W.P.
"CMS - A chunk management system", Software Practice and Experience, Vol.13, No.3 (March 1983), 273-285. Also as EUCS Departmental Report CSR-110-82.

Atkinson, M.P., Bailey, P.J., Chisholm, K.J., Cockshott, W.P. & Morrison, R.
"Current progress with persistent programming", presented at the DEC workshop on Programming Languages and Databases, Boston, April 1983.

Atkinson, M.P., Bailey, P.J., Chisholm, K.J., Cockshott, W.P. & Morrison, R.
"An approach to persistent programming", The Computer Journal, 1983, Vol.26, No.4, 360-365 - see PPRR-2-83.

Atkinson, M.P., Bailey, P.J., Chisholm, K.J., Cockshott, W.P. & Morrison, R.
"PS-algol a language for persistent programming", 10th Australian Computer Conference, Melbourne, Sept. 1983, 70-79 - see PPRR-2-83.

Morrison, R., Weatherill, M., Podolski, Z. & Bailey, P.J.
"High level language support for 3-dimension graphics", Eurographics Conference Zagreb, North Holand, 7-17, Sept. 1983. (ed. P.J.W. ten Hagen).

Cockshott, W.P., Atkinson, M.P., Chisholm, K.J., Bailey, P.J. & Morrison, R.
"POMS : a persistent object management system", Software Practice and Exerience, Vol.14, No.1, 49-71, January 1984.

Kulkarni, K.G. & Atkinson, M.P.
"Experimenting with the Functional Data Model", in Databases - Role and Structure, Cambridge University Press, Cambridge, England, 1984.

Atkinson, M.P. & Morrison, R.
"Persistent First Class Procedures are Enough", Foundations of Software Technology and Theoretical Computer Science (ed. M. Joseph & R. Shyamasundar) Lecture Notes in Computer Science 181, Springer Verlag, Berlin (1984).

Atkinson, M.P., Bocca, J.B., Elsey, T.J., Fiddian, N.J., Flower, M., Gray, P.M.D. Gray, W.A., Hepp, P.E., Johnson, R.G., Milne, W., Norrie, M.C., Omololu, A.O., Oxborrow, E.A., Shave, M.J.R., Smith, A.M., Stocker, P.M. & Walker, J.
"The Proteus distributed database system", proceedings of the third British National Conference on Databases, (ed. J. Longstaff), BCS Workshop Series, Cambridge University Press, Cambridge, England, (July 1984).

Atkinson, M.P. & Morrison, R.
"Procedures as persistent data objects", ACM TOPLAS 7, 4, 539-559, (Oct. 1985) - see PPRR-9-84.

Morrison, R.,Bailey, P.J., Dearle, A., Brown, P. & Atkinson, M.P.
"The persistent store as an enabling technology for integrated support environments", 8th International Conference on Software Engineering, Imperial College, London (August 1985), 166-172 - see PPRR-15-85.

Atkinson, M.P. & Morrison, R.
"Types, bindings and parameters in a persistent environment", proceedings of Data Types and Persistence Workshop, Appin, August 1985, 1-24 - see PPRR-16-85.

Davie, A.J.T.
"Conditional declarations and pattern matching", proceedings of Data Types and Persistence Workshop, Appin, August 1985, 278-283 - see PPRR-16-85.

Krablin, G.L.
"Building flexible multilevel transactions in a distributed persistent environment, proceedings of Data Types and Persistence Workshop, Appin, August 1985, 86-117 - see PPRR-16-85.

Buneman, O.P.
"Data types for data base programming", proceedings of Data Types and Persistence Workshop, Appin, August 1985, 291-303 - see PPRR-16-85.

Cockshott, W.P.
"Addressing mechanisms and persistent programming", proceedings of Data Types and Persistence Workshop, Appin, August 1985, 363-383 - see PPRR-16-85.

Norrie, M.C.
"PS-algol: A user perspective", proceedings of Data Types and Persistence Workshop, Appin, August 1985, 399-410 - see PPRR-16-85.

Owoso, G.O.
"On the need for a Flexible Type System in Persistent Programming Languages", proceedings of Data Types and Persistence Workshop, Appin, August 1985, 423-438 - see PPRR-16-85.

Morrison, R., Brown, A.L., Bailey, P.J., Davie, A.J.T. & Dearle, A.
"A persistent graphics facility for the ICL PERQ", Software Practice and Experience, Vol.14, No.3, (1986) - see PPRR-10-84.

Atkinson, M.P. and Morrison R.
"Integrated Persistent Programming Systems", proceedings of the 19th Annual Hawaii International Conference on System Sciences, January 7-10, 1986 (ed. B. D. Shriver), vol IIA, Software, 842-854, Western Periodicals Co., 1300 Rayman St., North Hollywood, Calif. 91605, USA - see PPRR-19-85.

Atkinson, M.P., Morrison, R. and Pratten, G.D.
"A Persistent Information Space Architecture", proceedings of the 9th Australian Computing Science Conference, January, 1986 - see PPRR-21-85.

Kulkarni, K.G. & Atkinson, M.P.
"EFDM : Extended Functional Data Model", The Computer Journal, Vol.29, No.1, (1986) 38-45.

Buneman, O.P. & Atkinson, M.P.
"Inheritance and Persistence in Database Programming Languages"; proceedings ACM SIGMOD Conference 1986, Washington, USA May 1986 - see PPRR-22-86.

Morrison R., Dearle, A., Brown, A. & Atkinson M.P.; "An integrated graphics programming environment", Computer Graphics Forum, Vol. 5, No. 2, June 1986, 147-157 - see PPRR-14-86.

Atkinson, M.G., Morrison, R. & Pratten G.D.
"Designing a Persistent Information Space Architecture", proceedings of Information Processing 1986, Dublin, September 1986, (ed. H.J. Kugler), 115-119, North Holland Press.

Brown, A.L. & Dearle, A.
"Implementation Issuses in Persistent Graphics", University Computing, Vol. 8, NO. 2, (Summer 1986) - see PPRR-23-86.

Kulkarni, K.G. & Atkinson, M. P.
"Implementing an Extended Functional Data Model Using PS-algol", Software - Practise and Experience, Vol. 17(3), 171-185 (March 1987)

Cooper, R.L. & Atkinson, M.P.
"The Advantages of a Unified Treatment of Data", Software Tool 87: Improving Tools, Advance Computing Series, 8, 89-96, Online Publications, June 1987.

Internal Reports

Morrison, R.
"S-Algol language reference manual", University of St Andrews CS-79-1, 1979.

Bailey, P.J., Maritz, P. & Morrison, R.
"The S-algol abstract machine", University of St Andrews CS-80-2, 1980.

Atkinson, M.P., Hepp, P.E., Ivanov, H., McDuff, A., Proctor, R. & Wilson, A.G.
"EDQUSE reference manual", Department of Computer Science, University of Edinburgh, September 1981.

Hepp, P.E. and Norrie, M.C.
"RAQUEL: User Manual", Department of Computer Science Report CSR-188-85, University of Edinburgh.

Norrie, M.C.
"The Edinburgh Node of the Proteus Distributed Database System", Department of Computer Science Report CSR-191-85, University of Edinburgh.

Theses

The following theses, for the degree of Ph. D. unless otherwise stated, have been produced by members of the group and are available from the address already given,

W.P. Cockshott
Orthogonal Persistence, University of Edinburgh, February 1983.

K.G. Kulkarni
Evaluation of Functional Data Models for Database Design and Use, University of Edinburgh, 1983.

P.E. Hepp
A DBS Architecture Supporting Coexisting Query Languages and Data Models, University of Edinburgh, 1983.

G.D.M. Ross
Virtual Files: A Framework for Experimental Design, University of Edinburgh, 1983.

G.O. Owoso
Data Description and Manipulation in Persistent Programming Languages, University of Edinburgh, 1984.

J. Livingstone
Graphical Manipulation in Programming Languages: Some Experiments, M.Sc., University of Glasgow, 1987

Persistent Programming Research Reports

This series was started in May 1983. The following list gives those which have been produced at 9th July 1986. Copies of documents in this list may be obtained by writing to the addresses already given.

PPRR-1-83	The Persistent Object Management System - Atkinson,M.P., Chisholm, K.J. and Cockshott, W.P.	£1.00
PPRR-2-83	PS-algol Papers: a collection of related papers on PS-algol - Atkinson, M.P., Bailey, P., Cockshott, W.P., Chisholm, K.J. and Morrison, R.	£2.00
PPRR-4-83	The PS-algol reference manual - Atkinson, M.P., Bailey, P., Cockshott, W.P., Chisholm, K.J. and Morrison, R	Presently no longer available
PPRR-5-83	Experimenting with the Functional Data Model - Atkinson, M.P. and Kulkarni, K.G.	£1.00
PPRR-6-83	A DBS Architecture supporting coexisting user interfaces: Description and Examples - Hepp, P.E.	£1.00
PPRR-7-83	EFDM - User Manual - K.G.Kulkarni	£1.00
PPRR-8-84	Progress with Persistent Programming - Atkinson,M.P., Bailey, P., Cockshott, W.P., Chisholm, K.J. and Morrison, R.	£2.00
PPRR-9-84	Procedures as Persistent Data Objects - Atkinson, M.P.,Bailey, P., Cockshott, W.P., Chisholm, K.J. and Morrison, R.	£1.00
PPRR-10-84	A Persistent Graphics Facility for the ICL PERQ - Morrison, R., Brown, A.L., Bailey, P.J., Davie, A.J.T. and Dearle, A.	£1.00
PPRR-11-85	PS-algol Abstract Machine Manual	£1.00
PPRR-12-87	PS-algol Reference Manual - fourth edition	£2.00
PPRR-13-85	CPOMS - A Revised Version of The Persistent Object Management System in C - Brown, A.L. and Cockshott, W.P..	£2.00
PPRR-14-86	An Integrated Graphics Programming Environment - second edition - Morrison, R., Brown, A.L., Dearle, A. and Atkinson, M.P.	£1.00
PPRR-15-85	The Persistent Store as an Enabling Technology for an Integrated Project Support Environment - Morrison, R., Dearle, A, Bailey, P.J., Brown, A.L. and Atkinson, M.P.	£1.00
PPRR-16-85	Proceedings of the Persistence and Data Types Workshop, Appin, August 1985 - ed. Atkinson, M.P., Buneman, O.P. and Morrison, R.	£15.00
PPRR-17-85	Database Programming Language Design - Atkinson, M.P. and Buneman, O.P.	£3.00
PPRR-18-85	The Persistent Store Machine - Cockshott, W.P.	£2.00
PPRR-19-85	Integrated Persistent Programming Systems - Atkinson, M.P. and Morrison, R.	£1.00
PPRR-20-85	Building a Microcomputer with Associative Virtual Memory - Cockshott, W.P.	£1.00
PPRR-21-85	A Persistent Information Space Architecture - Atkinson, M.P., Morrison, R. and Pratten, G.D.	£1.00
PPRR-22-86	Inheritance and Persistence in Database Programming Languages - Buneman, O.P. and Atkinson, M.P.	£1.00
PPRR-23-86	Implementation Issues in Persistent Graphics - Brown, A.L. and Dearle, A.	£1.00
PPRR-24-86	Using a Persistent Environment to Maintain a Bibliographic Database - Cooper, R.L., Atkinson, M.P. & Blott, S.M.	£1.00
PPRR-25-87	Applications Programming in PS-algol - Cooper, R.L.	£1.00
PPRR-26-86	Exception Handling in a Persistent Programming Language - Philbrow, P & Atkinson M.P.	£1.00
PPRR-27-87	A Context Sensitive Addressing Model - Hurst, A.J.	£1.00
PPRR-28-86b	A Domain Theoretic Approach to Higher-Order Relations - Buneman, O.P. & Ochari, A.	£1.00
PPRR-29-86	A Persistent Store Garbage Collector with Statistical Facilities - Campin, J. & Atkinson, M.P	£1.00
PPRR-30-86	Data Types for Data Base Programming - Buneman, O.P.	£1.00
PPRR-31-86	An Introduction to PS-algol Programming - Carrick, R., Cole, A.J. & Morrison, R.	£1.00
PPRR-32-87	Polymorphism, Persistence and Software Reuse in a Strongly Typed Object Oriented Environment - Morrison, R, Brown, A, Connor, R and Dearle, A	£1.00
PPRR-33-87	Safe Browsing in a Strongly Typed Persistent Environment - Dearle, A and Brown, A.L.	£1.00

PPRR-34-87	Constructing Database Systems in a Persistent Environment - Cooper, R.L., Atkinson, M.P., Dearle, A. and Abderrahmane, D.	£1.00
PPRR-35-87	A Persistent Architecture Intermediate Language - Dearle, A.	£1.00
PPRR-36-87	Persistent Information Architectures - Atkinson, M.P., Morrison R. & Pratten, G.D.	£1.00
PPRR-37-87	PS-algol Machine Monitoring - Loboz, Z.	£1.00
PPRR-38-87	Flexible Incremental Bindings in a Persistent Object Store - Morrison, R., Atkinson, M.P. and Dearle, A.	£1.00
PPRR-39-87	Polymorphic Persistent Processes - Morrison, R., Barter, C.J., Brown, A.L., Carrick, R., Connor, R., Dearle, A., Hurst, A.J.and Livesey, M.J.	£1.00
PPRR-40-87	Andrew, Unix and Educational Computing - Hansen, W. J.	£1.00
PPRR-41-87	Factors that Affect Reading and Writing with Personal Computers and Workstations - Hansen, W. J. and Haas, C.	£1.00
PPRR-42-87	A Practical Algebra for Substring Expressions - Hansen, W. J.	£1.00
PPRR-43-87	The NESS Reference Manual - Hansen, W. J.	£1.00