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Accommodating Individual Differences in Searching a Hierarchical File System

by

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(ABSTRACT)

Individual differences among users of a hierarchical file system were investigated. The results of a first experiment indicated that psychometric tests of vocabulary and spatial visualization were the best predictors of task performance, accounting for 45% of the variance in the data. The spatial predictor was found to be the most influential. This was dramatically illustrated by the fact that, on the average, subjects with low spatial ability took twice as long to perform the task as those with high spatial ability. Surprisingly, experience alone did not predict task performance. A comparison of the frequency of command usage between subjects with high and low spatial abilities revealed that those with low spatial ability were getting lost in the hierarchical file structure. Based on the concept of visual momentum, two changes to the interface were proposed. The changes consisted of a partial map of the hierarchy and an analog indicator of current file position. A second experiment compared the performance of users with high and low spatial abilities on the old Verbal interface and the new Graphical interface. The Graphical interface resulted in changes in command usage that were consistent with the predictions of the visual momentum analysis. Although these changes in strategy resulted in a performance advantage for the Graphical interface, the relative performance difference between High and Low Spatial groups remained constant across interfaces. However, the new interface did result in a decrease in the within-group variability in performance.

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INTRODUCTION

The rapid increase in availability of computer technology has resulted in a corresponding increase in the number of people who are being required to use computers in their daily activities. As a result, users of computer-based systems differ in terms of education, background, experience, and aptitudes. To ensure that all users are capable of using a system effectively and efficiently, it may be necessary to tailor the computer interface to the individual differences which characterize the diversity of the users.

The study of individual differences has a long history in psychology (McFarlane, 1925; Thurstone, 1938). Initial efforts in the area consisted of using factor analysis to describe the nature of mental abilities (Cooper and Mumaw, 1985). Theoretical research has been directed at cataloging the abilities that underlie human intelligence (Guilford, 1967). From a more applied perspective, psychometric testing procedures have been used as a selection tool (Ackerman and Schneider, 1985). The basic procedure consists of administering one or more ability tests to a group, and then selecting the people with the highest test scores for the job. In the area of training, individual differences have been used to identify Aptitude x Treatment interactions that enable instructors to tailor the instructional strategies to learner characteristics (Cronbach and Snow, 1977; Savage, Williges, and Williges, 1982). This study takes a similar approach but applies it to the area of software interface design. Thus, individual differences will be used as a means of tailoring the computer interface to the characteristics of the users of those systems.

Methodology

This research investigates individual differences among users of a computer-based hierarchical file system. Elkerton (1985) found that some computer novices learned to perform this task very quickly and actually approached expert performance, while others had much more difficulty in learning the task. The obvious question seems to be: Is there anything that can be done to improve the performance of those that are having difficulty with the task? It is very tempting to make changes to the software on an ad hoc basis in order to accommodate the individual differences. However, due to the complexity of the problem, such an approach is doomed to failure.

An excellent example of this is described by Cronbach and Snow (1977). They cite several studies in the area of instructional strategies that tried to take advantage of subjects' high spatial ability by presenting the instructional material in a pictorial, as opposed to verbal, format. Their studies, however, did not show an advantage for the pictorial format. Cronbach and Snow (1977) hypothesize that just because the training programs used diagrams does not make them spatial in nature. Spatial ability consists of complex cognitive processes such as visualization and orientation that are not necessarily invoked just because the material is presented in a pictorial format. Thus, there seems to have been an error on the part of researchers in matching the task demands to the particular characteristics of the students.

Although this example comes from the domain of training, the principle generalizes to the present discussion. Any attempt to accommodate individual differences must be based on a conceptual understanding of why certain people are having difficulty in performing the task. The complexities involved are much too great for any approach based on shallow inferences to succeed. Thus, it is useful to think about the major conceptual issues involved in accommodating individual differences. An idealized conceptual model of the problem is presented in Figure 1. The Venn diagram at the top of the figure illustrates the case where there are individual differences in task performance. The large circle represents the capabilities of those subjects who are having difficulty with the task. The smaller circle represents the task demands being imposed on them. It can be seen that the source of the difficulty is that the task is requiring people to do something which they are not capable of doing. Thus, there is a mismatch, or impoverished "cognitive coupling" (Fitter and Sime, 1980), between the task demands and the capabilities of the user, as represented by the shaded portion of the diagram. For people who can perform the task well, this area is negligible.

The model suggests two possible ways of accommodating the individual differences. The first of these, shown in the bottom left corner of Figure 1, is to redesign the task. The idea is to eliminate the mismatch by keeping the task demands within the capabilities of the user. An alternative approach, shown in the bottom right hand corner of Figure 1, is to leave the task as is and to add to the user's capabilities so that the mismatch is eliminated. This can be done either by training the user, or by providing on-line assistance. Regardless of the accommodation strategy chosen, the goal is to eliminate the mismatch between user capabilities and task demands, and thereby increase the

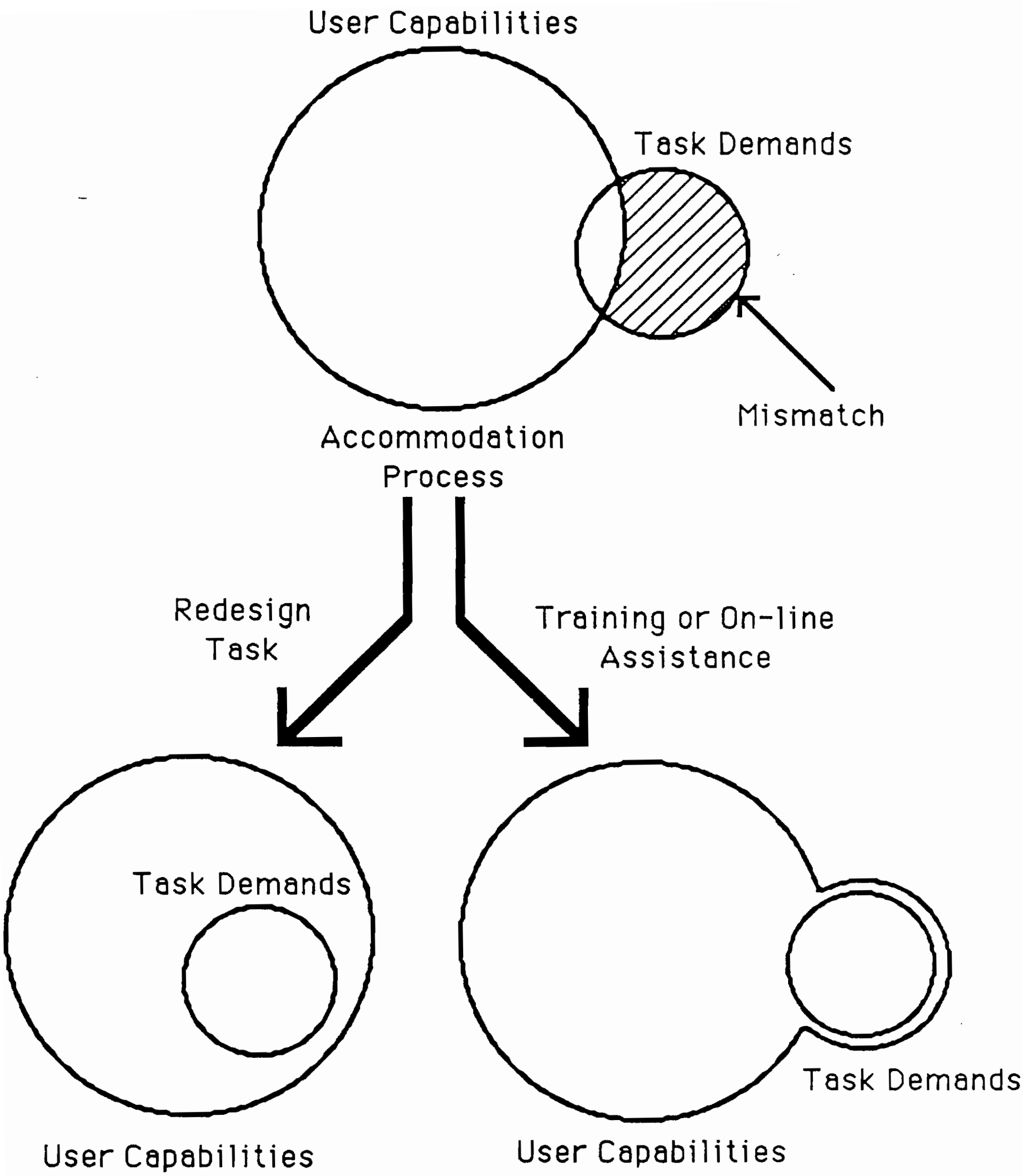

Figure 1. Idealized conceptualization of the process of accommodating individual differences.

cognitive coupling between user and machine. The choice of accommodation strategy for any given situation will depend on the characteristics of the users and task under consideration. For instance, if the source of the mismatch is a fixed ability of the user, it is unlikely that training will remedy the situation. On the other hand, if the source of the mismatch is a subtask that can only be incorporated one way then it will not be possible to redesign the task and yet maintain functionality. Although this conceptual model is idealized and general, it does help one to begin to consider the complexities involved in accommodating individual differences. Also, the model may suggest appropriate methodologies for developing an accommodation strategy.

Such a methodology has been proposed by Egan and Gomez (1985). While not derived from the model described above, their methodology fits in with the concepts described in the conceptual model. The methodology consists of three phases: assaying, isolating, and accommodating individual differences. The first step, the assay, involves discovering the important sources of individual differences in task performance. As an example, Egan and Gomez (1985) found that spatial memory and age were the main factors in determining how easy it was for novices to use a text editor. Specifically, older people and people with low spatial memory had more difficulty in performing the task. The second step in the methodology involves isolating the effects of user characteristics in particular task components. The purpose of this step is to identify the specific components of the task that are causing the variability in performance. Finally, in the accommodation phase, the problematic task components identified in the second phase are either changed or eliminated. By following this approach it should be possible to design a task so that more people are able to acquire the skills necessary to perform it.

It is beneficial to consider how the Egan and Gomez (1985) methodology can be integrated into the model described previously. Figure 2 is a graphical representation of the steps in the methodology couched within the framework of the conceptual model. The problem space is represented as a combination of three domains: that of the user, that of the task, and that of the interface. In addition, the vertical dimension represents a decomposition hierarchy (Rasmussen and Lind, 1981). The whole task, or user, is represented at the top level while lower levels represent parts or subsets of the whole. Thus, the first step in the methodology, the assay, can be seen as transfering the problem to a lower level in the decomposition hierarchy of the user domain by identifying the relevant subset of user characteristics. Similarly, the second step of isolating the individual differences can be conceptualized as moving to a lower level in the decomposition hierarchy of the task domain so as to identify the problematic task components. These two steps greatly simplify the complexity of the problem by focusing attention on the relevant user and task elements. This reduces the size of the problem space, although developing the accommodation strategy is still not trivial. The problem lies in the fact that it is not possible to compare these two sets of information; one is described in terms of the task and another in terms of the user. What is required at this point is an integration of the two descriptions. This can be done by identifying the demands being imposed on the user by the problematic task components, and the capabilities and limitations of the user from the relevant user characteristics. By bridging the gap between the user domain and the task domain, a better understanding of the reasons for the individual differences in task performance can be acquired. By identifying and understanding the source of the difficulty, it becomes much easier to devise a viable accommodation strategy.

The Egan and Gomez (1985) methodology, as shown in Figure 2, is consistent with the Cognitive Systems Engineering (CSE) approach to systems design (Hollnagel and Woods, 1983). The CSE approach recognizes that each part of the system, the human

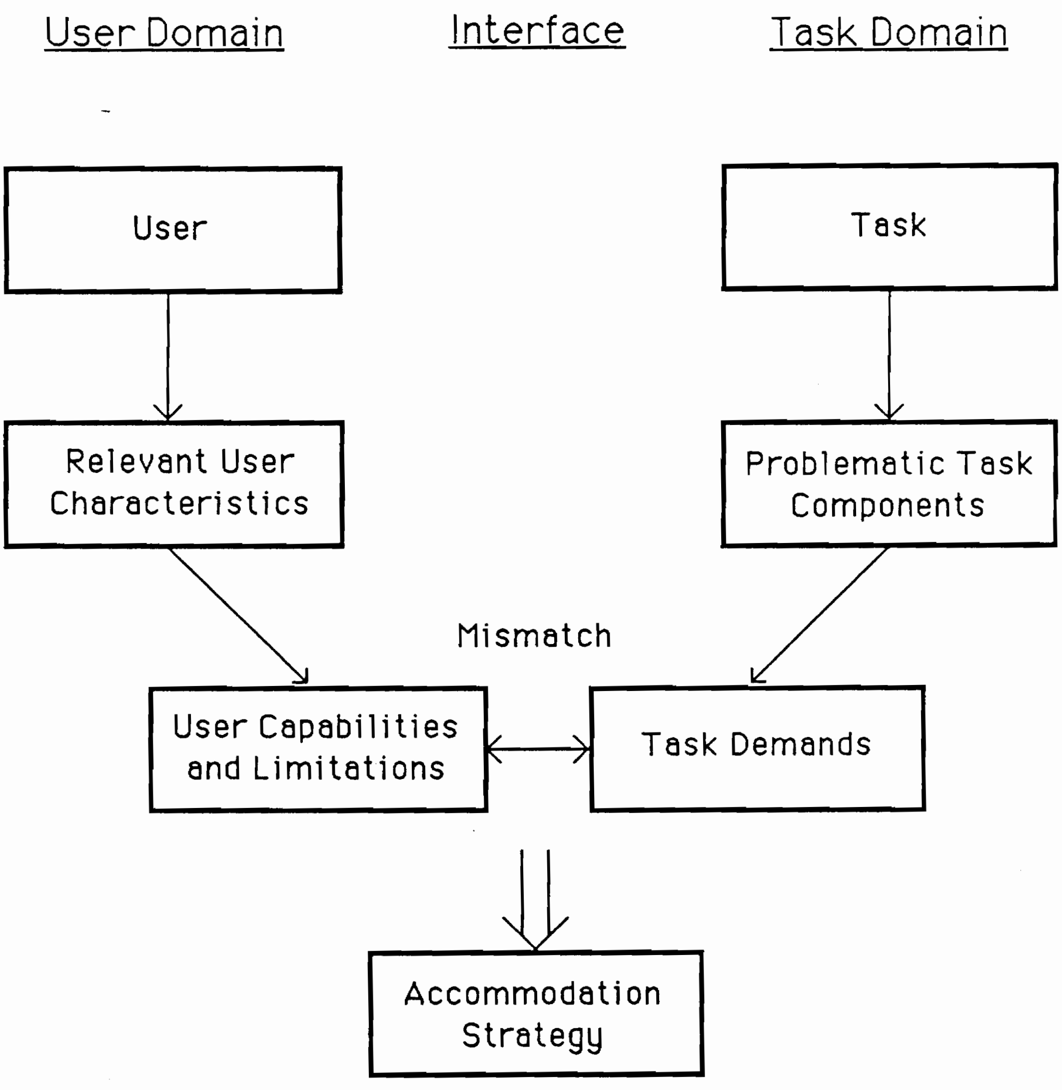

Figure 2. Graphical representation of the Egan and Gomez (1985) methodology.

and the task, should be described from its own point of view, the human as a psychological entity and the task as a physical entity, before they are integrated (Hollnagel, 1983). Because neither part can be described in terms of the other, it is important to consider the unique characteristics of both the human and the machine. The Egan and Gomez (1985) methodology accomplishes this by first assaying and isolating the individual differences before attempting to accommodate them. Mismatches of the type shown in Figure 1 result from the failure to "... address explicitly the demands a system places on the human element" (Hollnagel and Woods, 1983, p. 590). As a result, "The man-machine interface can only be built to support the operator's cognitive activities if these activities are understood" (Hollnagel and Woods, 1983, p. 594). This is in fact the main strength of the Egan and Gomez (1985) methodology: an accommodation strategy is developed from an understanding of why individual differences in task performance exist in the current system.

However, there are a few limitations with this approach that merit attention. First, as Egan and Gomez (1985) point out, even when a significant amount of effort has been put into the first two steps, the design remedies are not always obvious. However, there is little doubt that assaying and isolating the individual differences, before trying to accommodate them, greatly increases the chance of obtaining a useful design. A second problem is that the process, since it is one of redesign, will be biased by the pre-existing design. This could be avoided by starting the design process from scratch. On the other hand, adopting an incremental design approach will result in a significant savings of time and resources. Perhaps the greatest difficulty in following the methodology is taking into account the fact that parts of the task may be interrelated in complex ways (Hollnagel, 1983). In some cases, changing or eliminating a task component may have a major effect on how the user perceives the task, and therefore can qualitatively change the way the task is performed. Anticipating such an effect is extremely difficult. Finally, there is a problem of conflict. In a review of the literature on individualized software interfaces, Rich (1983) observed that system features that make the task easier for one type of user often make it more difficult for another. One resolution to this problem is to design an adaptive interface that changes itself according to the characteristics of the user. As a simple example, a system would be capable of providing extensive and elaborate on-line documentation, or a very brief, terse help function, depending on whether the user was known to be a novice or an expert, respectively. Of course, if the interface obtained by following the approach described above is found to be better for all users, then there will be no need to provide an adaptive interface.

EXPERIMENT 1

The Egan and Gomez (1985) methodology was adopted in this research to accommodate individual differences in searching a computer-based hierarchical file system. An initial experiment was conducted to determine which ability measures are accurate predictors of task performance, and which task components are causing the most difficulty for the slow subjects. In the terminology of Egan and Gomez (1985), this first experiment is restricted to assaying and isolating the individual differences. A secondary objective of this experiment was to assess the magnitude of the differences in task performance.

Method

Subjects. A total of 30 subjects, 14 of whom were females, volunteered for the study. Subjects' ages ranged from 18 to 31 years, with a mean of approximately 21 years. Each subject was paid a total of $35 for participating in the study.

Experimental design. Subjects were assigned to one of two groups according to the number of hours of their interactive computer experience. The experience of subjects in the Novice Group ranged from 0 to 20 hours, while the experience of subjects in the Experienced Group ranged from 100 to 1000 hours. There were 15 subjects in each of the two groups.

Task environment. The task environment used in the present study was developed by Elkerton (1985). The subject's goal was to locate a specific piece of information (the target) in a hierarchical file system. There are a total of 15 files in the three-level hierarchy, as shown in Figure 3. The number of lines in a file, also shown in Figure 3, ranges from 55 to 447, with a total of 2780 lines in the entire hierarchy. All of the files contain information about armored personnel carriers, army operations, combat support, and tanks. The information in the files is structured by the use of hierarchies, tables, paragraphs, and lists. On each trial subjects were required to locate a target that existed on only one line of the system.

To locate the target, subjects were provided with 12 search commands that could be selected via a touch screen display, as shown in Figure 4. The display also showed the name of the file currently being displayed (top left corner of the screen), the number

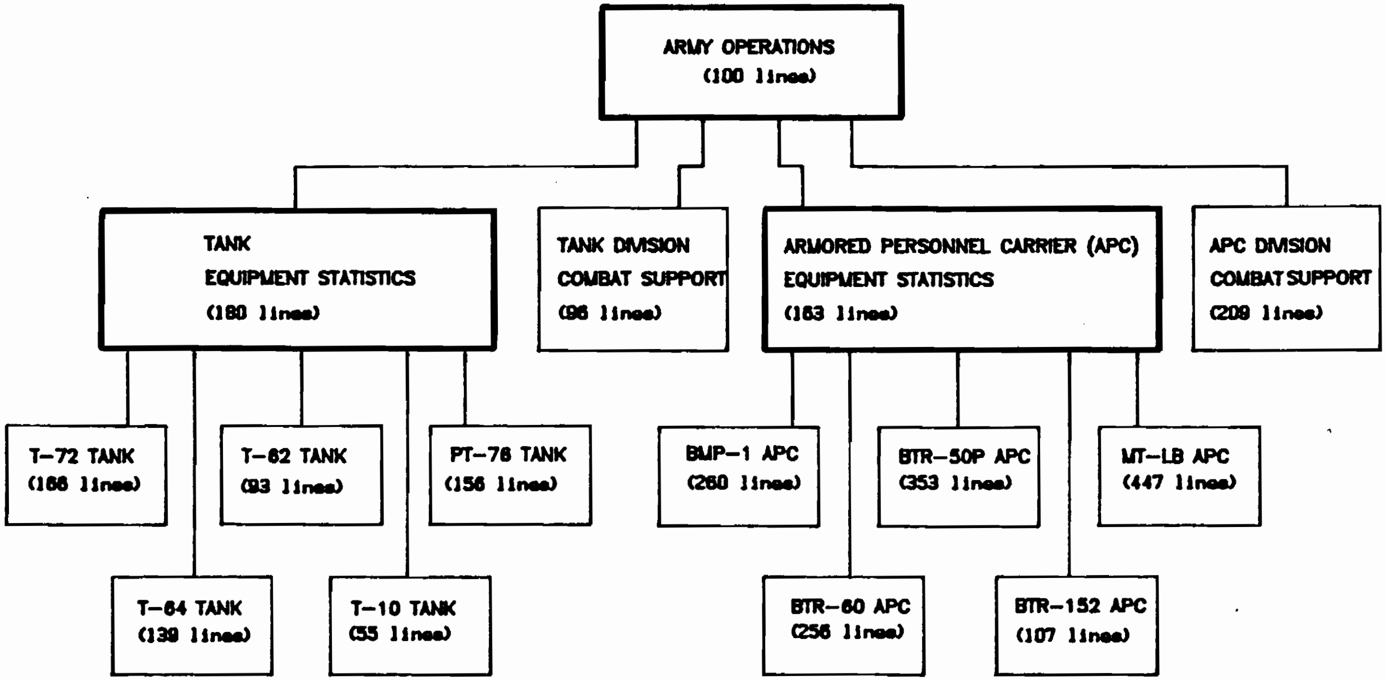

Figure 3. Hierarchical file structure, adapted from Elkerton (1985).

of lines in the current file (top right corner of the screen), and a 7-line window into the current file (top half of screen). Subjects' commands appeared on the input and message line located in the center of the screen. The output produced by the search commands was displayed in the work area in the bottom left corner of the screen. Subjects selected a command by touching the appropriate box on the lower right hand portion of the screen.

A complete description of the 12 search commands is provided by Elkerton (1985). The commands can be divided into three categories: file selection commands (FILE SELECT, ZOOM IN, and ZOOM OUT), large movement commands (INDEX, SEARCH, SEARCH-AND, SEARCH-AND-NOT, and SECTION), and small movement commands (PAGE UP and DOWN, SCROLL UP and DOWN).

The file selection commands are used to traverse the file hierarchy. The ZOOM IN procedure is used to move down to a file that is one level lower in the hierarchy than the currently selected file. Conversely, the ZOOM OUT procedure enables subjects to move up one level in the hierarchy. The FILE SELECT command provides a more direct way of selecting a file. Using it, subjects can select any file that is lower in the hierarchy than the current file. Thus, it is possible to go directly from the top level to any file at the lowest level in the hierarchy. These commands enable subjects to select and view any file in the hierarchy. All of the remaining commands are used to search for information. It is important to note that the scope of the search commands is limited to the currently selected file. That is, it is only possible to search for information within the current file. To search for information in other files, subjects must first use one of the three file select procedures discussed here to select the new file; only then can they search for information in that new file.

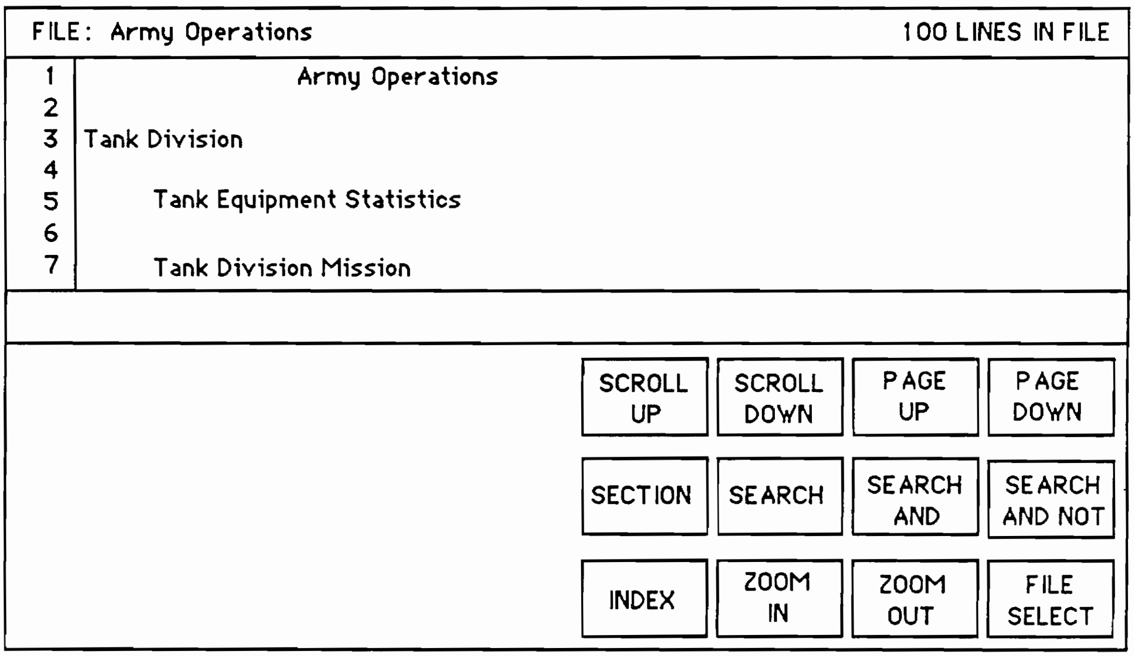

Figure 4. File system workstation display, adapted from Elkerton (1985).

The large movement commands allowed subjects to take advantage of the structure provided within each file. For instance, the SECTION procedure is analogous to a table of contents. When it is selected, a menu of the sections and subsections contained within the current file is displayed in the work area. The 7-line window is then positioned at the beginning of the selected section. The INDEX procedure is analogous to an index of the topics contained in the current file. Its operation is similar to the SECTION command. An index of the topics covered in the current file is displayed in the work area, and the 7-line window is then placed at the point in the file where the topic of interest is located. The search string procedures enable subjects to locate strings of text within the current file. The SEARCH command allows subjects to locate a specific text string. The SEARCH-AND/SEARCH-AND-NOT variants are merely multiple string searches that use Boolean logic. The SEARCH-AND command enables subjects to search for two strings that are located within at most seven lines of each other. The SEARCH-AND-NOT command adds the constraint that a third string should not appear near the first two. For example, a search for Tank-AND-Regiment-NOT-Orange would try to find a 7-line segment of the file where both Tank and Regiment appear, but Orange does not.

The fine movement commands enable subjects to move the current file through the window either one line (SCROLL UP or DOWN), or seven lines (PAGE UP or DOWN) at a time. Both of these commands can be used continuously. Once subjects thought they had located the target, they hit a function key and entered the line number of the target. The target had to be in the 7-line window for the response to be accepted. If the subject's response was correct, a message to that effect was displayed, and a new trial was presented. If the subject's response was incorrect, a message to that effect was displayed along with a suggestion to continue searching for the target. The primary performance measure is the time taken to find the target. Secondary performance measures include the total number of search operations used per trial, and the number of different search operations used on each trial.

Apparatus. The hierarchical information retrieval system software was implemented on a VAX 11/750 computer. An elevated time-sharing priority was used during the study to ensure that the system response time was consistent across sessions. Information was displayed on two Digital Equipment Corporation VT100 terminals. The primary terminal displayed the interface shown in Figure 4, while the secondary terminal displayed the targets. The search commands were selected via a Carroll Touch Technology touch entry screen installed on the primary terminal. Additional inputs were typed on a VT100 keyboard.

Pre-testing sessions. The first two sessions of the experiment, each lasting for about 1 hour and 45 minutes, consisted of pre-testing. Subjects were measured on the battery of 21 predictors summarized in Table 1. Three demographic variables were included in the test battery: sex, hours of experience with interactive computer systems, and number of computer courses taken. These last two were included to test the effect of previous computer experience and knowledge on task performance.

Previous research has suggested that cognitive style is an important factor influencing behavior in computer-based tasks (Ambardar, 1984; Benbasat, Dexter, and Masulis, 1981; Shneiderman, 1980). Therefore, two measures of cognitive style were included in the test battery. The Abstract Orientation Scale (O'Connor, 1972) characterizes people as being either abstract or concrete. Concrete thinkers tend to be poor at integrating conceptual data in assessing complex problems. They also tend to organize

Table 1. Candidate Predictors of Task Performance

Spatial	Demographic
Flexibility of Closure	Sex
Perceptual Speed	Computer Experience
Spatial Orientation	Computer Courses
Spatial Scanning	
Spatial Visualization	Cognitive Style
Visual Memory	Abstractness
	Field Dependency
Verbal	
Vocabulary	Other
Reading Rate	Anxiety
Comprehension	Information Processing Rate

data into relatively few conceptual dimensions. Abstract thinkers, on the other hand, tend to show a greater sensitivity to available cues, as well as a greater ability to use these appropriately and completely in problem solving. Overall, people with an abstract cognitive style tend to be better problem solvers. As an example, Hendrick (1979) found that concrete people were slower and more reluctant to change their set in searching for solutions to a problem. It was hypothesized that slow subjects may have a predominantly concrete cognitive style.

The second measure of cognitive style included in the present study was the Embedded Figures Test (1971). With this test, subjects are classified as being either field dependent (FD) or field independent (FI). Subjects who are FI experience parts of a visual field as being discrete from the background, while for those who are FD, perception is strongly dominated by the overall organization of the surrounding field. Scores on the EFT have been found to be related to performance on tasks that require perceptual disembedding, i.e., tasks that require the separation of part of the field from the background. It was hypothesized that successful performance on the information retrieval system requires subjects to disembed the target from the surrounding information in the file. According to this hypothesis, faster subjects will tend to be predominately FI.

Because the information contained in the files is verbal in nature, subjects with greater verbal ability are expected to perform the task more quickly. In fact, other researchers have found verbal ability to be a good predictor of performance in computer-based tasks requiring reading (Egan and Gomez, 1985). Thus, the Nelson-Denny Reading Test (1973) was included as a measure of verbal ability. This test is composed of three separate sections: reading rate, vocabulary, and comprehension. Each of these was included as a candidate predictor.

To complement the measures of verbal ability, several measures of spatial ability were also included in the test battery. All of these were selected from the Kit of Factor-Referenced Cognitive Tests (Ekstrom, French, and Harmon, 1976). Two forms of each of the following five subsets of spatial ability were selected: flexibility of closure (forms 2 and 3), perceptual speed (forms 2 and 3), spatial orientation (forms 1 and 2), spatial scanning (forms 1 and 2), and spatial visualization (forms 1 and 2). These particular tests were selected because they have been found to be accurate measures of spatial ability (Dupree and Wickens, 1982). In addition, a test of visual memory (form 2) was also included in the test battery. Egan and Gomez (1985) found that visual memory was highly correlated with text editing performance. Due to the spatial nature of the file structure, it is conceivable that subjects who could remember the structure would perform the task more quickly.

Anxiety has been suggested as a correlate of performance on computer-based tasks (Shneiderman, 1980; Spielberger, 1977). Consequently, the State-Trait Anxiety Inventory (1983) was chosen as a candidate predictor. The STAI provides two measures: state anxiety and trait anxiety. A person's momentary level of anxiety is obtained by subtracting the trait anxiety score from the state anxiety score. If this difference is zero, then the subject is in a neutral state; if the difference is positive, the subject is under stress; if the difference is negative, the subject is relaxed. The final measure included in the test battery was the subject's information processing rate. This was calculated by having subjects perform a choice reaction time task with 1, 2, and 3 bits of uncertainty, and then calculating the slope of the Hick's Law function (Wickens, 1984). In total, 21 predictors were selected for the test battery, some of which were multiple forms of the same construct.

Training session. After the two pre-testing sessions, subjects participated in a self-paced training session of approximately 2.5 hours. The training was presented on a VT100 terminal and was supplemented with oral instructions presented over a Digital Equipment Corporation DECtalk speech synthesizer. Initially, all subjects were provided with a map of the file structure and a listing of the information contained in all of the files. They were then given detailed instructions as to both the type of information and organization of the document. Subjects were then trained in the use of each of the 12 search commands. Following the instruction for each command, subjects were given two trials to practice the exclusive use of that command. Towards the end of the session, subjects performed 12 practice trials with all search commands available. During the training session, subjects were allowed to refer to the map of the hierarchy and the hard copy of the information in the files. Finally, subjects received a criterion test of their knowledge of the information retrieval system. All subjects were required to score at least 70% in order to be included in the experiment, thereby ensuring that they all posessed a minimum amount of system knowledge. The training was the same for all subjects, regardless of their experience.

Data collection session. In the final data collection session, subjects were presented with 4 warmup trials followed by 2 sets of 12 targets. A five-minute break was given between sets. All subjects received the same targets, but the order of presentation was randomized for the test targets. The order of presentation of the warmup trials was kept constant. During this session, subjects did not have access to the map of the hierarchy nor the hard copy listing of the information in the files. In summary, the entire experimental procedure consisted of two pre-testing sessions, a training session, followed by the data collection session. On the average, subjects took approximately seven hours to complete the experiment.

Results and Discussion

Assaying the individual differences. The analyses described in this section are directed at identifying the predictors of task performance. The summary tables for all the ANOVAs performed in Experiment 1 are provided in Appendix A. First, Pearson product-moment correlation coefficients were calculated between all predictors and the three measures of task performance. Of the 21 predictors, 6 were significantly correlated with at least one performance index as shown in Table 2. Two of the predictors, vocabulary and comprehension, are subsets of verbal ability, while the other four are subsets of spatial ability. From Table 2 one can see that the time to find a target is the most sensitive of the performance measures since all six predictors were correlated with it.

These six predictors were then put into a stepwise regression equation to determine the best overall prediction equation. Since Time was the most sensitive performance index, it was chosen as the dependent variable for the equation. The overall best equation was chosen by a two step process. First, of all the one-variable models, the one maximizing the variance accounted for was selected. A similar process was performed for all the two-variable models, three-variable models, and so on up to the single 6 variable model. Of these 6 models the one with the lowest Mallows' Cp was chosen as the best equation (Draper and Smith, 1981). This equation is shown in Table 3. The equation contained two predictors and accounted for 45% of the variance in the data.

Table 2. Correlations Between Predictors and Performance

Predictor	Time	Total Commands	Different Commands
	Performance Index		
Vocabulary	-0.41 *	-0.42 *	-0.34
Comprehension	-0.37 *	-0.35	-0.26
Spatial Scanning (1)	-0.38 *	-0.34	-0.33
Flexibility of Closure	-0.41 *	-0.30	-0.25
Spatial Visualization (1)	-0.47 **	-0.42 *	-0.44 *
Spatial Visualization (2)	-0.57 ***	-0.46 *	-0.46 *

* $p < 0.05$ ** $p < 0.01$ *** $p < 0.001$

One of the predictors, vocabulary, is verbal in nature while the other, spatial visualization, is spatial in nature. The fact that the spatial predictor has a larger beta weight and a larger R-squared value indicates that it is the most predictive of the two variables.

Intuitively, one would expect that computer experience would also be correlated with task performance. Indeed, this is the case: people with more hours of interactive computer experience took less time to perform the task, r (30) = -.34, p = .06. However, when spatial visualization ability is partialled out, the correlation between time and experience is negligible, r (30) = -.15, p > .1. This suggests that experience alone does not affect performance. The main reason that experience and time are correlated is that people with more computer experience also tended to have better spatial ability, r(30) = .39, p = .03. One explanation for this result is that people with low spatial ability stay away from computers, and therefore never become experienced. This hypothesis of self-selection has been put forth by other researchers as well (Gomez, Egan, and Bowers, 1986). Alternatively, working with computers could help individuals develop spatial ability. In fact, previous research indicates that scores on psychometric tests of spatial ability can be improved with training (Blade and Watson, 1955; Brinkman, 1966). Based on the data collected it is not possible to test which of these explanations is correct. However, the finding that experience alone does predict performance is interesting nonetheless.

Another purpose of this study was to assess the magnitude of the individual differences in task performance. If these differences are of practical significance, as opposed to mere statistical significance, then it becomes economically feasible to redesign the software interface in order to accommodate the individual differences. If, on the other hand, the magnitude of the differences is small, it is not worth going through the redesign effort since the benefits will be small relative to the cost involved. To assess the

Table 3. Prediction Equation for Time to Find Target

Raw Score Regression Equation

T = 516.29 - 1.67V - 16.09S

where T = Time

V = Vocabulary

S = Spatial Visualization

	Variable	
	Vocabulary (V)	Spatial Visualization (S)
Normalized Beta Weight	-0.35	-0.54
R-squared	0.12	0.33
F	6.14	14.07
p	0.02	0.001

magnitude of the differences, subjects were divided into two equal sized groups according to their vocabulary scores, and an ANOVA with time as the dependent variable was performed. The average times to find a target for the High and Low Verbal groups were not significantly different, $F(1,28) < 1$, $p > .1$. A similar analysis was performed with subjects divided into two groups according to their spatial visualization scores instead. Results indicate that the Low Spatial group took more time to find a target than the High Spatial group, $F(1, 28) = 8.26$, $p = .0077$. Figure 5 illustrates the dramatic performance difference between the two groups. On the average, subjects with low spatial ability took twice as long to find a target as those with high spatial ability (average times were 192.02 s and 94.53 s, respectively). The average times to find a target ranged from 53.54 s to 513.17 s, almost one order of magnitude. Obviously, redesigning the software interface so as to accommodate people with low spatial ability could result in enormous savings.

Isolating the individual differences. Before redesigning the interface, one must first identify which components of the task are causing the most difficulty for the subjects with low spatial ability. By performing this step, one has a much better idea of what parts of the task need to be changed or eliminated in order to accommodate people with low spatial ability. A comparison of command selection strategies of subjects with high and low spatial ability should be useful in isolating the individual differences.

The analysis of search command selection was based on a polling procedure developed by Elkerton and Williges (1985). Conceptually, each subject is given a vector of 12 votes, one for each of the 12 search procedures. A vote is cast for a search procedure if it is selected at least once during a trial. The votes are summed across the 24 experimental trials to yield the total polls for each search command. These are then converted

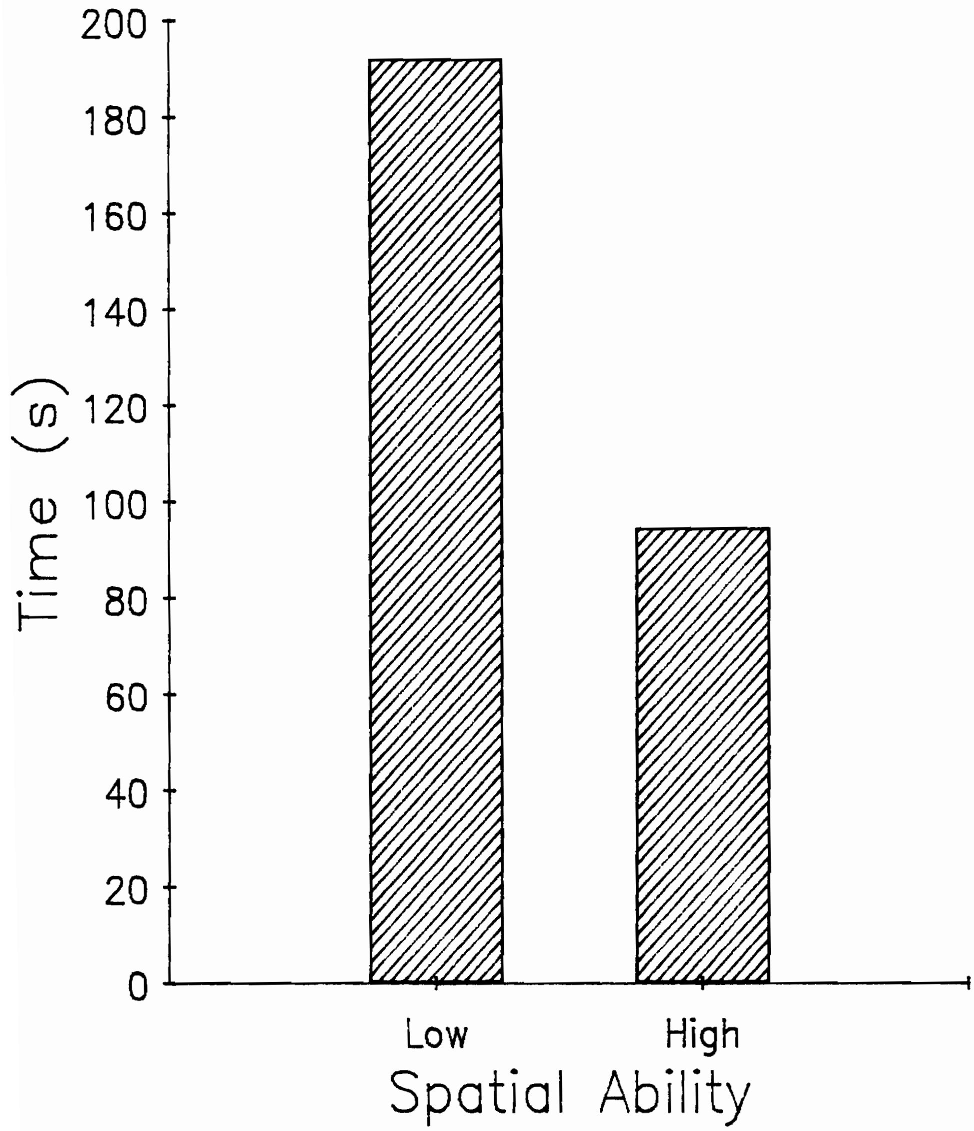

Figure 5. **Average time per trial for high and low spatial ability groups.**

into a proportion indicating the relative use of a search command for each subject. The polling procedure protects against the possibility of bias due to the use of highly repeated search procedures in that each command is counted only once per trial per subject.

As before, subjects were divided into two groups according to their spatial visualization scores. ANOVAs were then performed for each of the 12 commands. The two groups differed in their usage of three commands: ZOOM OUT, $F(1,28) = 26.58$, $p < .0001$; SCROLL UP, $F(1,28) = 4.88$, $p = .0355$; and SCROLL DOWN, $F(1,28) = 5.40$, $p = .0277$. Subjects with low spatial ability used these three commands more frequently than subjects with high spatial ability, as shown in Figure 6. Elkerton (1985) observed a similar pattern of command selection differences between computer novices and experts. The ZOOM OUT command has a unique function in the information retrieval system; it is the only command which allows subjects to move up in the hierarchy. Therefore, the results suggest that subjects with low spatial ability were going into the incorrect files, and then had to go back up the hierarchy to go into the file where the target was located. In effect, subjects were getting lost in the hierarchical file structure.

The greater use of the SCROLL UP and SCROLL DOWN commands by subjects with low spatial ability can be interpreted as an indication that they were getting lost within each file as well. Because they did not know where they were within the file, low spatial subjects scrolled up and down in order to find the information that they were looking for. This result replicates an earlier finding in a study requiring subjects to search within a one-file system, where slower subjects were also found to use scrolling procedures more often than faster subjects (Elkerton and Williges, 1985).

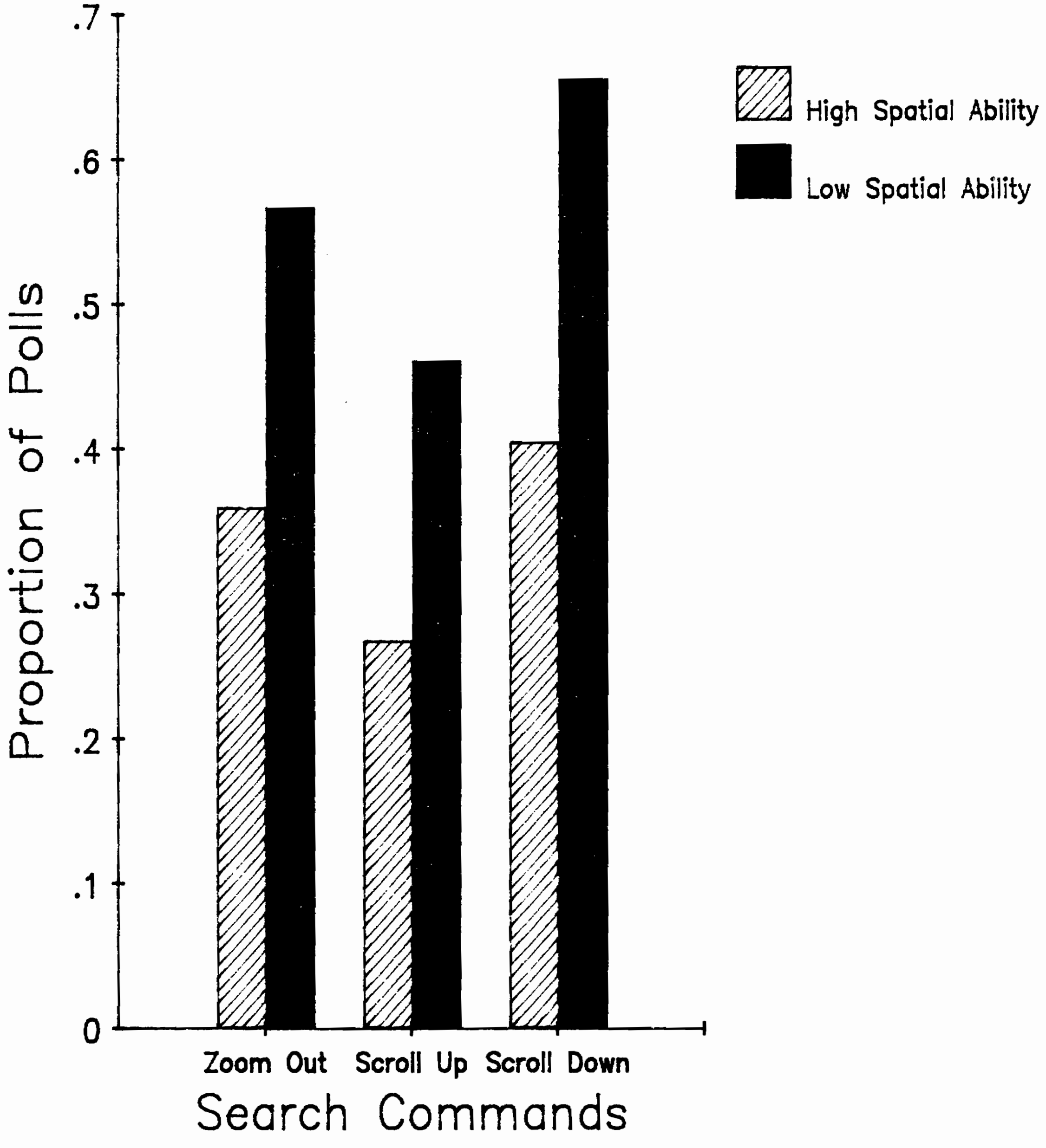

Figure 6. Average frequency of search command usage for high and low spatial ability groups.

Conclusions

The assay of the individual differences revealed that psychometric tests of vocabulary and spatial visualization were the best predictors of performance on the hierarchical information retrieval system. The spatial predictor was the most influential of the two, as illustrated by the fact that subjects with low spatial ability took twice as long to perform the task as those with high spatial ability. Contrary to expectations, the results indicated that experience alone does not predict performance. The attempt to isolate the sources of individual differences revealed that subjects with low spatial ability were getting lost, not only in the hierarchy, but within files as well. The magnitude of the performance differences between high and low spatial ability subjects suggests that redesigning the interface to accommodate those with low spatial ability could result in substantial savings.

The next step in the Egan and Gomez (1985) methodology is to accommodate the individual differences in task performance. As shown in Figure 1, this can be accomplished in three ways; by changing the task, by training the users, or by providing on-line support. However, just because the individual differences have been assayed and isolated does not guarantee that the accommodation will be successful. This difficulty is acknowledged by Egan and Gomez (1985, p. 215): "The step of accommodating individual differences not only tests the analyses that precede it, but it also tests the theory of how an experimental manipulation ... will change the original task." Although the assay and the isolation phases locate the locus of the individual differences in specific task components and certain user characteristics, they do not provide the designer with enough information to predict whether a given accommodation scheme will be successful. Therefore, to strengthen the conceptual basis from which an accommodation strategy will be developed, a review of the literature was conducted. By examining previous research it should be possible to gain a deeper understanding of the sources of the individual differences and thereby suggest a feasible accommodation strategy.

SELECTING AN ACCOMMODATION STRATEGY

Multiple Resource Theory

The fact that the two main predictors of performance were spatial and verbal ability measures is consistent with Wickens' theory of multiple resources. He and his colleagues have performed various experiments that have led them to conclude that there are two different codes of representation in working memory, one verbal and the other spatial (Wickens, Mountford, and Schreiner, 1981; Wickens, Sandry, and Vidulich, 1983; Wickens, Vidulich, and Sandry-Garza, 1984). A spatial task is defined as one requiring "a judgement or integration concerning the three axes of translation or orientation," while a task is considered verbal if it "requires the use of language or some arbitrary symbolic coding for its completion" (Wickens et al., 1983, p. 228). It should be noted that the verbal-spatial labels should be considered endpoints of a continuum, not disjoint resources. Multiple resource theory has been used mainly to predict performance on tasks involving time-sharing. The theory predicts that there will be less of a performance decrement when two tasks require different resources as compared to when both of the tasks are competing for the same resource pool. Although the file search task does not involve time-sharing, it may be possible to use multiple resource theory to predict the effectiveness of alternative accommodation strategies.

Visual Momentum

The getting-lost phenomenon has also been previously documented by other researchers (Billingsley, 1982; Elm and Woods, 1985). "Getting lost in a display network means that the user does not have a clear conception of relationships within the system, does not know his present location in the system relative to the display structure, and finds it difficult to decide where to look next within the system" (Woods, 1984, p. 230). This seems to be the problem that the slow subjects in the first experiment were experiencing. The fast subjects, on the other hand, did not demonstrate these difficulties. This suggests that people with low spatial ability, more specifically, spatial visualization, are particulary susceptible to the getting-lost phenomenon.

Based on research in cognitive psychology, Woods (1984) introduces the concept of visual momentum to account for the getting-lost phenomenon. (To avoid confusion, it should be noted that the concept of visual momentum used here is that described by Woods, 1984, and not that discussed by Hochberg and Brooks, 1978. However, Hochberg, 1978 has conducted some research that is unrelated to his concept of visual momentum, but which does lend support to Woods' definition of visual momentum). Visual momentum is a measure of the effort required to integrate and extract information across a set of displays (Woods, 1984). When there is a high degree of visual momentum, it becomes very easy for users to assimilate new data after a transition to a new display. In the case of the hierarchical file system, high visual momentum means that it is relatively easy for users to know where they are in the hierarchy. On the other hand, when visual momentum is low, information extraction is slow and error prone. This results in the getting-lost phenomenon, as indicated by the frequent use of the ZOOM OUT command. Thus, the frequency of usage of the ZOOM OUT command can be used as a measure of visual momentum for the present system.

The frequency of usage of SCROLL UP and SCROLL DOWN are also related to the concept of visual momentum. The difference between these commands and ZOOM OUT is that the latter results in a transition to a new subfile in the hierarchy, while the former results in a transition *within* a subfile. The frequent usage of ZOOM OUT implies that the user does not have a cognitive map of the hierarchy. The cause behind the frequent usage of the scrolling commands is more subtle. Rather than being a *result* of poor visual momentum, the frequent use of the scroll commands is a reflection of the subjects' decision to *adopt a strategy that inherently has a greater degree of visual momentum associated with it.*

Research conducted on the perceptual consequences of various techniques for editing motion pictures explains why this is so. Hochberg (1978) has shown that the time required to integrate successive scenes in a motion picture is related to the amount of overlap in the two scenes. Thus, continuous transitions, such as a pan shot or a tracking shot, contain visual information about the location of one view with respect to the next, and therefore result in high visual momentum. Discontinuous transitions, also called cuts, result in low visual momentum unless the viewer is provided some information with which to understand the transitions. There are several techniques that can be used to improve the visual momentum associated with cuts. One of these is to maximize the amount of overlap between scene cuts; another is to use a long shot to provide a schematic map that allows the viewer to anticipate views (Hochberg, 1978). The time required to comprehend a cut depends on how well the viewer has been prepared to expect the sequence.

The analogy to the hierarchical file system is evident. The scroll commands provide continuous transitions by maximizing the overlap between successive displays, while other commands, such as SEARCH, INDEX, and SECTION provide discontinuous cuts to the next display, i. e., they result in a discrete jump to a new place in the current file. Thus, there is a tradeoff between efficiency and cognitive load. The use of the scroll commands, while very slow, facilitates the integration of information across successive displays by maximizing the overlap between successive views. Commands such as SEARCH, on the other hand, are much more efficient since they take the user to the information he is looking for in one step (provided the user is in the correct file and the correct string was searched for); in Hochberg's terms, these commands provide a discontinuous transition to a new scene. However, these commands put more of a burden on the user to keep track of where he is in the file after each successive move. The problem lies in the fact that, in the hierarchical file system, there is no equivalent of a long shot with which to give the users an overview of the file they are in.

The data of the first experiment indicate that subjects with high spatial ability were better able to keep track of where they were in the file without resorting to the use of the scroll commands. In contrast, subjects with low spatial ability were not able to deal with the added cognitive effort of keeping track of where they were in the file after a discontinuous cut. Thus, they adopted a strategy (increased use of the scroll commands), which provided them with continuous transitions between views. The drawback was an increase in the average time to find a target. The important thing to realize, however, is that these subjects compensated for their lack of spatial ability by using commands which provide them with higher visual momentum than the discontinuous commands. These findings also show that, to attain an acceptable level of performance, people with low spatial ability need displays with more visual momentum than people with high spatial ability.

Improving Visual Momentum

Inter-file transitions. The analogy to Hochberg's work suggests various ways in which to improve the visual momentum of the system. For instance, the equivalent of a long shot should result in an improvement in the subjects' ability to determine where they are in the hierarchy, where they can go to next, and where everything else is in relation to their current position. The computer equivalent of a long shot is a map of the file structure, similar to Figure 3. By making such a map available, the visual momentum of the system should increase. This should be reflected by a decrease in the frequency of use of the ZOOM OUT command, and therefore, a decrease in the average time to find a target. The addition of a map should facilitate the cognitive mapping of the environment. Without a relatively accurate and complete cognitive map, people will tend to get lost; just as the subjects with low spatial ability did in the hierarchical file system. Intuitively, providing users with a map would seem to make the task of cognitive mapping much easier. In fact, pictorial representations of complex structures have been found to facilitate the development of a cognitive map (Billingsley, 1982).

However, as shown in Figure 2, to accommodate the individual differences in this particular task it is necessary to aid people with low spatial ability in particular. Will the presentation of a map of the structure aid this subset of users? Intuitively, one could argue both sides of the issue. It would seem to make sense that providing subjects with a map would help them in remembering where they are in the hierarchy, and where all the other files are in relation to their current position in the hierarchy. On the other hand, one could conceivably argue that a map is a spatial form of representation, and that since the subjects are lacking in that ability, it would be of little use to them because they would not be able to extract the information they needed from it. Fortunately, research performed at the Rand Corporation provides empirical evidence as to which of these two opposing views is correct. Thorndyke and Goldin (1981) divided their subjects into two groups, good and poor cognitive mappers, according to the accuracy of their spatial knowledge about their own community. They found that the only characteristic that distinguished between the two groups was spatial ability. In a related study, Goldin and Thorndyke (1981) examined the skills of the same subjects in learning a new environment, map learning, map using, map interpretation, spatial judgements based on a memorized map, and navigation in a new environment based on a memorized map. Their results indicate that good cognitive mappers, when compared to poor cognitive mappers, excel in their ability to encode and retain knowledge of spatial relationships and manipulate their internal knowledge representation in order to compute spatial judgements. More importantly, there was no difference between the two groups' abilities to extract and use information from a map. On the basis of these results, it is expected that providing a map of the hierarchy will aid the performance of subjects with low spatial ability.

Intra-file transitions. In addition to not knowing which file they were in, the slow subjects in the first experiment were also having difficulty in keeping track of their position within the currently selected file. This finding is consistent with the research of several cognitive psychologists indicating that cognitive maps are internally represented in a hierarchical structure (Hirtle and Jonides, 1985; Lehtio, Poikonen, and Tuunainen, 1980; McNamara, 1986). These researchers have found that people have multiple internal representations of a given environment, with the higher level representations containing general spatial information and the lower level representations containing more detailed information about the environment. Within this framework, it seems that the slower subjects have difficulty in acquiring and retaining spatial information at both the higher and the lower levels of representation. As discussed above, presenting subjects with a map should aid them in keeping track of where they are in the hierarchy (higher level representation), but another aid is required for them to be able to know where they are in the current file (lower level representation).

Again, the analogy to film editing suggests a possible remedy. What is needed is a long shot, not of the hierarchy, but of *the currently selected file*. One possible form that such an aid might take is an analog indicator in the shape of a rectangle, much like the indicator of current file position provided in the standard Apple Macintosh interface. The top and bottom of the rectangle would represent the top and bottom of the current file, and a horizontal line would be drawn in the rectangle to indicate the current position in the file. This type of change to the interface should result in a change in strategy on the part of the low spatials. Recall that the reason that the low spatials used the scrolling commands so much was that they could not deal with the burden of keeping track of where they were in the current file after a discontinuous cut. The analog indicator provides a means of relieving this burden. Thus, there should no longer be any need to tradeoff efficiency for a decrease in cognitive load. The result should be a switch in emphasis from the scroll commands to the more efficient discontinuous commands, such as SEARCH. This change in strategy should lead to a corresponding improvement in performance.

Spatial representations. Will these two proposed changes in the interface improve the performance of both the high and the low spatial ability subjects, or just the low? Other researchers have found that aids of the type proposed above are usually quite effective in improving the performance of all users (Elm and Woods, 1985; Herot, 1984; Sebrechts, Deck, and Black, 1983). Providing information from a user's point of view facilitates the development of a mental model of the system (Nievergelt and Weydert, 1980). Even though the information being provided to the user may be the same, the way that information is represented influences the amount of information that can be processed during problem solving (Mayer, 1976). A spatial metaphor of the type proposed here is especially powerful. By presenting information in this way, users can transfer the knowledge they already possess about how to navigate through an environment, and use it on the problem at hand (Carroll and Thomas, 1982). The use of the spatial metaphor thereby provides a conceptual framework that enables users to organize their knowledge about the system, and allows them to interact with the system in a very natural, almost intuitive, manner. Therefore, it is expected that the proposed aids will improve the performance of all users. Users with low spatial ability are expected to benefit the most since their performance is so poor to begin with. In the case of users with high spatial ability, there is only so much they can improve before the factors limiting their performance become perceptual and psychomotor, rather than cognitive, in nature.

Multiple resource theory revisited. It is interesting to compare the predictions extracted from the literature reviewed above to those made by Wickens' multiple resource theory. Recall that this theory postulates that there are two fundamental codes of representation in working memory, one spatial and the other verbal. Wickens and Weingartner (1985) found that, in terms of resource theory, the difference between people with high and low spatial ability is that people with high spatial ability have a greater amount of spatial resources available to them. Thus, the theory predicts that the introduction of the aids described above will improve the performance of people with high spatial ability; the theory makes no prediction in the case of people with low spatial ability (C. D. Wickens, personal communication, April 7, 1986). Unfortunately, it is not possible to make predictions about the manipulation of greatest interest in the current study. In all fairness, this is not surprising since the theory is intended for time-sharing tasks, where it has been very effective in predicting human behavior.

Summary

This review of the literature has been instrumental in identifying the sources of the individual differences among users of the hierarchical file system. The problem lies in the system's low visual momentum and the inability of subjects with low spatial ability to deal with the resulting increase in cognitive load. The analogy to Hochberg's (1978) research on editing of motion pictures suggests that the addition of an analog indicator showing the current file position and a map of the file structure should help to accommodate the individual differences in task performance.

These changes to the interface should result in several observable changes in performance. The map of the hierarchy should cause a decrease in the frequency of usage of the ZOOM OUT command, indicating an increase in visual momentum. It is also predicted that the addition of the analog indicator will result in a decrease in the frequency of usage of the scroll commands, and an increase in the frequency of usage of more efficient, discontinuous commands such as SEARCH. These changes in strategy should also produce a decrease in the average time to find a target. Although the new interface should improve the performance of all subjects, those with low spatial ability are expected to profit the most from the changes.

EXPERIMENT 2

A second experiment was conducted to test the hypotheses generated from the literature review. In a more general sense, this second experiment is also an evaluation of the methodology that has been adopted. The utility of the methodology is a direct function of how instrumental it is in achieving the goal set for this research: To provide empirical evidence that by taking individual differences into account it is possible to design an interface that enables all users, regardless of their abilities, to use the system effectively and efficiently.

Before describing the details of this second experiment, the approach that was adopted with respect to the implementation of the new interface will be discussed. It was decided that the comparison between the old and the new interface should be as rigorous as possible. The two interfaces present subjects with exactly the same information. The only difference is that, in the new interface, some information is presented in a graphical, as opposed to verbal format. The likelihood of improving the performance of all subjects would be greater if more information were presented in the new interface. For instance, a map of the hierarchy could be displayed at all times. This is the approach that would be adopted in any real-world application. However, a more conservative approach was adopted in this experiment to provide a stringent test of the methodology's effectiveness. If performance improvements are observed under these conditions, then there will be no doubts as to the utility of the methodology in accommodating individual differences. Thus, the general hypothesis being tested is that performance will be improved by merely displaying some information in a graphical, rather than verbal, format.

In spite of the rigor with which the comparison is being made, there is a small problem in interpreting the results of the study. If, as expected, the new interface results in a performance increment, the improvement can be attributed to either of two causes. It can be argued that the improvement was due to the information being presented in a graphical form, or it could be argued that it had nothing to do with the presentation format, but instead was due to the greater salience of the information in the new interface. It is conceivable that a better implementation of the interface in a verbal format would nullify any improvement that may be observed due to a graphical format. Although this is a very subtle consideration, it is worthwhile to acknowledge its existence.

Method

Experimental design. Subjects were assigned to either the High or Low Spatial ability group according to their scores on a pre-test. To maximize the sensitivity of the design, only subjects that fell into the upper or lower quartiles of spatial ability were included in the experiment. Within each group, subjects were randomly assigned to either the old

Verbal interface or the new Graphical interface. In addition, the effects of verbal ability were controlled for through the assignment of subjects to groups. Thus, the experimental design consisted of a 2 x 2 between-subjects, factorial design with 2 Interface treatments (Verbal and Graphical) and 2 Spatial Ability groups (High and Low Spatial). There were 10 subjects in each condition.

Subjects. A total of 75 subjects volunteered for the study. Of these, 28 were excluded due to the pre-test criteria and another 7 were excluded because they failed the criterion test after training. Thus, a total of 40 subjects, 7 of whom were females, participated in the experiment. Subjects' ages ranged from 18 to 27 years, with a mean of approximately 21 years. Each subject was paid $5 per hour for participating in the study.

Task environment. The Verbal interface was the one used in the first experiment. The Graphical interface was identical except for the two differences described below. First, the FILE SELECT command, which enables subjects to select any file that is lower in the hierarchy than the current file, was modified. As shown in Figure 7, the Verbal interface presents a list of the selectable files on the primary display, while the Graphical interface presents the files on the secondary display in the form shown in Figure 8. Also, for the Graphical interface a message was printed on the primary display indicating that the files that were displayed in reverse video in the map had subfiles below them. It is important to note that only the files *below* the currently selected file are shown, just as in the Verbal interface. Of course, when subjects use the FILE SELECT command from either the Tank Equipment Statistics file or the Motorized Rifle Equipment Statistics file, different files are displayed than those shown in Figures 7 and 8. However, the format of presentation shown in these figures is kept constant for each of the interfaces.

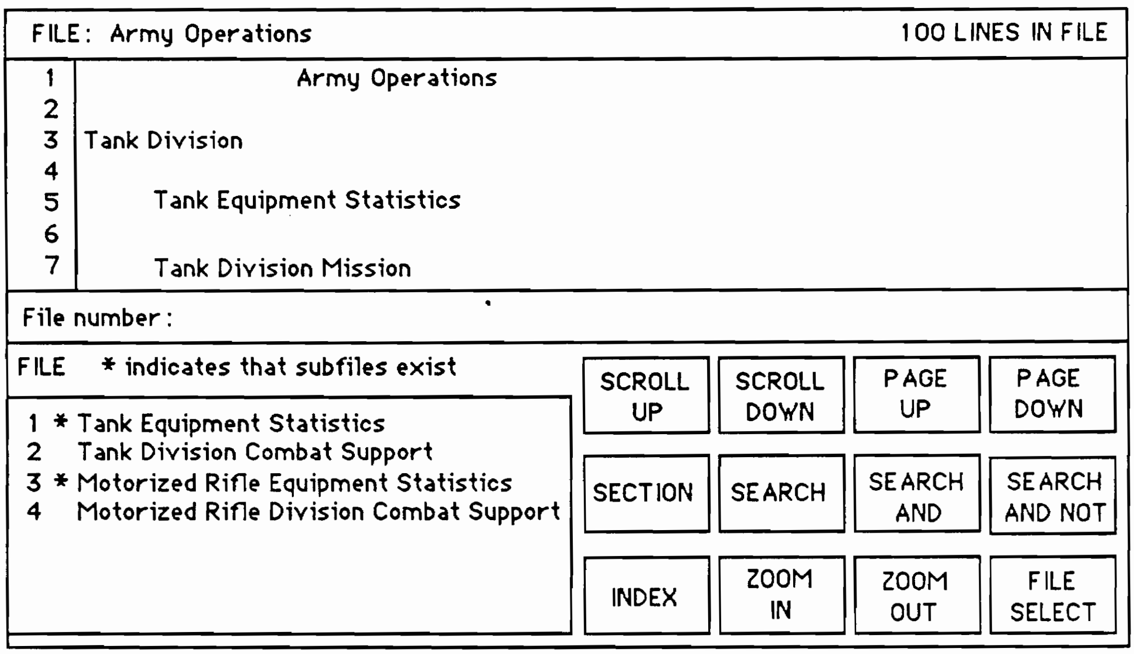

Figure 7. File select command with Verbal interface.

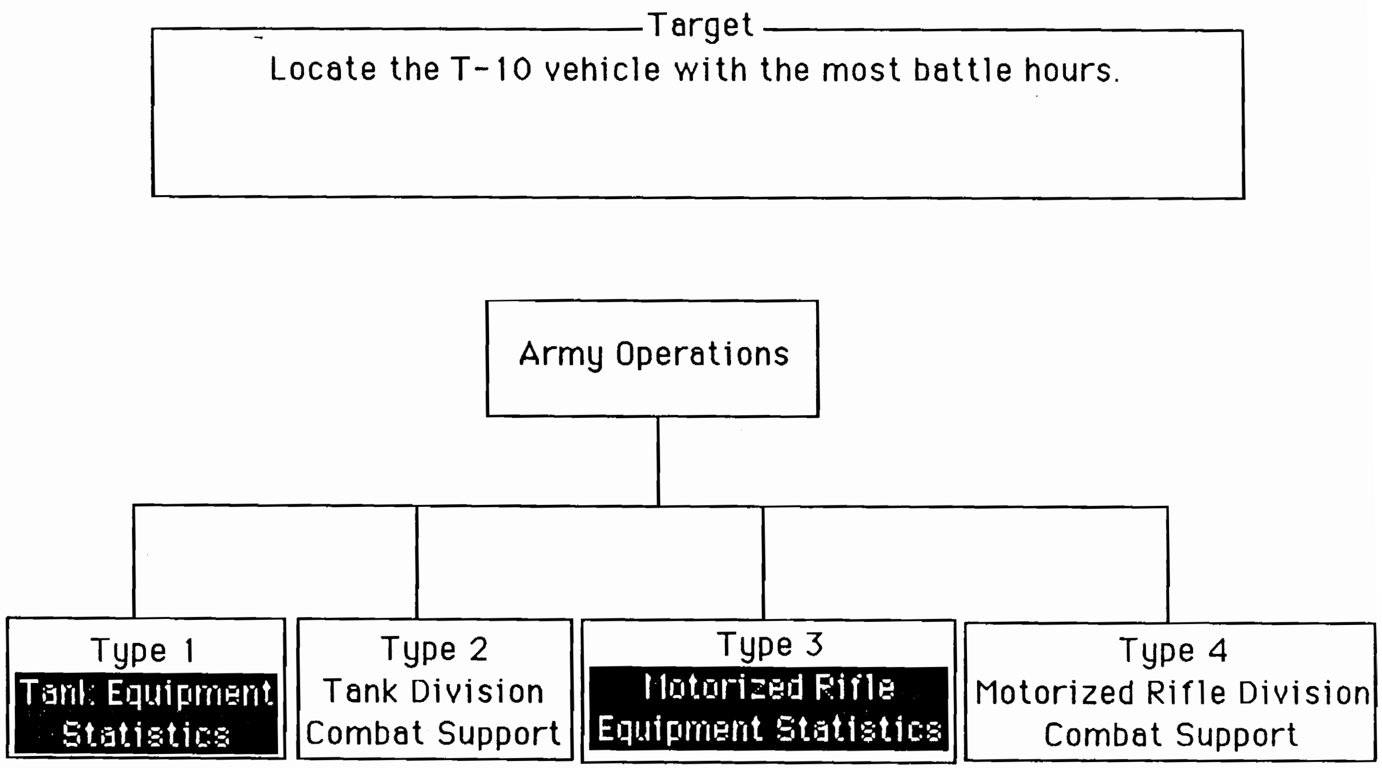

Figure 8. File select command with Graphical interface.

Second, instead of listing the number of lines in the current file in the top right-hand corner of the display (see Figure 7), a small rectangular analog indicator illustrated in Figure 9 was used to let the subjects know how long the file is, as well as their current position in the file. These were the only differences between the two interfaces.

Apparatus. The apparatus used in this second experiment was identical to that used in the first experiment.

Pre-testing session. The first session of the experiment consisted of pre-testing and lasted approximately 30 minutes. During this time, subjects filled out a demographic questionnaire, a test of spatial visualization ability (VZ-2), and a test of verbal ability (vocabulary portion of the Nelson-Denny reading test). These were the tests that were found to be the best predictors of task performance in Experiment 1. The spatial ability test was used to screen the subjects and to assign them to either the High or Low Spatial group. This was done by setting cutoff scores for each group, based on the distribution of scores from the first experiment. The spatial ability test scores from that experiment were submitted to a Kolmogorov-Smirnov goodness-of-fit test to see if they deviated significantly from normality. The analysis indicated that the scores were normally distributed, $D = 0.1226$, $p > 0.20$. Based on the distribution parameters of this sample, cutoff scores were calculated so as to select the upper and lower quartiles of the distribution. Thus, subjects who scored 14 or less were included in the Low Spatial group, while those who scored 18 or more were assigned to the High Spatial group. Subjects who scored between 15 and 17 were not included in the remainder of the experiment.

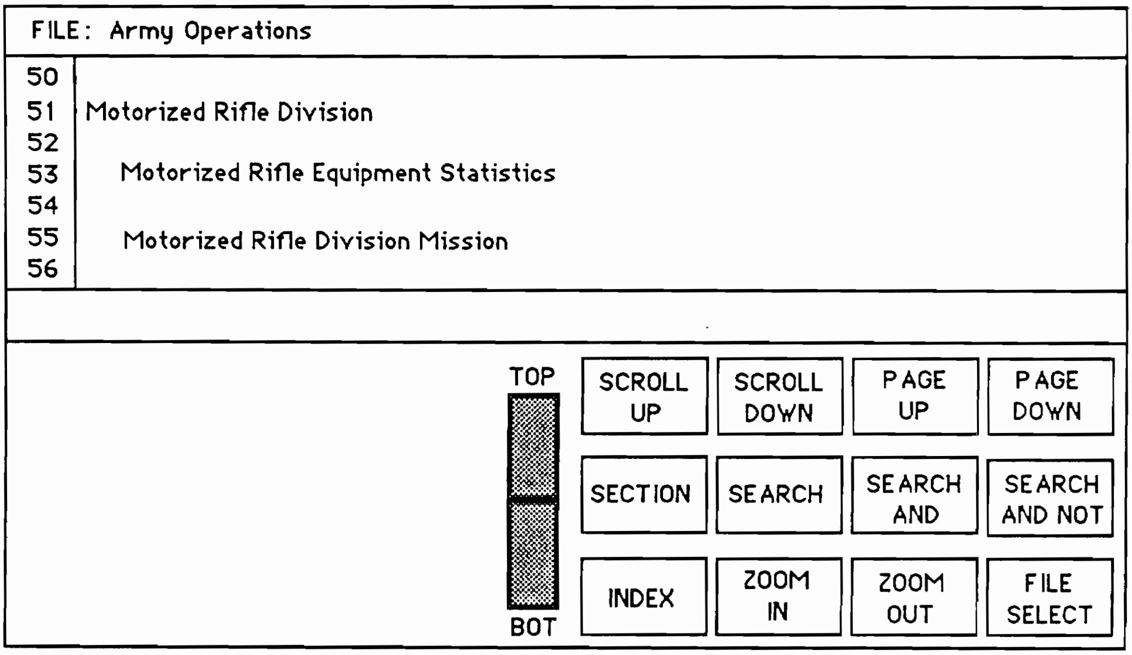

Figure 9. Analog indicator in Graphical interface.

Training session. The second session consisted of training and lasted approximately 2.5 hours. For subjects in the Verbal interface conditions, the training session was identical to that of the first experiment. The training for those in the Graphical conditions differed only with respect to the use of the FILE SELECT command and the analog indicator. Otherwise, the two training procedures were identical. As in the first experiment, at the end of training subjects were given a test of their knowledge of the information retrieval system. All subjects were required to score at least 70% in order to be included in the experiment, thereby ensuring that they all posessed a minimum amount of system knowledge. Subjects experiencing the same interface were given the same training, regardless of their spatial ability.

Data collection session. As in the first experiment, the data collection session consisted of four warmup trials followed by two sets of 12 trials on the task. The targets were the same as those used in the first experiment. To summarize, the entire procedure consisted of one pre-testing session, a training session, followed by a data collection session. On the average, the experiment lasted for approximately 5 hours in total.

Results and Discussion

Replication of relationship between experience and performance. An interesting finding from Experiment 1 that is worthwhile replicating is the relationship between computer experience and task performance. Recall that, as would be expected, subjects with more computer experience averaged less time to find the targets. However, when spatial ability was partialled out, there was no correlation between computer experience and task performance. The only reason more experienced subjects were faster was because they tended to have greater spatial ability. In the second experiment, again computer experience was significantly correlated with Time, r (40) = -.34, $p < .03$. When spatial ability was partialled out, however, the correlation between computer experience and task performance was not statistically significant, r (40) = .23, $p > .1$. Just as in Experiment 1, the results indicate that the only reason that experience is correlated with performance is that more experienced subjects tend to have greater spatial ability. As mentioned previously, this is an interesting finding for it indicates either that people with low spatial ability never acquire much computer experience, or alternatively, that experience with computers increases one's score on tests of spatial ability.

This finding also has important implications for research that attempts to classify users (see Potosnak, 1986). For the most part, studies of this type classify users according to the amount of computer experience they have (Potosnak, 1983). The consistent findings of this research suggest that this may not be a good classification scheme. Instead, researchers should investigate other variables, such as spatial ability in this case, which are the underlying cause of differences in behavior. In situations where relevant user characteristics are not correlated with computer experience, the usual practice of classifying users according to experience will only serve to mask the important underlying relationships between user characteristics and task performance.

Excluded subjects. It is important to investigate the characteristics of the subjects that were excluded from the experiment due to failing the criterion test of system knowledge. Of the seven subjects who were excluded, six were in the Low Spatial group. The only subject who was in the High Spatial group had an extremely low vocabulary score

(27%). Except for one subject, all others had vocabulary scores below 60%. The lone exception had a 95% vocabulary score but scored only 35% on the spatial test, the lowest score of all who were tested. The pattern seems to be clear. The subjects who were excluded tended to be low in both spatial and verbal ability. The two exceptions scored very high on one test and very low on the other. These findings are consistent with the results from the predictor equation shown in Table 3. Finally, the fact that four of the subjects were in the Verbal condition and three were in the Graphical condition suggests that the interface had no effect on subjects' ability to pass the criterion test. An interesting issue for future research would be to determine whether or not these subjects would reach the level of the others, if given enough practice.

The effects of interface on performance. The main hypothesis for this experiment was that the Graphical interface would result in improved performance. To test this predicition, ANOVAs were performed with each of the three performance measures as dependent variables. The results are shown in Table 4. The summary tables for the ANOVAs performed for Experiment 2 are provided in Appendix B.

For Time, the main effect of spatial ability was significant as expected, $F\ (1, 36) = 9.32$, $p = .004$. Subjects in the High Spatial group took less time on the average to find a target than those in the Low Spatial group (111.1 s compared with 153.0 s, respectively). The main effect of Interface was not significant, $F\ (1, 36) = 3.40$, $p = .07$, but the data were in the predicted direction.

As shown in Table 4, the other two performance measures, average total number of commands used per trial and average number of different commands used per trial, did show significant improvements in performance due to the Graphical interface, $F\ (1, 36) = 4.0$, $p = .05$, and $F\ (1, 36) = 8.26$, $p = .007$, respectively. The subjects in the

Table 4. Effects of Interface on Performance.

Performance Measure	Interface		F (1, 36)	p
	Verbal	Graphical		
Time	144.7	119.4	3.4	0.07
Total Commands	15.5	12.4	4.0	0.05
Different Commands	4.83	4.32	8.26	0.0067

Graphical groups averaged fewer total commands per trial (12.4 compared with 15.5 for the Verbal groups). The strongest effect of the Graphical interface was in reducing the average number of different commands that subjects used per trial (4.32 compared with 4.83 for the Verbal interface). It was also expected that the Low Spatial group would benefit the most from the Graphical interface but the lack of significant interactions for all three dependent measures indicates that this did not occur. The High and Low Spatial groups profited equally from the new interface.

The variability in performance also differed across interface groups. The variances in Time for the Verbal and Graphical interfaces were 4231.5 and 1470.72 for the Low Spatials, and 1533.51 and 300.33 for the High Spatials, respectively. Cochran's test for homogeneity of variance (Winer, 1971) was used to test the significance of these differences. Results indicate that the difference in variance for the High Spatials is statistically significant, $C\ (2, 9) = .84, p < .05$, while the difference for the Low Spatials, although large, is not statistically significant, $C\ (2, 9) = .74, p > .05$. Thus, performance with the Graphical interface was more consistent across subjects than with the Verbal interface.

Overall, these results demonstrate the superiority of the Graphical interface. The evidence is convincing; compared to the Verbal interface, the Graphical interface resulted in decreases in total number of commands used per trial, different number of commands used per trial, and within-group variability in Time. Contrary to expectations, the improvement in performance was equal across groups of spatial ability, as evidenced by small, nonsignificant interactions.

The effects of interface on command usage. The concept of visual momentum predicted that the Graphical interface would also result in certain changes in the frequency of usage of certain commands. As in Experiment 1, the polling procedure of Elkerton and

Williges (1985) was used to calculate the frequency of usage of each command. ANOVAs were performed for each of the 12 commands. The results for those commands which showed a significant main effect of Interface, along with those commands which were predicted to show a significant difference and did not, are given in Table 5.

The frequency of usage of the ZOOM OUT command is a measure of how often users get lost in the hierarchy. In other words, it is an indicator of the visual momentum supported by the system. It was predicted that the partial map of the hierarchy would result in an improvement in visual momentum, as indicated by a decrease in ZOOM OUT usage. As shown in Table 5, the data are in the predicted direction but a statistically significant difference was not observed. The lack of significance can be attributed to the conservative implementation of the Graphical interface. If the map of the hierarchy was displayed all the time, rather than only when the FILE SELECT command was chosen, then there probably would have been a significant decrease in the usage of ZOOM OUT.

The visual momentum analysis also predicted that the analog indicator would cause a decrease in the frequency of use of SCROLL DOWN and SCROLL UP. As shown in Table 5, only the SCROLL DOWN command showed a statistically significant decrease, $F(1,36) = 4.44$, $p = .04$. The fact that the SCROLL DOWN command resulted in a significant difference, whereas the SCROLL UP command did not, can be explained by considering the circumstances under which scrolling commands were typically used in the Verbal interface. Usually, subjects who constantly relied on the scrolling commands would use them right after moving to a new file in the hierarchy. Since the display window is placed at the top of the file after a move to a new file, subjects typically used SCROLL DOWN more often than SCROLL UP. The Graphical interface seems to have been successful in cutting down this excessive use of SCROLL DOWN.

Table 5. Effects of Interface on Frequency of Command Usage.

Command	Interface		F (1, 36)	p
	Verbal	Graphical		
ZOOM OUT	0.46	0.42	1.46	0.24
SCROLL DOWN	0.55	0.40	4.44	0.04
SCROLL UP	0.42	0.33	1.63	0.21
SEARCH-AND	0.27	0.35	4.37	0.04
SECTION	0.32	0.13	6.24	0.02

The addition of the analog indicator was also expected to result in an increase in the frequency of usage of more efficient discontinuous commands such as SEARCH, rather than the inefficient scroll commands. As shown in Table 5, this prediction was confirmed by an increase in the usage of the SEARCH-AND command, $F(1, 36) = 4.37$, $p < .05$. This command consists of a search for two or more strings with the Boolean AND operator. The reason why SEARCH-AND showed an increase whereas SEARCH did not is explained by the fact that most targets had several keywords. Thus, it would be more efficient for subjects to use the SEARCH-AND command than the SEARCH command because it would allow them to take full advantage of the cues provided by the target. The use of SEARCH-AND-NOT was helpful only for a few of the targets. Thus, it is not surprising that the Graphical interface did not result in an increase in the usage of this command. Of course there are other discontinuous commands that the subjects could have chosen to use (e. g. PAGE UP, PAGE DOWN, SECTION, and INDEX). However, the SEARCH-AND command is much more accurate and more efficient than any of these other commands, and thus, it was used more often with the Graphical interface.

The decreased use of the SECTION command with the Graphical interface shown in Table 5 was not predicted. At first glance, it is difficult to understand why the Graphical interface would produce this change in command strategy. However, while observing subjects in the Verbal group, it was noted that they would often use the SECTION command when they actually intended to use the FILE SELECT command. A comparison of these two commands, illustrated in Figures 7 and 10, shows why this is so. Both SECTION and FILE SELECT display a list of alternatives that the subjects must choose from. The confusion results from the fact that the format for these two commands is identical. It is easy to see how subjects could get the two commands

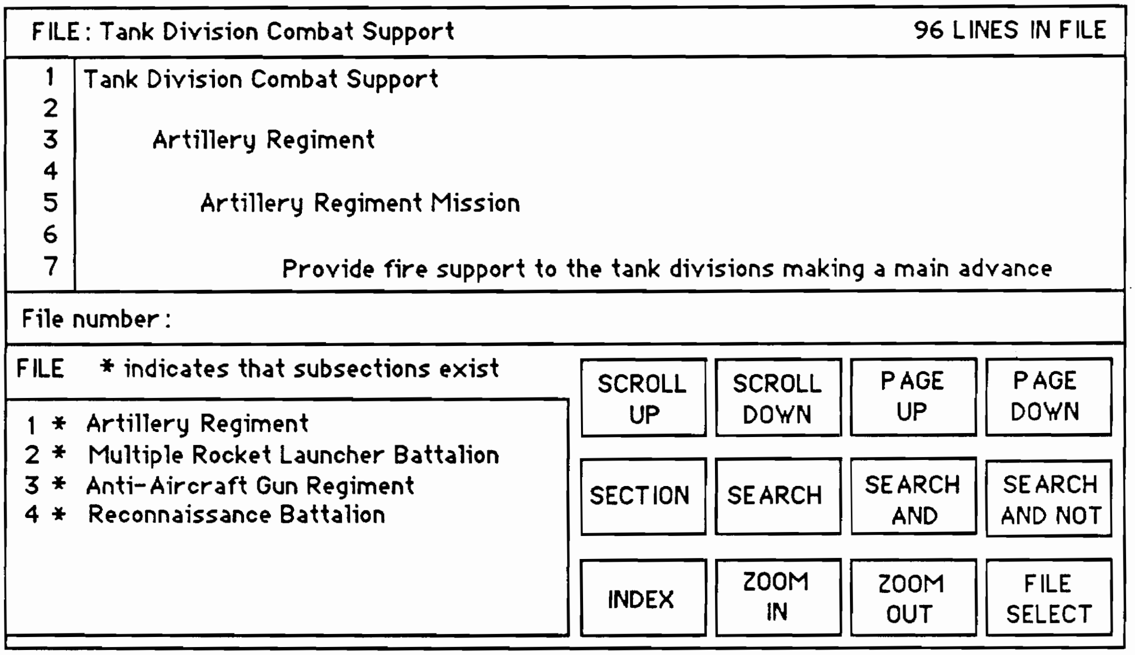

Figure 10. Section command with Verbal interface.

confused. In the Graphical interface, however, the FILE SELECT command was changed so that it would display a partial map of the hierarchy, as shown in Figure 8, rather than the table shown in Figure 7. This change inadvertently eliminated the confusion that existed in the Verbal interface between SECTION and FILE SELECT. Also, the fact that FILE SELECT was used on almost every trial suggests that the proportion of times that SECTION was mistakenly used in place of FILE SELECT may have been relatively high. The result was that there was a decrease in the frequency of usage of the SECTION command with the Graphical interface, $F\,(1, 36) = 6.24, p < .02$. This inadvertent change in strategy provides an excellent example of how difficult it is to anticipate all the consequences of changing or eliminating a task component. As was the case here, these modifications can sometimes change the way the user perceives the task, and therefore can qualitatively change the way the task is performed. Fortunately, in this case the modification resulted in a positive change in strategy.

To summarize, the Graphical interface produced a change in subjects' command usage compared to the Verbal interface. The results show that the new interface caused decreases in the use of SCROLL DOWN and SECTION, as well as causing an increase in the use of SEARCH-AND. These changes in command usage led to an improvement in performance. With the exception of SECTION, the findings are consistent with the predictions extracted from the visual momentum analysis.

However, it was also predicted that the changes in strategy and the resulting improvement in performance would be greatest for the Low Spatial subjects. The lack of significant interactions indicate that this prediction was not confirmed. Thus, the Graphical interface resulted in improved performance for all subjects, but it was not very effective in reducing the individual differences in performance between High and Low Spatial subjects. The only finding indicating a reduction in individual differences was the decreased inter-group performance variability for those subjects receiving the Graphical interface. To explain why the performance changes did not interact with spatial ability, it is useful to reconsider the reasoning that lead to this prediction. It was argued that the High Spatial subjects would not improve as much because their performance was already quite good with the old interface. Thus, it was expected that a ceiling effect would be observed, i. e., the High Spatials would only improve slightly because they would reach a baseline level beyond which they could not improve further. Meanwhile, the Low Spatials, because their performance was so poor to begin with, would have much more room for improvement before they experienced a ceiling effect.

Following from this reasoning, there are at least two possible explanations why the Low Spatial subjects did not improve more than the High Spatial subjects. First, it is possible that the duration of the experiment was not sufficiently long to enable High Spatials to reach a performance ceiling. Perhaps, if a longitudinal study were conducted, the High Spatials would cease to improve after a certain amount of practice, while the Low Spatials would continue to improve. Second, it is also possible that the manipulation of interface did not reduce the load on spatial ability, but instead reduced the need for some other general ability in which the two subject groups were equal. This would also result in an interface that would be better for all subjects, as was observed. Only more research can determine which of these explanations is correct.

The effects of spatial ability on command usage. In Experiment 1, there were several differences in frequency of command usage between subjects with high and low spatial ability. Specifically, subjects with low spatial ability used the ZOOM OUT, SCROLL UP, and SCROLL DOWN commands more often than those with high spatial ability. ANOVAs were performed to determine if these strategy differences were present in this

Table 6. Effects of Spatial Ability on Frequency of Command Usage.

	Spatial Ability			
Command	Low	High	F (1, 36)	p
ZOOM OUT	0.46	0.42	1.46	n. s.
SCROLL DOWN	0.49	0.45	< 1	n. s.
SCROLL UP	0.39	0.36	< 1	n. s.

experiment. The results are shown in Table 6. Although the subjects with high spatial ability used each of these commands less often than those with low spatial ability, none of the differences were statistically significant. Thus, it seems that the differences between the two groups were not as great as in Experiment 1. This is confirmed by the performance data. In Experiment 1, high spatial subjects averaged 94.53 s to find a target, while low spatial subjects averaged 192.02 s. In Experiment 2, subjects in the Verbal interface groups averaged 164.64 s and 124.75 s for the Low and High groups, respectively.

Originally, it was thought that the comparatively smaller degree of individual differences in the second experiment was due to a difference in the abilities of the subjects in the two samples. Accordingly, the test scores of the subjects in Experiment 1 were compared with those of the subjects that were in the Verbal interface groups in Experiment 2. The results are shown in Table 7. Tests were performed to compare the means between the two samples, but none of the differences were statistically significant, $p > .05$. Thus, the relative reduction in individual differences in task performance in the second experiment cannot be attributed to a difference in the abilities of the subjects in the two samples.

Conclusions

The comparison of the Verbal and Graphical interfaces yielded some interesting findings. Subjects in the Graphical conditions showed a relative decrease in the use of SCROLL DOWN and SECTION, as well as an increase in the use of SEARCH-AND.

Table 7. Comparison of abilities between Expt 1 subjects and Verbal interface subjects from Expt 2.

	Low Spatial		High Spatial	
Test	Expt 1	Expt 2	Expt 1	Expt 2
Spatial	13.2	11.4	18.7	18.4
Vocabulary	67.7	54.8	72.5	68.1

These changes in command usage produced a corresponding improvement in performance for the Graphical interface as compared to the Verbal interface. Except for the unexpected change in SECTION usage, these results are consistent with the predictions of the visual momentum analysis described in the literature review. Contrary to expectations, the improvements due to the Graphical interface were the same for High and Low Spatial subjects. Two plausible explanation for this finding were discussed. The Graphical interface also resulted in a decrease in performance variability.

To summarize, the new Graphical interface proved to be better than the old Verbal interface, but it was not entirely successful in eliminating the individual differences in performance. Although subjects in the Graphical conditions outperformed those in the Verbal conditions, the relative performance difference between High and Low Spatials remained constant across interfaces.

GENERAL DISCUSSION

The literature investigating individual differences among users of computer systems is scarce (Vicente, Hayes, and Williges, in press). What little research that has been done has usually attempted to find a relationship between user characteristics and interaction styles (e. g. Ambardar, 1984). From an applied perspective this is insufficient.

This research has attempted to go beyond those modest goals. Initially, a conceptual model was developed to consider the complexities involved in accommodating individual differences. Given an understanding of the problem, the first goal of this research was to show that individual differences do indeed matter. The only way to convince designers that individual differences are an important design factor is to provide empirical evidence of the costs associated with ignoring them. The order of magnitude difference in performance between the fastest and the slowest subjects in Experiment 1 is a dramatic illustration of the importance of individual differences. The second goal of this research was to show that individual differences in task performance could be reduced. To achieve this goal, the methodology of Egan and Gomez (1985) was adopted. This methodology proved to be quite useful for it helped to identify the relevant user characteristics and task components that were the sources of the individual differences. Once these had been identified, a review of the relevant psychological literature was conducted. This review uncovered the concept of visual momentum which, in turn, suggested ways in which the interface should be modified to improve performance. The concept of visual momentum was strong enough that it even made specific predictions about what effects the new interface would have on command usage and performance. The results of Experiment 2 were remarkably consistent with these predictions. As Moray (1984) states, experimental and cognitive psychology contain a wealth of information that can be useful to the human factors engineer. The importance of the literature review to the results obtained in this research attests to this.

Although the new interface proved to be better than the old interface, it was not entirely successful in reducing the individual differences in task performance. It should be noted, however, that there are at least two plausible reasons for the failure to confirm the prediction. It is proposed that the reason why subjects with low spatial ability did not improve more than those with high spatial ability is that the practice that subjects had with the task was insufficient to allow such an effect to be observed. It is hypothesized that if subjects were given more practice, the performance of those with high spatial ability would asymptote, while that of the low spatial ability subjects would continue to improve, thus producing an interaction between interface type and spatial ability. A longitudinal study would have to be performed to test this hypothesis. In fact, such a study could also be used to determine whether the relationship between experience and performance is due to learning or self-selection. An alternative explanation for the lack of interaction is that the interface manipulation did not eliminate the need for spatial ability, but instead removed the need for some other general ability that the two groups were equal in, thereby improving the performance of both groups.

The fact that the new interface did not result in a considerable decrease in individual differences only serves to reinforce the warnings of Egan and Gomez (1985): assaying and isolating the individual differences does not guarantee that a successful accommodation strategy will be developed. The results of this research also reinforce Hollnagel's (1983) statement that very little is known about the effects that changing a task can have on resulting behavior. The inadvertent decrease in the usage of SECTION that was caused by the Graphical interface is a perfect example of a change in a task causing an unexpected change in behavior. Fortunately, in this case the change was a beneficial one. For the most part, however, the unpredictable changes in behavior will not be desirable ones.

This does not mean that researchers should give up trying to accommodate individual differences. Quite to the contrary, it means that much more research needs to be performed. But for research in this area to have any practical impact at all, a change in focus is essential. In the past, one of the primary uses of individual differences has been as a selection tool. The approach adopted in this work and the work of Egan and Gomez (1985) is quite different. Instead of trying to find the right person for the task, whenever possible, attempts should be made to design interfaces so that everyone, regardless of their abilities, will be able to use them efficiently and effectively. In other words, the proposed approach attempts to adapt the task to the person, not the person to the task. Future research in this area should be directed at discovering how to go about achieving this goal.

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Appendix A.

ANOVA Summary Tables For Experiment 1

Source	df	MS	F	p
Time				
Verbal Ability (V)	1	4603.38	.42	.5232
Subjects (S/V)	28	11015.03		
Time				
Spatial Ability (Sp)	1	71277.38	8.26	.0077
Subjects (S/Sp)	28	4168.05		
Scroll Up				
Spatial Ability (Sp)	1	.2809	4.88	.0355
Subjects (S/Sp)	28	.0576		
Scroll Down				
Spatial Ability (Sp)	1	.4723	5.40	.0277
Subjects (S/Sp)	28	.0875		
Zoom Out				
Spatial Ability (Sp)	1	.3212	26.58	.0001
Subjects (S/Sp)	28	.0121		

Source	df	MS	F	p
Page Up				
Spatial Ability (Sp)	1	.001	.03	.8701
Subjects (S/Sp)	28	.05		
Page Down				
Spatial Ability (Sp)	1	.06	.67	.4210
Subjects (S/Sp)	28	.09		
Section				
Spatial Ability (Sp)	1	0	0	.9456
Subjects (S/Sp)	28	.07		
Zoom In				
Spatial Ability (Sp)	1	.04	.34	.5623
Subjects (S/Sp)	28	.11		
File Select				
Spatial Ability (Sp)	1	0	.01	.9430
Subjects (S/Sp)	28	.10		
Search				
Spatial Ability (Sp)	1	.02	.23	.6379
Subjects (S/Sp)	28	.09		
Search-And				
Spatial Ability (Sp)	1	0	.06	.8110
Subjects (S/Sp)	28	.02		
Search-Not				
Spatial Ability (Sp)	1	0	.12	.7346
Subjects (S/Sp)	28	0		
Index				
Spatial Ability (Sp)	1	.07	1.82	.1886
Subjects (S/Sp)	28	.04		

Appendix B.

ANOVA Summary Tables For Experiment 2

Source	df	MS	F	p
Time				
Interface (I)	1	6398.37	3.40	.0736
Spatial (Sp)	1	17560.29	9.32	.0042
Sp x I	1	40.60	.02	.8841
Subjects (S/SpI)	36	67819.61		
Total Commands				
Interface (I)	1	93.51	4.00	.0531
Spatial (Sp)	1	73.06	3.13	.0855
Sp x I	1	1.72	.07	.7876
Subjects (S/SpI)	36	841.36		
Different Commands				
Interface (I)	1	2.65	8.26	.0067
Spatial (Sp)	1	.210	.66	.4236
Sp x I	1	.015	.05	.8289
Subjects (S/SpI)	36	11.55		
Zoom Out				
Interface (I)	1	.016	1.46	.2350
Spatial (Sp)	1	.016	1.46	.2350
Sp x I	1	.000	.03	.8573
Subjects (S/SpI)	36	.395		
Scroll Up				
Interface (I)	1	.079	1.63	.2102
Spatial (Sp)	1	.010	.20	.6594
Sp x I	1	.000	.01	.9319
Subjects (S/SpI)	36	1.75		

Source	df	MS	F	p
Scroll Down				
Interface (I)	1	.228	4.44	.0422
Spatial (Sp)	1	.018	.36	.5524
Sp x I	1	.001	.03	.8680
Subjects (S/SpI)	36	1.85		
Section				
Interface (I)	1	.331	6.24	.0172
Spatial (Sp)	1	.052	.98	.3295
Sp x I	1	.004	.07	.7957
Subjects (S/SpI)	36	1.91		
Search-And				
Interface (I)	1	.080	4.37	.0437
Spatial (Sp)	1	.010	.54	.4667
Sp x I	1	.000	.00	.9722
Subjects (S/SpI)	36	.660		
Page Up				
Interface (I)	1	0	.04	.8488
Spatial (Sp)	1	.07	2.0	.1659
Sp x I	1	.01	.40	.5336
Subjects (S/SpI)	36	.032		
Page Down				
Interface (I)	1	.05	1.25	.2706
Spatial (Sp)	1	0	.03	.8648
Sp x I	1	.09	2.48	.1237
Subjects (S/SpI)	36	.04		
Zoom In				
Interface (I)	1	.14	1.44	.2386
Spatial (Sp)	1	0	.03	.8662
Sp x I	1	.02	.26	.6138
Subjects (S/SpI)	36	.09		
File Select				
Interface (I)	1	.03	.49	.4869
Spatial (Sp)	1	0	.02	.8891
Sp x I	1	.09	1.53	.2234
Subjects (S/SpI)	36	.06		
Search				
Interface (I)	1	.03	1.95	.1716
Spatial (Sp)	1	.06	3.25	.0797
Sp x I	1	.01	.33	.5674

Source	df	MS	F	p
Subjects (S/SpI)	36	.02		
Search-Not				
Interface (I)	1	0	1.06	.3103
Spatial (Sp)	1	0	1.06	.3103
Sp x I	1	0	0	1.0
Subjects (S/SpI)	36	0		
Index				
Interface (I)	1	.04	1.77	.1918
Spatial (Sp)	1	.01	.59	.4462
Sp x I	1	.02	.76	.3900
Subjects (S/SpI)	36	.03		

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Virginia Polytechnic Institute & State University	M.S.	1987	Human Factors
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PROFESSIONAL SOCIETIES

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RESEARCH & TEACHING ACTIVITIES

Sept. 1985 - March 1987	Research assistant at Virginia Tech on Army Research Institute contract in area of adaptive human-computer interfaces. Goals included designing an interface that compensates for individual differences among users, thereby increasing the efficiency with which they perform a hierarchical file search task.

Jan. 1985 - April 1985	Teaching assistant for a Man-Machine Systems Analysis course taught by Prof. John Senders, at the University of Toronto.
June 1984 - June 1985	Research assistant for Prof. Neville Moray at the University of Toronto on NASA contract in the area of mental workload. Performed experiments to evaluate validity of spectral analysis of sinusarrhythmia as a measure of mental effort.
May 1984 - June 1984	Employed as a research assistant to help conduct an experiment on verbalizable knowledge. This research is still being pursued in collaboration with Prof. Penelope Sanderson, now at University of Illinois at Urbana-Champaign.
1982 (Summer)	Research assistant at the University of Toronto Computer Systems Reseach Institute on contract in the area of computer-aided instruction. Responsibilities consisted of writing a user friendly, CAI software package for the Apple II+.

RESEARCH PAPERS & PUBLICATIONS

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