

**A Controlled Experiment to Identify and Test  
A Representative Primitive Set of User Object-Oriented Cursor  
Actions**

by

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Master of Science

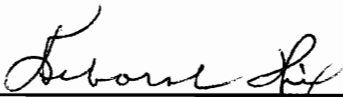
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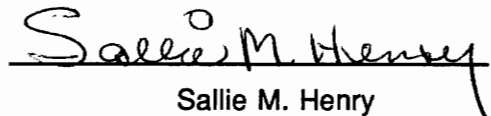
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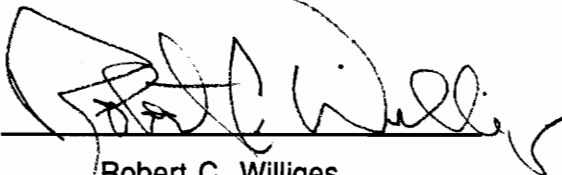
H. Rex Hartson, Chair



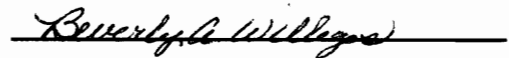
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Committee Chairman: H. Rex Hartson  
Computer Science

(ABSTRACT)

A method for decomposing the user cursor action component of human-computer interfaces into individual components based on the four categories: target size, target distance, target direction, and selection mode, was investigated. A primitive task set consisting of the Cartesian product of specific elements of the four categories listed above was proposed based on observation of user tasks and a cursor action benchmark task set was developed to measure a user's performance for each element of the set of primitive elements with a given cursor control device. An experiment was conducted to test the proposed primitive task set and associated benchmark task set as a predictor of performance for a set of representative graphics tasks. The predicted times and actual times were shown to have very strong correlations and the data were also shown to conform to Fitts' Law.

A description of the experiment, the data collected, and the analysis of these data are included.

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## **Chapter 1: Introduction**

### **1.1 Introduction**

To ask the question "What is the best cursor control device?" is to open a Pandora's box of opinions and confusion. English [ENGL67] showed that the mouse was the most appropriate cursor control device for target acquisition tasks, whereas Mehr and Mehr [MEHR72] showed that the trackball performed better for target acquisition tasks. These are just two of the many studies that have disagreed on the subject of the "best" cursor control device. Even if these studies agreed on the best cursor control device, target acquisition is only a part of most user tasks. Furthermore, standard measurements that apply to the typical user may not apply to users with physical disabilities or to other special populations of computer users. Epps [EPPS86] added to the dilemma by showing that target acquisition tasks are not uniformly predictive of more general tasks such as word processing and graphics. This would suggest that there are elements of user tasks such as text entry and thought which are not represented by target acquisition tasks. However, this might also suggest that there are elements of user cursor control which are not represented by typical target acquisition tasks. Brownlow [BROW90] points out that there is no consensus on what aspects of object-oriented cursor manipulation are significant. The goal of this research is to identify and describe a representative primitive set of significant user cursor-control actions and to develop a benchmark task set to test a user's ability to perform each of those actions with a given device.

## 1.2 Literature Review

As Norman suggests, a gap exists, in using computing systems, between the intentions of the user and the ability to express those intentions through the physical interface [NORM86]. While Norman refers to this "Gulf of Execution" in the cognitive sense, the physical aspect of this "Gulf" is interesting as well. In order to bridge this gap or gulf, the first step is to examine the intentions or task requirements of the user. Much work has been done in the area of task analysis. Thachenkary and Conrath [THAC82] (see Figure 1) and Helander [HELA85] (see Figure 2) provide two excellent examples of taxonomies of office tasks. These taxonomies were developed by observing and interviewing subjects in the workplace, thus providing not only a useful sample of office work but also an example of observation-driven task decomposition which will be very useful in later chapters.

Given this type of observation-driven taxonomy of the user's intended work, it is then possible to associate those tasks that are appropriate for completion on a computer with the appropriate software as shown by Czaja [CZAJ87] (see Figure 3). It is important to note that this type of task by feature matrix may be very different from user to user, especially in the case of non-able-bodied computer users. Tasks such as appliance control or call handling which may not be appropriate for completion on a computer for an able-bodied user will become not only appropriate but necessary computer tasks for many non-able-bodied users.

| Task Descriptors   | Percentage of Time |               |
|--|--------------------|---------------|
|  | Management         | Nonmanagement |
| Advising, Counseling, Assisting, Recommending,<br>Problem Solving, Instruction, Acting as Liason | 12.9               | 5.3           |
| Bookkeeping, Accounting, Calculating, Inventorying, Invoicing                                    | 2.0                | 48.1          |
| Deciding, Authorizing, Approving   | 12.8               | 2.5           |
| Evaluating, Auditing, Controlling, Coordinating  | 17.7               | 11.6          |
| Completing Forms, Filing, Recording, Logging   | ---                | 7.7           |
| General Administration, Paperwork  | 3.1                | ---           |
| Human Relating, Supervising, Appraising Performance  |                    |               |
| Staffing, Motivating   | 21.1               | 7.3           |
| Informing, Reporting   | 4.4                | 4.2           |
| Interactive Formal Meetings  | 3.0                | ---           |
| Orders, Requests, Invoices, Bills  | ---                | 3.0           |
| Planning, Budgeting, Analyzing   | 16.2               | 2.5           |
| Arranging/Scheduling of Meetings, Appointments   | ---                | 7.3           |
| Selling, Convincing, Persuading, Advertising   | 8.2                | 1.7           |
| Typing, Transcribing, Copying, Writing   | ---                | 4.5           |
| Total  | 101.4              | 102.7         |

Figure 1: Taxonomy of Office Tasks

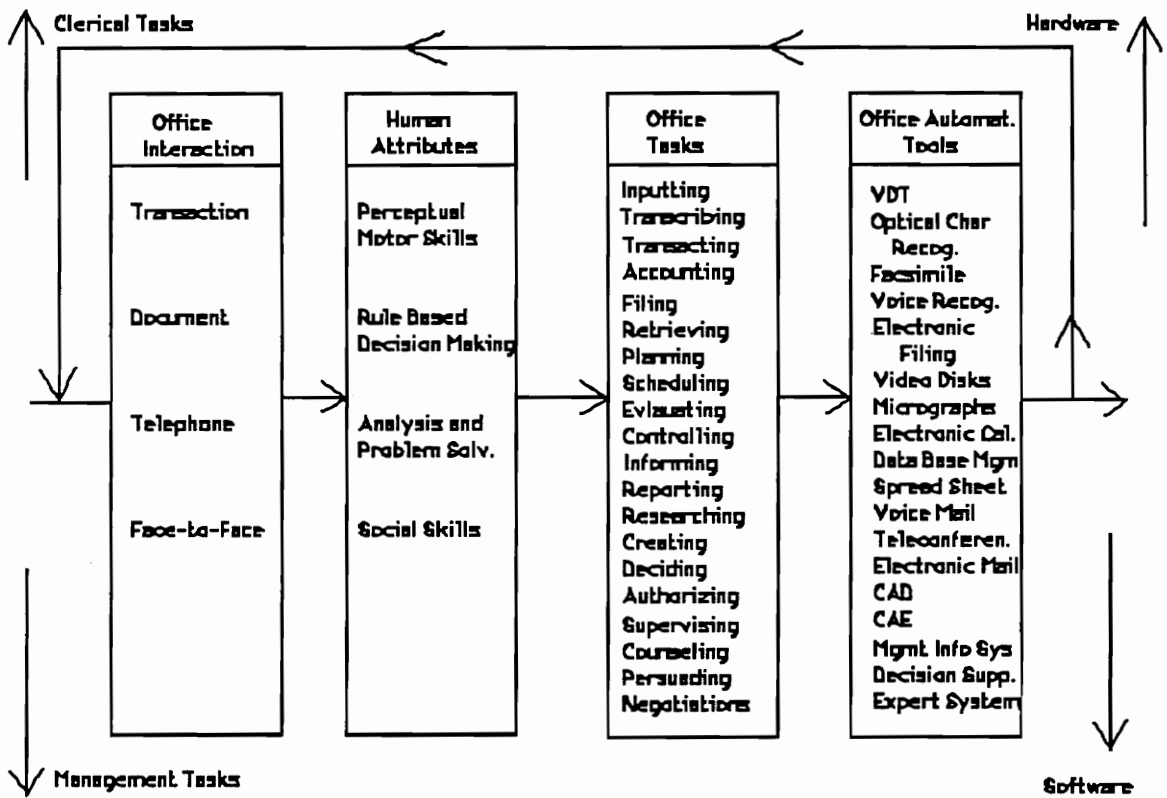


Figure 2: Taxonomy of Office Tasks

| AUTOMATION FEATURES | OFFICE TASKS  |                        |                      |                         |             |                 |             |
|---------------------|---------------|------------------------|----------------------|-------------------------|-------------|-----------------|-------------|
|                     | DOCUMENT PREP | MEETING AND CONFERRING | FLING AND RETRIEVING | PLANNING AND SCHEDULING | COMMUNICAT. | DECISION MAKING | TRANSACTING |
| WORD PROCESSING     | ●             |                        | ●                    |                         |             |                 | ●           |
| ELECTRONIC MAIL     |               |                        |                      |                         | ●           |                 |             |
| ELECTRONIC FILING   |               |                        | ●                    |                         |             |                 |             |
| VOICE MAIL          |               |                        |                      |                         | ●           |                 |             |
| DATABASE MANAGEMENT |               |                        |                      | ●                       |             | ●               |             |
| CONFERENCING        |               |                        |                      |                         | ●           |                 |             |
| ELECTRONIC CALENDAR |               |                        |                      | ●                       |             |                 |             |
| SPREADSHEET         |               |                        |                      | ●                       |             | ●               | ●           |
| DECISION SUPPORT    |               |                        |                      |                         |             | ●               | ●           |

Figure 3: Task by Feature Matrix

Once the user's intended tasks have been identified and the appropriate software has been selected, the next step is to examine the interface manipulation or user action required to perform those tasks. Again, as the generic office task was decomposed into more specific component tasks, the user interfaces of these component tasks must also be divided into their component parts. This decomposition is necessary in order to allow for the development of benchmark tasks for specific user task areas such as graphics, word processing, or spreadsheet management.

Substantial work has been done in the area of decomposing office tasks into representative benchmark tasks. Roberts [ROBE83] and Mohageg [MOHA89] demonstrated the feasibility of developing benchmarks through observation and objective measurement. Roberts developed and tested a benchmark task set for word processing, while Mohageg developed and tested a benchmark task set for graphics. These benchmark task sets would certainly be useful in the context of studying user performance and/or behavior within the given user task area. However, in order for these benchmark task sets to be applied to cursor control device selection, a user would have to be tested on a benchmark task set, for every task area in which they wanted to work, with every available cursor control device. This conclusion is based on Epps' finding that there is substantial variability in the performance of a cursor control device depending on the type of task involved. Epps concluded that this variability was due to the varying levels of precision required across different tasks. Subjecting a user to a benchmark task set for each task area in which they would work, for each available device, would be a lengthy and tedious process and would

introduce factors such as physical endurance, mental fatigue, and availability of resources.

### **1.3 Approach**

It would appear that a more reasonable approach would be to decompose the task-specific benchmark sets into a primitive task set that is representative of all the low level or primitive cursor actions required in all user tasks. One possible solution would be the use of a set of simple target acquisition tasks to predict user performance with various devices. However, as listed above, Epps has shown that this type of task is not uniformly predictive of performance on more general composite tasks. Target acquisition tasks basically represent moving to a particular target perhaps over a specific distance and to a specific target size, and then selecting that target. While this type of user cursor-control action is a part of composite tasks, it is not the only part. As mentioned above, target acquisition does not include the interface elements of text entry or thought. However, neither shall this research include these elements since they are outside the realm of user cursor actions. Of more concern to this research is that simple target acquisition does not address the issues of direction and dragging, or select-on moves as dragging will be referred to here. Therefore, in order to include those actions not represented by target acquisition, the development of a representative set of primitive elements of user cursor actions must at least start with the task area benchmark sets that have already been proven to be representative by Roberts and Mohageg.

Again, as Roberts and Mohageg have shown, tasks such as the task area benchmark sets can be decomposed through observation and objective measurement into their component movement parts. Analysis of Roberts' benchmark for word processing and Mohageg's benchmark for graphics was done by videotaping three subjects performing the two benchmark task sets on a Macintosh SE using Microsoft Word for word processing and MacDraw for graphics. Analysis of these sessions suggests the following set of basic user cursor movement directions and selection modes (see Figure 4).

---

**Cursor Directions**

Right  
Left  
Up  
Down  
Diagonally up (left to right)  
Diagonally up (right to left)  
Diagonally down (left to right)  
Diagonally down (right to left)

**Selection Mode**

Select Switch Down  
Select Switch Up

---

**Figure 4: Direction and Selection Components of Cursor Movement**

The elements of the proposed set of cursor movement directions can be combined to represent the direction of an arbitrary cursor movement. The representation is an abstraction of the real movement by being path independent (i.e. the direction is the straight line path from the starting position to the target). Fitts' Law states that the time to move from a starting point A to a target B is a function only of the distance between A and B and the size of B [FIT54] (see Figure 5). Certainly, this implies that the time to complete any target acquisition style task will be independent of direction. However, Brownlow [BROW90] suggests that direction may have possible applications to special user populations. Direction may be of particular concern to non-abled computer users who may have difficulty with movement in one direction and not in another.

---

### **Fitts' Law**

Movement Time =  $a + b ((2 * \text{Amplitude of movement}) / \text{Width of target})$

where a and b are constants,

a = Y intercept,

b = slope.

---

Figure 5: Fitts' Law

The set of selection modes represents the users action with respect to the devices selection switch. For example, in the case of a one-button mouse, Select Switch Down would represent Mouse Down. The generic terms Select Switch Up and Select Switch Down will be used due to the diversity of ways in which cursor control devices implement the selection function. The term Select Click is used to represent the action of a Select Switch Down followed by a Select Switch Up with no cursor movement in between. Appendix A provides a thorough discussion of these terms and their device specific attributes.

Epps suggested a representative decomposition of the target acquisition component of graphics and word processing into five square target sizes and four target distances (see Figure 6). The Cartesian product of the direction, selection mode, target size, and target distance components of cursor control forms a set of fundamental elements or primitive tasks. These are tasks that represent a single action taken over a specific distance, in a specific direction and on an object of a specific size. An example of one of these tasks would be to move 2 cm to the right to a target which is 0.13 cm square while holding the select switch down.

---

Target Size

0.13 cm

0.27 cm

0.54 cm

1.07 cm

2.14 cm

Target Distance

2 cm

4 cm

8 cm

16 cm

---

Figure 6: Epps' Size and Distance Components of Cursor Movement

## 1.4 Hypothesis

This primitive task set (direction X distance X target size X selection mode) is proposed to be representative of the cursor actions required to perform any given computer task. It is important to note that this set of primitive elements does not include the elements of typing or thought which were mentioned above. The set is intended only to represent cursor actions. This set includes the variables of direction and selection mode not normally attributed to target acquisition tasks.

It is the goal of this research effort to prove that given the frequency of occurrence of each of the elements of the set of primitive tasks within a given user-composite task and a benchmark measurement of a user's ability to perform the primitive task with a given input device, it would then be possible to predict the user's performance on the given composite task with that input device.

In order to substantiate the claim that the proposed set of basic elements of cursor movement is representative and predictive of user device performance, the following conditions should hold:

- all user cursor movements observed must be representable by either  
the elements or some combination of the elements of  
the proposed set,

- the experimental method should produce data which conforms to the previous work in this area such as Fitts' Law,
- in general, through statistical analysis, it must be shown that the users' device performance on the primitive element or low level benchmark tasks shows a strong correlation to the users' device performance on the graphics task set when the performance measurements (time) from the low level benchmark tasks are combined linearly with the frequency of occurrence, within the graphics task, of the primitive elements which the benchmark task tested.

Chapter 2 describes the experiment and the data that were collected. Chapter 3 provides a full description of the analysis of the collected data and Chapter 4 discusses the conclusions drawn from the analysis as well as the possibilities for future research.

## **Chapter 2: Method**

### **2.1 Experimental Design**

The experiment to test the representational strength of the elements of the proposed primitive task set and the predictive ability of the low level benchmark tasks associated with the primitive task set was conducted using able-bodied subjects in the Human-Computer Interaction Laboratory on the campus of Virginia Tech. The experiment was a within-subject design (i.e. the data collected were compared only with other data collected from the same subject) with task completion time as the only dependent variable. Each of the subjects completed three sessions over a period of several days. Each session lasted between 1 and 2 hours and was devoted to a particular device with the device order altered by rotation among subjects to balance the effects of device order.

The computer selected for this experiment was the Apple Macintosh SE. This computer was chosen due to the availability of the HyperCard environment in which to develop the cursor movement benchmark set described below, as well as the availability of the MacDraw object-oriented graphics package in which the Mohageg graphics benchmark task set was developed. This set is described later in this chapter. The choice of the Macintosh SE eliminated the 16 cm target distance, as listed in Figure 6, from the set of primitive elements since this distance was not applicable to the limited screen size of this computer. Further, the choice of the HyperCard environment in which to

develop the primitive element or cursor movement benchmark task set eliminated the 0.13 cm target size, as listed in Figure 6, from the set of primitive elements since this target size was not attainable in HyperCard.

The cursor-control devices chosen for this experiment were the Apple Macintosh one button mouse, the Kensington Turbo Mouse (a trackball with mouse button and a mouse hold button), and the cursor keys as defined by the Apple Macintosh system utility Easy Access (see Figure 7). These device types were chosen due to the availability of previous research literature pertaining to them [CARD78] [ENGL67] [EPPS86] [MEHR72].

Another factor influencing the choice of these three device types was the diversity of physical movement required to operate each device. The previous research in this area, as cited above, suggests that for able bodied subjects, the mouse will generally be the faster device. This same research suggests that for able-bodied subjects the cursor keys will be more cumbersome and thus much slower for target acquisitions tasks than either the mouse or the trackball. However, because of the diversity of physical movements required for each device, a non-able-bodied computer user may provide very different results.

The subjects for this experiment were selected on a volunteer basis from a wide variety of age groups and computer experience levels. However, only those volunteers without previous experience with the mouse and the trackball were selected. Previous experience with the cursor keys was not expected to have any effect due to the unique design of the cursor keypad (see Figure 7).

As mentioned above, the low level benchmark tasks were developed in HyperCard. Each of these tasks were designed to test a single element of the primitive set of user cursor actions. The complete low level benchmark task set is described in Appendix B.

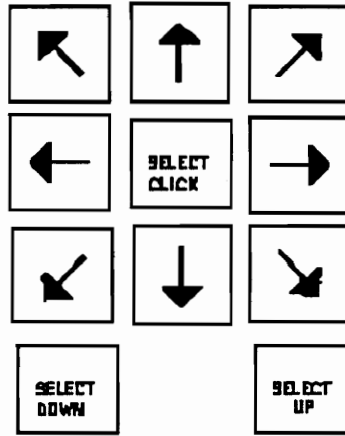


Figure 7: Cursor Key Layout

Each of the three sessions followed the same procedure with the subject using a different device each session. The control/display ratio setting for each device was set to the manufacturer's suggested setting: the slowest setting for cursor keys, the second slowest for the turbo mouse and the second fastest for the mouse. These settings for the mouse and the turbo mouse were constants while the setting for the cursor keys included the use of a key repeat rate accelerator allowing for acceleration over distance as a directional arrow key was held down. These settings were used since they had previously been shown, by the manufacturers, to be the optimum settings, on average, for an able-bodied user group. A pretest of three subjects was run to validate the primitive element set and the experimental method. The data collected during this pretest were used as input to make minor adjustments to the experimental method. This pretest was followed by a data collection period for fourteen subjects. Twelve subjects were needed to balance device order across subjects. Due to an inconsistency in method and an accident in which data were lost, two subjects' data had to be replaced.

The interface representation language UAN or User Action Notation [HART90] was used to give a detailed description of each of the user tasks involved in each of the sessions. This notation was chosen for this research due to its effectiveness in describing object-oriented user cursor actions. Augmentation to this interface design/description notation to represent direction and distance of movement as well as target size is one of the products of this research. For the purposes of this research, the following symbols are used

(see Figure 8). These symbols are broken down into the four components of the primitive task set: distance, direction, selection mode, and target size.

A generic UAN description for a move to target operation might be:

~ x y [target].

In this example, x would represent one of the eight directional notations as shown in Figure 8. Y would represent the distance to the target in cm and target would be replaced with the actual target name from the list of target names and sizes also listed in Figure 8. These three notations are the proposed augmentations to UAN.

---

| <u>Category</u>    | <u>Symbol</u>  | <u>Description</u>  |
|--------------------|--|---|
| Generic Moves      | ~<br>~[target]   | move<br>move to target  |
| Distance Notation  | ~xx<br>~xx[target]   | move xx centimeters<br>move xx centimeters to target  |
| Direction Notation | ~ > [target]<br>~ < [target]<br>~ ^ [target]<br>~ v [target]<br>~ / ^ [target]<br>~ \ ^ [target]<br>~ / v [target]<br>~ \ v [target] | move right to target<br>move left to target<br>move up to target<br>move down to target<br>move diagonally up (l to r) to target<br>move diagonally up (r to l) to target<br>move diagonally down (r to l) to target<br>move diagonally down (l to r) to target |
| Selection Notation | select switch down<br>select switch up<br>select click   | select current position<br>unselect current position<br>select, then unselect current position<br>(combination of down then up)   |
| Target Notation    | target0.27<br>target0.54<br>target1.07<br>target2.14   | the 0.27 cm target<br>the 0.54 cm target<br>the 1.07 cm target<br>the 2.14 cm target  |

---

Figure 8: User Action Notation With Augmentation

## **2.2 Benchmark Training**

Each session began with a short training session to familiarize the subjects with the tasks that they were to perform in the Cursor Movement Benchmarks. This training consisted of a short demonstration followed by a practice session. In order to equalize practice between the three devices, each subject performed exactly 60 practice trials chosen at random from the low level benchmark task set. This relatively high number of practice trials was chosen not only to equalize practice between the devices but also to minimize any learning effect throughout the experiment. The training lasted approximately one-half hour. Figure 9 shows a UAN description of several elements of the primitive element or low level benchmark task set. See Appendix A for a complete UAN description of the elements of the low level benchmark task set used in the practice sessions.

---

| Task    | User Action                     | System Response                                     |
|---------|---------------------------------|---|
| Task 1: | ~ > 8 [ target]<br>Select click | start timer<br>stop timer, record data, reset timer |
| Task 2: | ~ < 8 [ target]<br>Select click | start timer<br>stop timer, record data, reset timer |
| Task 3: | ~ ^ 8 [target]<br>Select click  | start timer<br>stop timer, record data, reset timer |
| Task 4: | ~ v 8 [ target]<br>Select click | start timer<br>stop timer, record data, reset timer |

---

Figure 9: UAN description of a sample of the low level benchmark tasks used in the training session.

### **2.3 The Cursor Movement Benchmark Tests**

Each session continued by having the subject perform the tasks of the low level benchmark task set which consisted of 192 trials per device (8 directions X 4 target sizes X 3 distances X 2 selection modes). The order of these trials was chosen at random. The data collected included time to perform the task, number of errors, average error distance from the target, and maximum error distance from the target. An error was defined as select switch on outside the target area for the 96 trials involving select switch up moves and as select switch off outside the target area for the 96 trials involving select switch down moves. The error distance was measured as the number of pixels from the current cursor location to the edge of the target and then converted to centimeters. Erroneous keypresses were recorded but not accepted. Therefore, error time is included in task completion time, so the collection of error data had no effect on the task completion time data.

These tasks were constructed such that the subject had to move the cursor from a beginning point to an ending point with distance, target size, direction, and selection mode varying from task to task. For these tasks, time was recorded internally in HyperCard. For the select up moves, timing began when the cursor moved off the starting position and ended when the target was selected. For the select down moves, timing began when the cursor moved off the starting position and ended when the select up action was taken on the target. Figure 9 above shows the UAN description for several of the tasks in the low level benchmark set. See Appendix B for a complete description of the

primitive element or low level benchmark task set. These tasks took approximately one-half hour to complete.

## **2.4 Training for the Mohageg Graphics Benchmark Set**

The session continued with a thorough training session to familiarize the subject with the MacDraw graphics package. This was the graphics package used in the Mohageg graphics benchmark tasks. This set of tasks was chosen due to its completeness and simplicity. This training included a demonstration as well as a practice session. Practice time was equalized among the three devices by having each subject perform all eleven of the benchmark tasks for practice before beginning data collection. Again, as with the low level benchmark tasks, this large number of practice tasks was not only designed to equalize practice among the devices but also to eliminate any user thought time or confusion during the actual graphics benchmark trials. To reduce further any cognitive effect on the task time, the experimenter asked the subject to describe the process for completing the task before beginning each task.

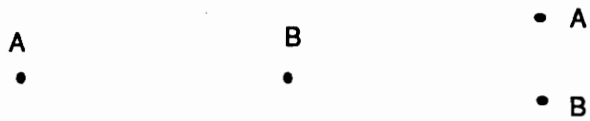
Figure 10 shows an example of two of the eleven tasks of the Mohageg graphics benchmark set. See Appendix C for a complete listing of the graphics benchmark set. Note that the tasks appear on the screen with instructions and the necessary objects for the task already provided. The graphics benchmark task set used in this experiment and listed in Appendix C actually represents a subset of the Mohageg graphics benchmark set with all duplicate tasks

removed. This portion of the session took approximately one-half hour to complete.

---

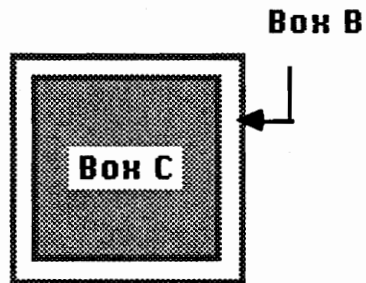
---

1. Draw a straight line between the points A and B.



---

2. Draw a box so that it covers Box C, but is surrounded by Box B.



---

Figure 10: Sample tasks from the Mohageg graphics benchmark set.

## **2.5 The Mohageg Graphics Benchmark Set**

The session concluded with the subject performing the eleven basic graphics tasks of the Mohageg benchmark with each device. Time to perform each task was measured in seconds using a software facility called Superclock. The Superclock icon appeared in the top right-hand corner of the screen. When the subject was ready to begin, the experimenter would have the subject describe to him the steps to perform the given task. The subject then had to select the Superclock icon to start the timer. They selected that icon again to stop the timer when they had completed the task. The experimenter then recorded the time and reset the timer.

Figure 10 above shows a sample of the tasks from the Mohageg graphics benchmark set. A full description of this set is provided in Appendix C. As mentioned above, the eleven elements of the graphics benchmark task set used in this experiment actually represent a subset of the Mohageg graphics benchmark set with all duplicate tasks removed. This final part of the session took approximately one-half hour to complete.

## **2.6 Data Collected**

A large variety and volume of data were collected in each of the three sessions. However, for purposes of analysis for this research, task completion time was the only dependent variable. The graphics benchmark portion of each session was videotaped in order to aid in the filtering of cognitive time from task completion times. A description of this process is included in Chapter 3.

Other data collected during these sessions included average error distance from target, maximum error distance from target, and total number of errors per trial. These data were collected only during the low level benchmark tasks along with task completion time for each task.

## **Chapter 3: Results**

### **3.1 User Action Notation Analysis of Tasks**

The first step in the analysis of the data was to describe fully the tasks of the Mohageg graphics benchmark set using the augmented User Action Notation. Figures 11, 12, and 13 provide the UAN descriptions of the eleven tasks of the graphics benchmark set. It should be noted that for completeness, each of these tasks descriptions includes a Select Click to start the timer as the first action even though this movement is not timed.

The UAN descriptions of the graphics tasks are necessary in order to determine the frequency of occurrence of each of the primitive task elements within each graphics task.

| Task    | User Action  | System Response   |
|---------|--|---|
| Task 1: | select click<br>~ /v 8 [target0.54]<br>select click<br>~ \v 4 [target0.27]<br>select down<br>~ > 4 [target0.27]<br>select up<br>~ /^ 8 [target0.54]<br>select click<br>~ > 8 [target0.27]<br>select down<br>~ v 2 [target0.27]<br>select up<br>~ /^ 8 [target0.54]<br>select click | start timer<br><br>select line tool, tool hilites<br><br>draw line<br><br>select line tool, tool hilites<br><br>draw line<br><br>stop timer |
| Task 2: | select click<br>~ /v 8 [target0.54]<br>select click<br>~ > 8 [target0.27]<br>select down<br>~ \v 4 [target0.27]<br>select up<br>~ /^ 8 [target0.54]<br>select click  | start timer<br><br>select box tool, tool hilites<br><br>draw box<br><br>stop timer  |
| Task 3: | select click<br>~ /v 8 [target0.54]<br>select click<br>~ > 8 [target0.27]<br>select down<br>~ \v 4 [target0.27]<br>select up<br>~ /^ 8 [target0.54]<br>select click  | start timer<br><br>select circle tool, tool hilites<br><br>draw circle<br><br>stop timer  |
| Task 4: | select click<br>~ /v 8 [target0.54]<br>select click<br>~ > 8 [target0.54]<br>select click<br>~ /v 4 [target0.54]<br>select click<br>~ > 4 [target0.54]<br>select click<br>~ \^ 4 [target0.54]<br>select click<br>~ /^ 8 [target0.54]<br>select click                               | start timer<br><br>select triangle tool, tool hilites<br><br>draw triangle<br>draw triangle<br>draw triangle<br><br>stop timer              |

Figure 11: UAN description of Tasks 1 Through 4 of the Mohageg Graphics Benchmark Set.

| Task    | User Action  | System Response  |
|---------|--|--|
| Task 5: | select click<br>~ /v 8 [target2.14]<br>select down<br>~ > 8 [target2.14]<br>select up<br>~ /^ 8 [target0.54]<br>select click   | start timer<br><br>grab box<br>move box<br>release box<br><br>stop timer   |
| Task 6: | select click<br>~ /v 8 [target2.14]<br>select click<br>~ /^ 2 [target0.27]<br>select down<br>~ /^ 2 [target1.07]<br>select up<br>~ > 4 [target2.14]<br>select click<br>~ \^ 2 [target0.27]<br>select down<br>~ /v 2 [target1.07]<br>select up<br>~ /^ 8 [target0.54]<br>select click | start timer<br><br>select box<br><br>get control of box<br>resize box<br><br><br><br>get control of box<br>resize box<br>release box<br><br>stop timer |
| Task 7: | select click<br>~ /v 8 [target1.07]<br>select click<br>~ /^ 2 [target0.27]<br>select down<br>~ /^ 2 [target0.27]<br>select up<br>~ /^ 8 [target0.54]<br>select click   | start timer<br><br>get control of circle<br><br><br>resize circle<br><br>stop timer  |
| Task 8: | select click<br>~ /v 8 [target2.14]<br>select down<br>~ > 8 [target1.07]<br>select up<br>~ /^ 8 [target0.54]<br>select click   | start timer<br><br>grab circle<br>move circle<br>release circle<br><br>stop timer  |

Figure 12: UAN description of Tasks 5 Through 8 of the Mohageg Graphics Benchmark Set.

| Task                | User Action         | System Response |
|---------------------|---------------------|-----------------|
| Task 9:             | select click        | start timer     |
|                     | ~ /v 8 [target0.54] |                 |
|                     | select down         |                 |
|                     | ~ \v 8 [target0.54] | select objects  |
|                     | select up           |                 |
|                     | ~ \^ 2 [target2.14] |                 |
|                     | select down         | grab objects    |
|                     | ~ > 8 [target0.54]  | move objects    |
|                     | select up           |                 |
|                     | ~ \^ 8 [target0.27] |                 |
|                     | select down         |                 |
|                     | ~ \v 2 [target0.27] | resize objects  |
| select up           |                     |                 |
| ~ /^ 8 [target0.54] |                     |                 |
| select click        | stop timer          |                 |
| Task 10:            | select click        | start timer     |
|                     | ~ /v 8 [target0.27] |                 |
|                     | select down         | grab line       |
|                     | ~> 8 [target0.54]   | move line       |
|                     | select up           | release line    |
|                     | ~ /v 8 [target0.27] |                 |
|                     | select down         | grab line       |
|                     | ~ > 8 [target0.54]  | move line       |
|                     | select up           | release line    |
|                     | ~ /^ 8 [target0.54] |                 |
| select click        | stop timer          |                 |
| Task 11:            | select click        | start timer     |
|                     | ~ /v 8 [target0.54] |                 |
|                     | select click        | select line     |
|                     | ~ > 2 [target0.27]  |                 |
|                     | select down         | control line    |
|                     | ~ < 2 [target1.07]  | size line       |
|                     | select up           | release line    |
|                     | ~ v 2 [target0.27]  |                 |
|                     | select click        | select line     |
|                     | ~ ^ 2 [target0.27]  |                 |
|                     | select down         | control line    |
|                     | ~ ^ 2 [target0.27]  | size line       |
|                     | select up           | release line    |
|                     | ~ /^ 8 [target0.54] |                 |
| select click        | stop timer.         |                 |

Figure 13: UAN description of Tasks 9 Through 11 of the Mohageg Graphics Benchmark Set.

### 3.2 Analysis of Results With Respect to Fitts' Law

The second step in the analysis of the data was to validate the data and the method with respect to previous work that has been done in the area of object-based interfaces and Fitts' Law [CARD78]. As mentioned earlier, direction was included as a factor in the low level benchmark task set because of its application to special populations of computer users. However, the data for this research were from able bodied subjects. Therefore, the data should conform to Fitts' Law. Fitts' Law, simply stated, says that the time necessary to move from point A to point B is a function of the distance from A to B and the size of the target B [FIT54] (see Figure 5 above). This implies that the graph of movement time versus the function  $(2 * \text{target distance}(\text{or amplitude}))/\text{target size}(\text{or width})$  should approach that of a straight line with the slope of that line being the b constant in the Fitts' Law equation and the Y intercept of that line being the a constant in that equation. A regression analysis was run using the average movement times for each of the twelve distance and target size combinations across all subjects, devices, directions, and selection modes. Figure 14 shows the resulting regression line, scatter plot, slope and intercept equation and R-squared value. This figure shows a resulting slope or b constant of 2.757 and a resulting intercept or a constant of 1.209. The R-squared value of .767 describes the quality of the fit of the points to the regression line and in this case, the fit is very good.

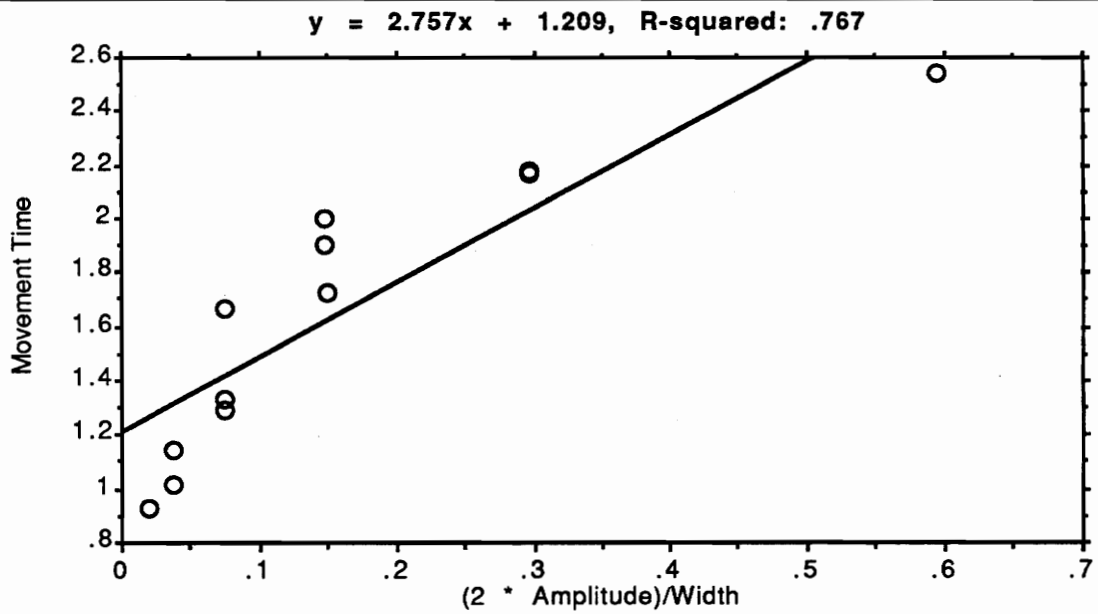


Figure 14: Fitts' Law regression analysis.

### **3.3 Correlation of Predicted and Actual Completion Times**

The task completion time for each primitive task for each user was multiplied by the associated frequency of occurrence of that primitive task within the graphics task as determined from the UAN description of the graphics tasks. The sums of these multiplications for each graphics task for each device were used as a predictor of task completion time on that graphics task for that device for each user. For example, graphics task 1, as described in Figure 11, is made up of seven unique primitive elements. Therefore, the prediction of task completion time for task 1 will be based on the sum of the completion times for each of the seven primitive tasks. Task completion time on the graphics tasks was measured in two ways. First, the raw score as recorded from the software facility Superclock was recorded. Second, videotape analysis was used to subtract any seconds in which the cursor did not move. This was done using a stop frame Video Cassette Recorder. If the cursor was in the same location for a full second, then that second was subtracted from the raw score. This adjusted task completion time is the one that was used in the analysis described below. This was an attempt to remove any further cognitive effect not already filtered by the experimental method. Figure 15 shows a sample table of predicted and actual task completion times for a specific subject and device, for each of the eleven graphics tasks. A listing of the full data, raw and adjusted actual times, as well as the predicted task completion times, is included as Appendix D.

The table in Figure 15 is labeled as subject 1k, meaning subject 1, device k or cursor keys. The eleven rows are the predicted and actual

completion times for the eleven graphic tasks in the same order as they appear in Appendix C. The data in this figure is organized as follows:

- The columns represent the raw task completion time,
- the adjusted completion times (after removing any whole seconds in which the cursor did not move),
- the ta (target acquisition average) prediction which uses the average over all 192 trials times the number of targets or actions in each task,
- the directional prediction which uses only the single benchmark trial which matches target size, distance, direction, and selection mode as a predictor,
- the average prediction which uses the average of the eight trials that match excluding direction,
- the adj. average prediction which takes the average of the six trials remaining that match excluding the direction after the high and low values are removed.

A more detailed description of the method of generating these predictions is given below.

| <u>Task Completion Times</u> |            |                    |                                   |  |   |  |
|------------------------------|------------|--------------------|-----------------------------------|--|---|--|
| <u>Actual</u>                |            |                    | <u>Predicted</u>                  |  |   |  |
| <u>Task#</u>                 | <u>Raw</u> | <u>Adjusted(*)</u> | <u>TA</u><br>192<br><u>Trials</u> | <u>Directional</u><br>Single<br><u>Trial</u> | <u>Average</u><br>8 Trials<br>Excluding<br><u>Direction</u> | <u>Adj. Average</u><br>6 Trials<br>Removing<br><u>High and Low</u> |
| 1                            | 32         | 32                 | 15.35                             | 18.63  | 17.79   | 17.87  |
| 2                            | 16         | 16                 | 8.77                              | 9.63   | 10.2  | 10.06  |
| 3                            | 23         | 23                 | 8.77                              | 9.63   | 10.2  | 10.06  |
| 4                            | 24         | 24                 | 13.16                             | 16.65  | 14.74   | 15.07  |
| 5                            | 11         | 11                 | 6.58                              | 5.31   | 5.34  | 5.23   |
| 6                            | 35         | 29                 | 15.35                             | 11.64  | 12.45   | 11.79  |
| 7                            | 17         | 17                 | 8.77                              | 8.61   | 8.21  | 7.89   |
| 8                            | 13         | 13                 | 6.58                              | 5.31   | 6.79  | 5.84   |
| 9                            | 44         | 41                 | 15.35                             | 17.11  | 16.65   | 16.54  |
| 10                           | 23         | 23                 | 10.97                             | 17.68  | 14.87   | 14.97  |
| 11                           | 24         | 24                 | 15.35                             | 17.55  | 15.15   | 14.31  |

Figure 15: Sample of table of actual and predicted task completion times(in seconds) for a specific subject and device for each of the eleven graphics tasks.

(\* Adjusted - removed time cursor not moving.)

Figures 16, 17, and 18 show the correlation coefficients for each subject for the cursor keys, the mouse, and the turbo mouse, respectively. Each chart shows three values for each subject: *directional*, *average*, and *adj. average*. The *directional* value represents the correlation coefficient with the predicted time calculated using the low level benchmark score including direction. This is to say that for each action identified in the graphics task, only the corresponding low level benchmark trial, including distance, target size, selection mode and direction, was used to calculate the predicted time. The *average* value represents the correlation coefficient with the predicted time calculated using the average of the eight low level benchmark trials with the same distance, target size, and selection mode. In this case, Fitts' Law was applied to find a prediction excluding direction. The *adj. average* value represents the correlation coefficient with the predicted time again calculated using the average of the eight low level benchmark trials with the same distance, target size, and selection mode. However, this average is taken over six values after the highest value and lowest value have been removed. This last value was computed in order to gain some measure of the effects of one-time high or low task completion times on the low level benchmark tasks in terms of the accuracy of the predictions.

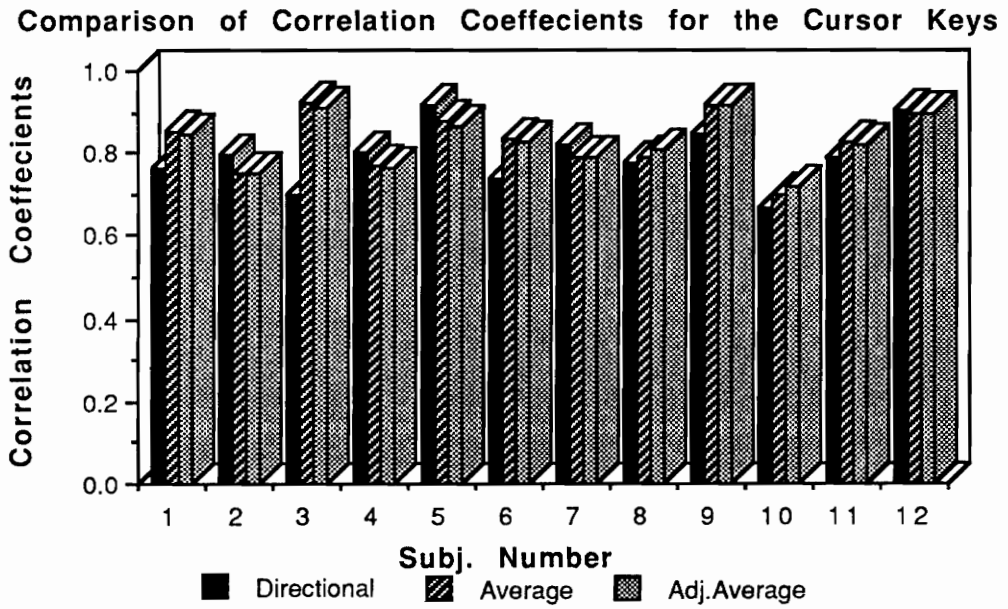


Figure 16: Correlation Coefficients by Subject for the Cursor Keys.

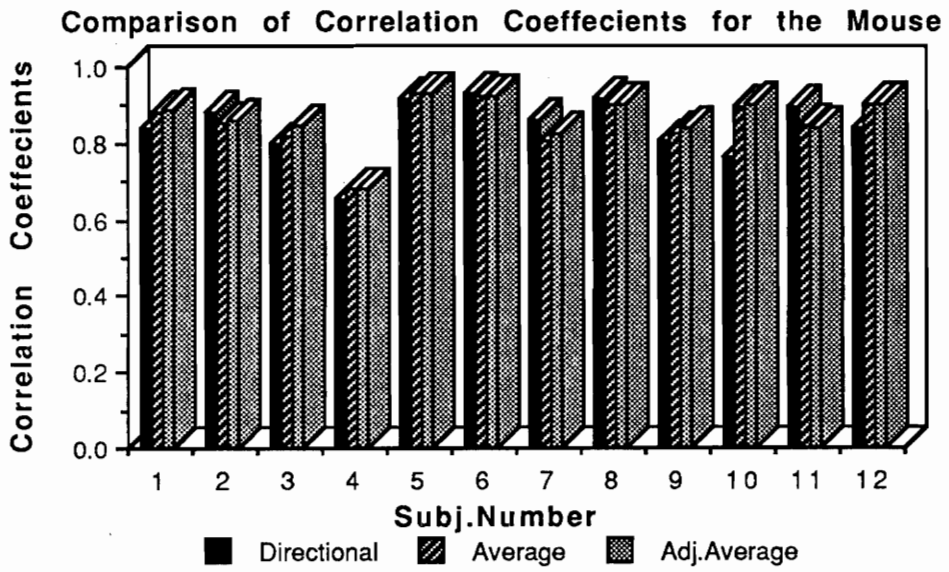


Figure 17: Correlation Coefficients by Subject for the Mouse.

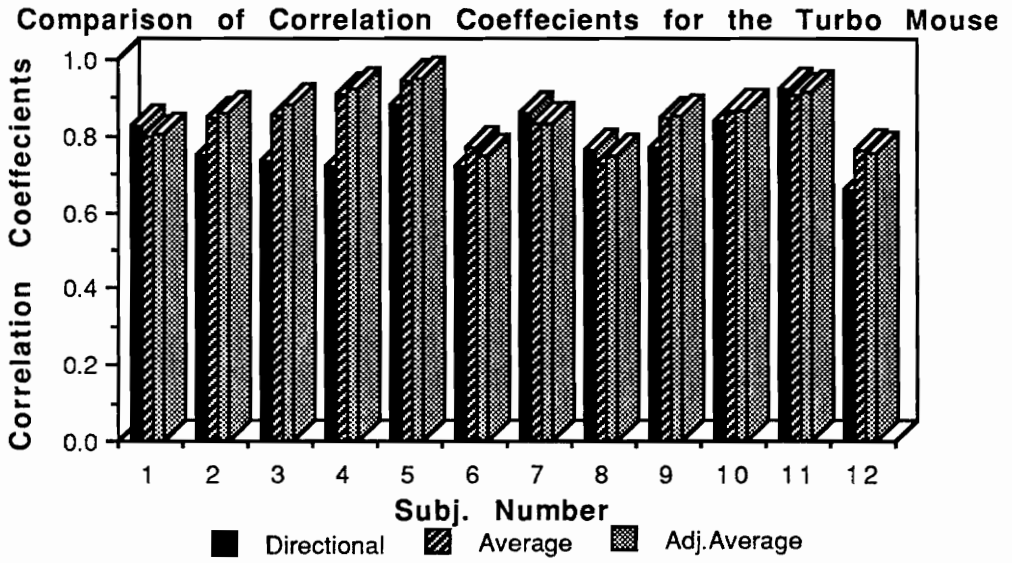


Figure 18: Correlation Coefficients by Subject for the Turbo Mouse.

Figure 19 shows the total average correlation coefficients and the average correlation coefficients by device for each of the three prediction techniques: *directional*, *average*, and *adj. average*, which were described above. It should be noted that this graph shows that the total overall average correlation between the *adj. average* prediction of the graphics tasks completion times from the low level benchmark and the actual graphics tasks completion times is slightly better than 0.845.

However, a great deal of variance did occur in a few cases. Figure 20 shows a graph of the correlation coefficients for the worst prediction generated by the benchmark task set out of 36 sets (12 subjects X 3 devices). As seen in figures 16, 17, and 18, however, correlation coefficients less than 0.75 were very rare. In fact, Figure 20 also shows a graph of the correlation coefficients for the best prediction generated by the benchmark task set. These values show a very nearly linear relationship between predicted task completion times and actual task completion times.

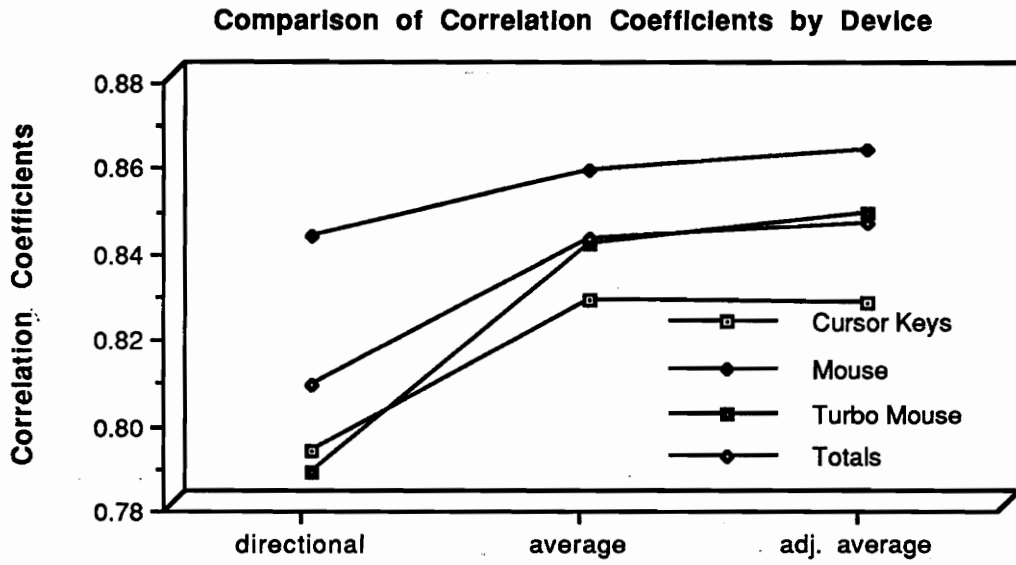


Figure 19: Correlation Coefficient Averages by Device and Total.

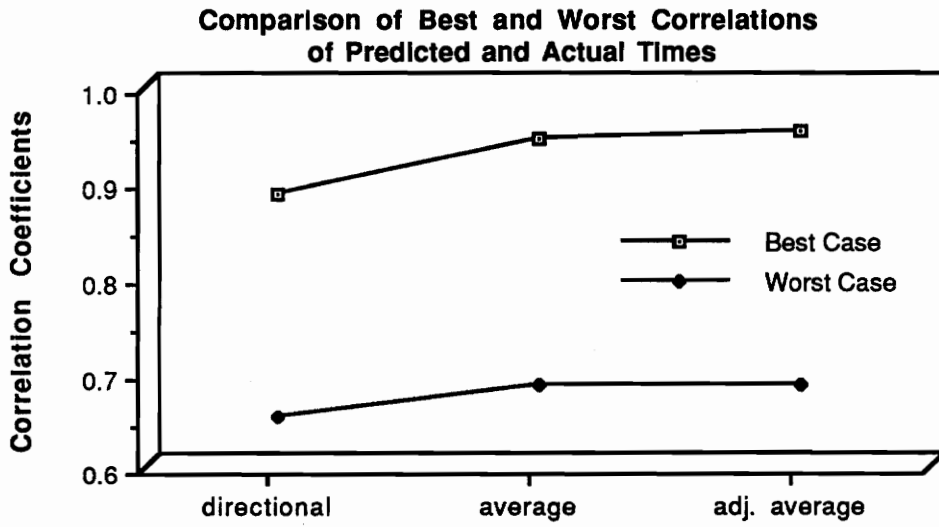
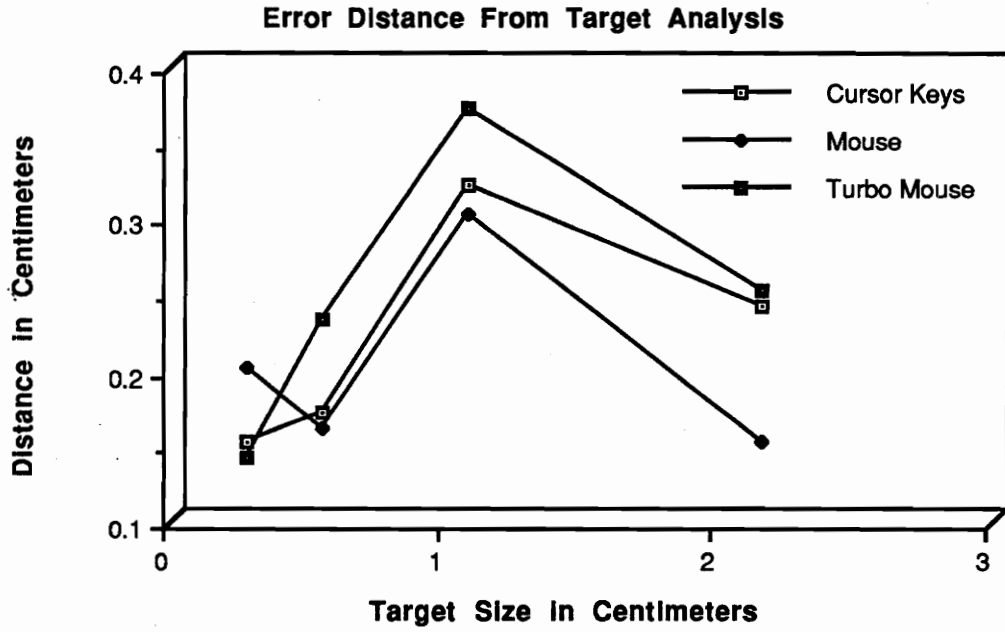


Figure 20: Best and Worst Correlations of Predicted and Actual Times.

### **3.4 Error Distance From Target Analysis**

The number of errors and error distance from target data were analyzed in an attempt to find either a formula, perhaps based on target size, or a constant representing the size of the error zone surrounding a target. Approximately 10% of all low level benchmark trials, or 600 trials contained errors. These data would have significant ramifications for research in the areas of snapping [HUDS90] and borders [WALK90]. Snapping is the idea of providing gravity or accelerated cursor movement to an icon as the user moves the cursor into a predefined area surrounding the icon. Borders provide for an impenetrable boundary to prevent the user from overshooting an icon particularly in the case of pull down menus.

The error distance from target data were averaged by target size in a cursory attempt to find some relationship between target size and error distance from target. Figure 21 shows a graph of average error distance from target as a function of target size. This graph is divided by device. Figure 22 shows the correlation matrix for the correlation of average error distance from target and target size. The last line in Figure 22 shows the correlation between error distance from target and target size for each device.



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Figure 21: Graph of Average Error Distance From Target With Target Size.

---

| <u>Name</u> | <u>Cursor Keys</u> | <u>Mouse</u> | <u>Turbo Mouse</u> | <u>Target</u> |
|-------------|--------------------|--------------|--------------------|---------------|
| Cursor Keys | 1                  | .695         | .946               | .544          |
| Mouse       | .695               | 1            | .659               | -.186         |
| Turbo Mouse | .946               | .659         | 1                  | .417          |
| Target Size | .544               | -.186        | .417               | 1             |

---

Figure 22: Correlation Matrix of for Error Distance vs. Target Size.

## **Chapter 4: Discussion**

### **4.1 Interpretation of Results and Conclusions**

The results of this research can be broken down into four areas. The first of these areas is the descriptive and representational strength of the elements of the primitive task set as described by the augmented User Action Notation. Figures 11, 12, and 13 demonstrate that the user cursor actions required to perform the eleven tasks of the Mohageg graphics benchmark task set can be described by the elements or some combination of the elements of the primitive task set. Thus, the combination of the primitive task set and the associated User Action Notation is sufficiently robust. Further, this notation description suggests the application of this primitive task set and the augmented UAN not only to the decomposition of the user action component of computer interfaces, but also to the design of this interface component as well.

The second of these areas is the analysis of the collected data with respect to Fitts' Law and the influence of the target size and target distance components of the primitive task set on task completion time. This analysis showed that, as Fitts' Law suggests, task completion time has a linear relationship to the function  $(2 * \text{amplitude}) / \text{width}$  which combines size and distance. This result is evident from the graph in Figure 14. This graph shows the resulting line, slope/intercept formula, R-squared value, and scatterplot from a regression analysis run on the twelve average movement times and the average of the size/distance function as taken across subject, device, selection

mode, and direction. This figure shows the constants for the Fitts' Law equation shown in Figure 5 above. The slope, or b constant, is 2.757. The y-intercept, or a constant, is 1.209. The R-squared value is 0.767. This value demonstrates that the linear function based on target size and target distance is good predictor of the actual movement times. It is interesting to note however, that there is a significant variance that is apparently not accounted for by the function based only on target size and target distance. This would suggest that elements such as thought, device, selection mode, or perhaps even direction may have a measurable effect on task completion times.

The third result of this research comes from the comparison analysis of the task completion times predicted by the low level benchmark task set and the actual task completion times for the graphics benchmark tasks. Figure 15 shows a sample table of predicted and actual completion times for the graphics benchmark tasks. This example demonstrates the fact that the predicted completion times are generally less than the actual completion times. There are two factors that account for this difference. First, the graphics tasks are generally more complex than the low level tasks as demonstrated by the UAN descriptions of the graphics tasks (see Figures 11, 12, and 13) which are combinations of the low level tasks. This implies that there is a larger cognitive component in the graphics tasks than in the low level benchmark tasks. Second, as mentioned earlier, the primitive task set and low level benchmark set are not intended to include the cognitive element of the user interface. Thus, the combination of these two factors suggest that there is a larger cognitive aspect in the graphics tasks than in the low level benchmark tasks, and this

difference is not accounted for by the low level benchmark. This means that the predicted task completion times should be, and generally are, less than the actual task completion times. However, the strong correlation between the predicted and actual times, as demonstrated by Figures 16, 17, and 18, suggests that this difference is a relatively constant factor for each subject.

Figures 16, 17, and 18 show the correlation coefficients for the predicted and actual task completion times for each of the three prediction methods described in Chapter 3. Two results are evident from these data. First, the low level benchmark task set effectively provided task completion time predictions with a very strong correlation to the actual task completion times. Second, the two prediction methods using values taken as a mean over several data points, namely the *average* and *adj. average* values, provide slightly better predictions of the actual task completion times than does the *directional* value, and the *adj. average* value provides the best prediction of the three methods. This second result is relatively easy to explain. Any prediction based on a single data point, as is the *directional* value, is subject to a higher degree of variance than a prediction based on an average across several data points. Further, the *adj. average* value tends to be the better of the three predictions since first, it is an average across several data points, and second, as described in Chapter 3, this average value is calculated after throwing out the highest and lowest data points. This tends to remove accidents and one time high or low performance from the prediction and thus provides a more accurate result. Figure 19 shows this result very vividly. This result also suggests that better predictions of task completion time using the directional component might be possible if more data

points were available so that the prediction could be calculated using the mean of several data points rather than a single data point.

The fourth result of this research is the examination of the relationship between error distance from target and target size. As Figures 23 and 24 show, no linear relationship was found between the error distance from target and the target size. However, the data do suggest that a relationship may exist between error distance from target, target size (for smaller target sizes), and specific devices. The graph in Figure 21 suggests removing the largest or 2.14 cm target size from the analysis since it would appear that the other data points represent a stronger correlation. After removing the largest target size, the following correlation coefficients are found between the error distance from target and the target size:

Mouse: 0.814

Cursor Keys: 0.974

Trackball: 0.998.

These data imply a nearly perfect linear relationship between error distance from target and target size for the smaller target sizes. This result strongly suggests further research in this area.

The results of this research are exciting, interesting, and motivating for future research in this area. In summary, the conclusions of this research are as follows:

- The elements of the primitive task set can be combined to represent the user cursor actions necessary to manipulate an object-oriented interface,

- The augmented User Action Notation is sufficient to fully describe the elements of the primitive set and thus, in combination, fully represent an object-oriented interface,

- The data that this task set produces conform to the precepts of Fitts' Law,

- The low level benchmark task set, which tests a user's ability to perform the elements of the set of primitive tasks with a given device, produces predictions of component task completion times with a very strong correlation to the actual component task completion times. These predictions are generally a constant factor less than the actual task completion times since there are elements of the component tasks interface, such as thought, which are not included in the primitive task set,

- The error distance from target data collected in this research suggest that there may be a strong relationship between error distance from target and target size especially for smaller target sizes,

- The data gathered here suggest that there elements of user cursor-action, namely distance, size, direction, and selection mode, which

certainly have an effect on a user's performance on a given task. This suggests that these elements, as described by the primitive task set should be of concern to interface, as well as interface device, designers.

## 4.2 Future Research

Several areas for future research present themselves from the results listed above. The first of these would be the expansion of the primitive task set, low level benchmark task set and UAN to include the text entry and thought elements which are not included here. A side issue of this research might be to determine what, if any, elements of a human-computer interface are not included in the group of cursor action, text entry, and thought. The goal of this research should be to determine what, if any, measurable effect each of these components has on task completion times. This might also include further investigation of the effects of direction and selection mode included here.

Second, the application of this research to non-able-bodied computer users should proceed as soon as possible. The current method of cursor control device selection for the physically handicapped is extremely subjective and utterly dependent on the availability of devices for trial and error sampling, and the availability of expertise in adapting the workplace to the disability. The use of this decomposition of the user-action component of the interface may allow for more standardized testing of cursor-control devices, as well as possibly pointing to the design of new devices. Further, this approach may be helpful in designing interfaces to minimize user action.

The third area of possible future research comes from the most surprising result of this research. That is the relationship between error distance from target and target size, especially for small targets. As mentioned earlier, this

research could have implications in every area of human-computer interface research and development.

### **4.3 Summary**

The motivation for this research effort is the potential technical benefit of a low level design, analysis and testing tool for human-computer interfaces. Current human-computer interface research efforts, such as snapping and borders, demonstrate the interest and the need for designing better interfaces. While the focus of this experiment is the comparison of cursor control devices, this low level decomposition of user tasks would certainly be useful in a design context as well. Further, as pointed out by Gillan [GILL90], the application of any metric or standard to human-computer interaction requires a detailed analysis of the users' tasks. Not only does this primitive task set provide a method and a notation for decomposing user tasks, it does it in such a way as to provide for simple analysis of the user interface with existing metrics such as Fitts' Law [CARD78]. A second potential benefit is the application of this testing method to special populations of computer users. There are over 7 million people in the United States who have specific limitations due to physical disability [ZIMM78]. For these individuals, computers may provide an avenue for remaining productive members of society. Decomposing user interfaces into their most basic elements may provide a less tedious and less subjective method of selecting the most appropriate input device or designing new ones.

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## Appendix A

### User Action Notation

The interface representation language UAN or User Action Notation [HART90] was used to give a detailed description of each of the user tasks involved in each of the sessions. This notation was chosen for this research due to its effectiveness in describing object-oriented user cursor actions. Augmentation to this interface design/description notation to represent direction and distance of movement as well as target size is one of the products of this research. For the purposes of this research, the following symbols are used (see Figure A1). These symbols are broken down into the four components of the primitive task set: distance, direction, selection mode, and target size.

A generic UAN description for a move to target operation might be:

~ x y [target].

In this example, x would represent one of the eight directional notations as shown in Figure 8. Y would represent the distance to the target in cm and target would be replaced with the actual target name from the list of target names and sizes also listed in Figure 8. These three notations are the proposed augmentations to UAN.

---

| <u>Category</u>    | <u>Symbol</u>  | <u>Description</u>  |
|--------------------|--|---|
| Generic Moves      | ~<br>~[target]   | move<br>move to target  |
| Distance Notation  | ~xx<br>~xx[target]   | move xx centimeters<br>move xx centimeters to target  |
| Direction Notation | ~ > [target]<br>~ < [target]<br>~ ^ [target]<br>~ v [target]<br>~ / ^ [target]<br>~ \ ^ [target]<br>~ / v [target]<br>~ \ v [target] | move right to target<br>move left to target<br>move up to target<br>move down to target<br>move diagonally up (l to r) to target<br>move diagonally up (r to l) to target<br>move diagonally down (r to l) to target<br>move diagonally down (l to r) to target |
| Selection Notation | select switch down<br>select switch up<br>select click   | select current position<br>unselect current position<br>select, then unselect current position<br>(combination of down then up)   |
| Target Notation    | target0.27<br>target0.54<br>target1.07<br>target2.14   | the 0.27 cm target<br>the 0.54 cm target<br>the 1.07 cm target<br>the 2.14 cm target  |

---

Figure A1: User Action Notation With Augmentation

The Select click action from the above notation actually represents a device specific procedure. For example, for the mouse this is merely a mouse click written in UAN as:

mouse v<sup>^</sup>.

For the turbo mouse, which has both a select (same as mouse) and a select hold ( which is the same as holding the mouse button down), the select click operation can be described in two ways:

select v<sup>^</sup>      or      select hold v<sup>^</sup>  
select hold v<sup>^</sup>.

Obviously, the first choice is the optimum choice, however, both are correct. The cursor keys are very similar to the turbo mouse in that the select click can be written in two ways:

select v<sup>^</sup>      or      select down v<sup>^</sup>  
select up v<sup>^</sup>.

Again, the first choice is the optimum method.

The Select Switch Down and Select Switch Up procedures present the same device specific characteristics as the Select Click procedure.

## Appendix B

### Cursor Movement Benchmark Training

Training began with a short demonstration of a set of target acquisition tasks by the experimenter. This was followed by a time for user practice. Care was given to equalizing practice among the experimental devices. As mentioned above, this was accomplished by having the subject perform exactly 60 practice trials. This set of practice trials was chosen at random from the Benchmark Task Set.

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#### UAN Task Descriptions of Training Tasks

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The 60 trials of the training were taken at random from the the expansion of the descriptors listed below. The list is expanded by substituting the three target distances (2cm, 4cm, and 8cm) and the 4 target sizes (target0.27, target0.54, target1.07, and target2.14, as listed above) in the appropriate positions in the notation.

| Task    | User Action                     | System Response                                     |
|---------|---------------------------------|---|
| Task 1: | ~ > 8 [ target]<br>Select click | start timer<br>stop timer, record data, reset timer |
| Task 2: | ~ < 8 [ target]                 | start timer   |

|         |                                  |   |
|---------|----------------------------------|---|
|         | Select click                     | stop timer, record data, reset timer                |
| Task 3: | ~ ^ 8 [target]<br>Select click   | start timer<br>stop timer, record data, reset timer |
| Task 4: | ~ v 8 [target]<br>Select click   | start timer<br>stop timer, record data, reset timer |
| Task 5: | ~ / ^ 8 [target]<br>Select click | start timer<br>stop timer, record data, reset timer |
| Task 6: | ~ / v 8 [target]<br>Select Click | start timer<br>stop timer, record data, reset timer |
| Task 7: | ~ \ ^ 8 [target]<br>Select Click | start timer<br>stop timer, record data, reset timer |
| Task 8: | ~ \ v 8 [target]<br>Select Click | start timer<br>stop timer, record data, reset timer |

| Task    | User Action  | System Response                                     |
|---------|--|---|
| Task 1: | Select Switch Down<br>~ > 8 [target]<br>Select Switch Up   | start timer<br>stop timer, record data, reset timer |
| Task 2: | Select Switch Down<br>~ < 8 [target]<br>Select Switch Up   | start timer<br>stop timer, record data, reset timer |
| Task 3: | Select Switch Down<br>~ ^ 8 [target]<br>Select Switch Up   | start timer<br>stop timer, record data, reset timer |
| Task 4: | Select Switch Down<br>~ v 8 [target]<br>Select Switch Up   | start timer<br>stop timer, record data, reset timer |
| Task 5: | Select Switch Down<br>~ / ^ 8 [target]<br>Select Switch Up | start timer<br>stop timer, record data, reset timer |
| Task 6: | Select Switch Down<br>~ / v 8 [target]<br>Select Switch Up | start timer<br>stop timer, record data, reset timer |
| Task 7: | Select Switch Down<br>~ \ ^ 8 [target]<br>Select Switch Up | start timer<br>stop timer, record data, reset timer |
| Task 8: | Select Switch Down<br>~ \ v 8 [target]<br>Select Switch Up | start timer<br>stop timer, record data, reset timer |

## Appendix C

### A Technical Description of The Cursor Movement Benchmark Set

The 192 trials of the cursor movement benchmark tasks as described here represent the fully crossed product of 8 directions, 3 distances, 4 target sizes and 2 selection modes. The 16 UAN task descriptions listed below can be expanded to the full 192 tasks by substituting the 3 distances (2cm, 4cm, and 8cm) and the 4 target sizes (target0.27, target0.54, target1.07 and target2.14, as listed above) into their appropriate positions in the notation. These tasks are in two groups, select off moves and select on moves.

-----  
**UAN Task Descriptions**  
**For the Cursor Movement Benchmark Set**  
-----

| Task    | User Action                      | System Response                                     |
|---------|----------------------------------|---|
| Task 1: | ~ > 8 [target]<br>Select Click   | start timer<br>stop timer, record data, reset timer |
| Task 2: | ~ < 8 [target]<br>Select Click   | start timer<br>stop timer, record data, reset timer |
| Task 3: | ~ ^ 8 [target]<br>Select Click   | start timer<br>stop timer, record data, reset timer |
| Task 4: | ~ v 8 [target]<br>Select Click   | start timer<br>stop timer, record data, reset timer |
| Task 5: | ~ / ^ 8 [target]<br>Select Click | start timer<br>stop timer, record data, reset timer |
| Task 6: | ~ / v 8 [target]<br>Select Click | start timer<br>stop timer, record data, reset timer |

|         |                                  |   |
|---------|----------------------------------|---|
| Task 7: | ~ ^ 8 [ target]<br>Select Click  | start timer<br>stop timer, record data, reset timer |
| Task 8: | ~ \v 8 [ target]<br>Select Click | start timer<br>stop timer, record data, reset timer |

The second group of tasks consist of select on moves.

| Task    | User Action   | System Response                                     |
|---------|---|---|
| Task 1: | Select Switch Down<br>~ > 8 [ target]<br>Select Switch Up   | start timer<br>stop timer, record data, reset timer |
| Task 2: | Select Switch Down<br>~ < 8 [ target]<br>Select Switch Up   | start timer<br>stop timer, record data, reset timer |
| Task 3: | Select Switch Down<br>~ ^ 8 [ target]<br>Select Switch Up   | start timer<br>stop timer, record data, reset timer |
| Task 4: | Select Switch Down<br>~ v 8 [ target]<br>Select Switch Up   | start timer<br>stop timer, record data, reset timer |
| Task 5: | Select Switch Down<br>~ / ^ 8 [ target]<br>Select Switch Up | start timer<br>stop timer, record data, reset timer |
| Task 6: | Select Switch Down<br>~ /v 8 [ target]<br>Select Switch Up  | start timer<br>stop timer, record data, reset timer |
| Task 7: | Select Switch Down<br>~ \^ 8 [ target]<br>Select Switch Up  | start timer<br>stop timer, record data, reset timer |
| Task 8: | Select Switch Down<br>~ \v 8 [ target]<br>Select Switch Up  | start timer<br>stop timer, record data, reset timer |

As mentioned above, the Select Click, Select Switch Down, and Select Switch Up, notations actually represent device specific procedures(see Appendix A).

## **Appendix D**

### **A Technical Description of the Mohageg Graphics Benchmark Tasks**

The session continued with the subject performing the eleven basic graphics tasks of the Mohageg graphics benchmark set. Time to perform each task was measured in seconds using the software facility Superclock. The Superclock icon appeared in the upper right-hand corner of the screen. The subject selected the icon at the beginning of each task to start the timer. The subject selected the icon again to signal the end of the task and stop the timer. The experimenter then recorded the time and reset the timer. To further reduce the effect of the cognitive aspect of these tasks, the subject was asked to describe how he was going to perform the task before timing begins. The graphics benchmark set used in this experiment and listed below actually represents a subset of the Mohageg benchmark with all duplicate tasks removed.

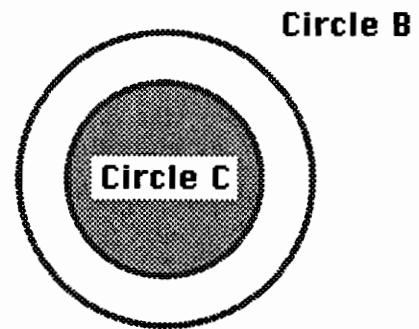
---

#### **Mohageg Graphics Benchmark Tasks**

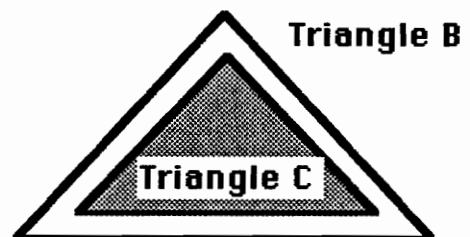
---



- 
3. Draw a circle that covers Circle C, but is surrounded by Circle B.



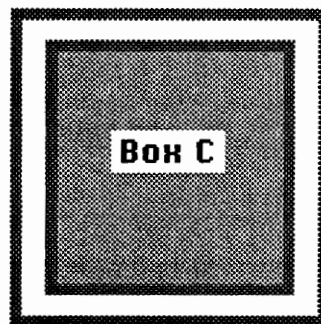
- 
4. Draw a triangle so that it covers Triangle C, but is surrounded by B.



---

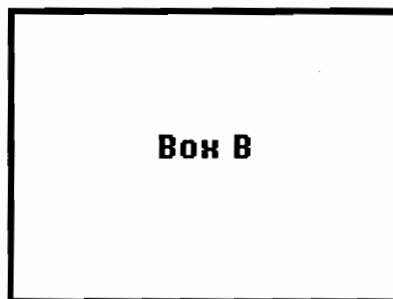
Position Box A such that it completely covers Box C, But is completely surrounded by Box B.

**Box B**



---

Resize each box so that each becomes a 1- by 1-inch square.



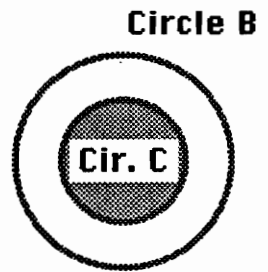
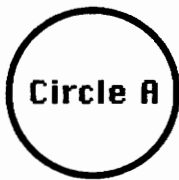
---

**Resize the ellipse such that it becomes a circle with a 1 inch diameter.**



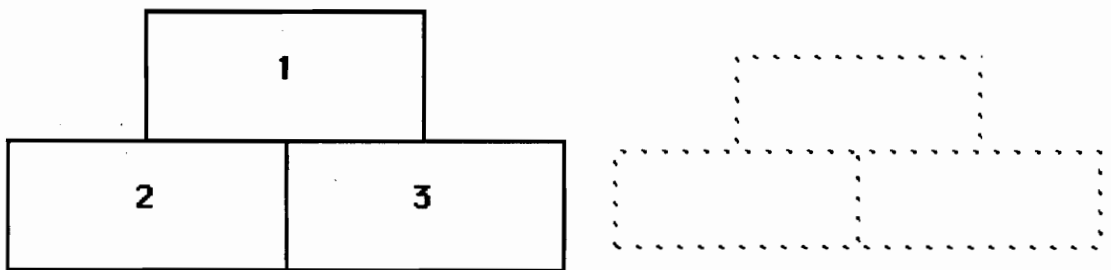
---

**Position Circle A such that it completely covers Circle C, but is completely surrounded by Circle B.**



---

Copy the figure on the left. Resize the copy so that it is the same size as the outlined figure on the right. Objects must be grouped before they are copied and Resized. Move the resized copy to the outlined position.



---

Place the lines on the left inside the rectangles on the right. No part of the lines should touch the sides of the rectangles.



---

**Resize each of these lines so that each is 1 inch long.**



## Appendix E

### Predictions and Actual Times for Each Subject for Each Device

The data below are organized by subject and by device with k representing cursor keys, m representing mouse, and t representing turbo mouse. The eleven rows are the predicted and actual completion times for the eleven graphic tasks. The columns represent the raw task completion time, the adjusted completion times (after removing any whole seconds in which the cursor did not move), the ta (target acquisition average) prediction which uses the average over all 192 trials times the number of targets or actions in each task, the directional prediction which uses only the single benchmark trial which matches target size, distance, direction, and selection mode as a predictor, the average prediction which uses the average of the eight trials that match excluding direction, and finally the adj. average prediction which takes the average of the six trials remaining that match excluding the direction after the high and low value are removed.

| Subj | 1k | raw | adjusted | ta    | directional | average | adjavg |
|------|----|-----|----------|-------|-------------|---------|--------|
| 32   | 32 | 32  | 32       | 15.35 | 18.63       | 17.79   | 17.87  |
| 16   | 16 | 16  | 16       | 8.77  | 9.63        | 10.2    | 10.06  |
| 23   | 23 | 23  | 23       | 8.77  | 9.63        | 10.2    | 10.06  |
| 24   | 24 | 24  | 24       | 13.16 | 16.65       | 14.74   | 15.07  |
| 11   | 11 | 11  | 11       | 6.58  | 5.31        | 5.34    | 5.23   |
| 35   | 29 | 29  | 29       | 15.35 | 11.64       | 12.45   | 11.79  |
| 17   | 17 | 17  | 17       | 8.77  | 8.61        | 8.21    | 7.89   |
| 13   | 13 | 13  | 13       | 6.58  | 5.31        | 6.79    | 5.84   |
| 44   | 41 | 41  | 41       | 15.35 | 17.11       | 16.65   | 16.54  |
| 23   | 23 | 23  | 23       | 10.97 | 17.68       | 14.87   | 14.97  |

|    |    |       |       |       |       |
|----|----|-------|-------|-------|-------|
| 24 | 24 | 15.35 | 17.55 | 15.15 | 14.31 |
|----|----|-------|-------|-------|-------|

| Subj 1m |          | ta   | directional | average | adjavg |
|---------|----------|------|-------------|---------|--------|
| raw     | adjusted |      |             |         |        |
| 12      | 12       | 6.25 | 7.87        | 7.97    | 7.75   |
| 7       | 7        | 3.57 | 4.6         | 4.71    | 4.59   |
| 7       | 7        | 3.57 | 4.6         | 4.71    | 4.59   |
| 11      | 11       | 5.35 | 7.94        | 7.29    | 6.97   |
| 5       | 5        | 2.68 | 2.93        | 2.7     | 2.62   |
| 11      | 9        | 6.25 | 5.79        | 5.66    | 5.43   |
| 5       | 5        | 3.57 | 3.81        | 3.8     | 3.68   |
| 4       | 4        | 2.68 | 3.12        | 3       | 2.95   |
| 17      | 15       | 6.25 | 6.64        | 6.91    | 6.84   |
| 8       | 8        | 4.46 | 5.37        | 5.42    | 5.35   |
| 14      | 8        | 6.25 | 6.92        | 6.54    | 6.24   |

| Subj 1t |          | ta   | directional | average | adjavg |
|---------|----------|------|-------------|---------|--------|
| raw     | adjusted |      |             |         |        |
| 12      | 12       | 7.57 | 9.68        | 11.14   | 10     |
| 10      | 9        | 4.32 | 5.98        | 5.81    | 5.49   |
| 9       | 9        | 4.32 | 5.98        | 5.81    | 5.49   |
| 11      | 11       | 6.49 | 7.67        | 8.78    | 8.39   |
| 8       | 6        | 3.24 | 2.85        | 3.05    | 2.96   |
| 19      | 15       | 7.57 | 7.48        | 6.81    | 6.55   |
| 9       | 7        | 4.32 | 4.84        | 4.61    | 4.44   |
| 6       | 6        | 3.24 | 2.77        | 3.34    | 3.23   |
| 20      | 17       | 7.57 | 9.63        | 10.1    | 8.99   |
| 10      | 10       | 5.4  | 8.31        | 6.83    | 6.55   |
| 21      | 15       | 7.57 | 7.62        | 8.33    | 8      |

| Subj 3k |          | ta    | directional | average | adjavg |
|---------|----------|-------|-------------|---------|--------|
| raw     | adjusted |       |             |         |        |
| 43      | 43       | 19.71 | 30.57       | 27.47   | 27.15  |
| 35      | 35       | 11.26 | 14.97       | 15.04   | 14.76  |
| 30      | 30       | 11.26 | 14.97       | 15.04   | 14.76  |
| 50      | 44       | 16.89 | 19.64       | 23.41   | 23.37  |
| 26      | 20       | 8.45  | 8.36        | 7.05    | 7.02   |
| 48      | 43       | 19.71 | 22.36       | 18.86   | 18.5   |
| 24      | 24       | 11.26 | 10          | 12.33   | 12.09  |
| 19      | 19       | 8.45  | 8.02        | 7.6     | 7.46   |

|    |    |       |       |       |       |
|----|----|-------|-------|-------|-------|
| 86 | 67 | 19.71 | 25.01 | 22.79 | 22.54 |
| 29 | 29 | 14.08 | 14.33 | 17.17 | 16.7  |
| 36 | 36 | 19.71 | 24.11 | 25.02 | 24.91 |

Subj 3m

| raw | adjusted | ta   | directional | average | adjavg |
|-----|----------|------|-------------|---------|--------|
| 12  | 12       | 6.41 | 7.41        | 8.05    | 7.79   |
| 9   | 9        | 3.67 | 5.75        | 4.91    | 4.71   |
| 10  | 10       | 3.67 | 5.75        | 4.91    | 4.71   |
| 14  | 14       | 5.5  | 6.68        | 6.6     | 6.46   |
| 6   | 6        | 2.75 | 2.46        | 2.81    | 2.77   |
| 14  | 14       | 6.41 | 5.78        | 5.4     | 5.25   |
| 7   | 7        | 3.67 | 3.66        | 3.71    | 3.63   |
| 6   | 6        | 2.75 | 2.66        | 2.79    | 2.73   |
| 17  | 15       | 6.41 | 8.61        | 8       | 7.85   |
| 14  | 12       | 4.58 | 7.59        | 6.84    | 6.66   |
| 14  | 14       | 6.41 | 6.61        | 5.9     | 5.74   |

Subj 3t

| raw | adjusted | ta   | directional | average | adjavg |
|-----|----------|------|-------------|---------|--------|
| 18  | 18       | 8.26 | 11.11       | 10.43   | 9.82   |
| 11  | 11       | 4.72 | 6.55        | 6.02    | 5.69   |
| 10  | 10       | 4.72 | 6.55        | 6.02    | 5.69   |
| 19  | 19       | 7.08 | 11.19       | 9.72    | 8.99   |
| 7   | 7        | 3.54 | 3.78        | 3.1     | 2.98   |
| 18  | 18       | 8.26 | 9.75        | 7.29    | 7.11   |
| 10  | 10       | 4.72 | 6.35        | 4.8     | 4.68   |
| 5   | 5        | 3.54 | 4.15        | 3.39    | 3.28   |
| 25  | 23       | 8.26 | 11.45       | 8.64    | 8.32   |
| 9   | 9        | 5.9  | 11.62       | 7.36    | 7.02   |
| 20  | 20       | 8.26 | 8.67        | 8.56    | 8.27   |

Subj 4k

| raw | adjusted | ta    | directional | average | adjavg |
|-----|----------|-------|-------------|---------|--------|
| 55  | 54       | 24.81 | 26.54       | 32.1    | 30.94  |
| 30  | 30       | 14.18 | 15.03       | 19.3    | 18.63  |
| 30  | 30       | 14.18 | 15.03       | 19.3    | 18.63  |
| 42  | 42       | 21.27 | 23.24       | 26.08   | 25.23  |
| 14  | 14       | 10.63 | 10.88       | 10.76   | 10.37  |
| 42  | 42       | 24.81 | 28.82       | 24.18   | 23.32  |

|    |    |       |       |       |       |
|----|----|-------|-------|-------|-------|
| 26 | 26 | 14.18 | 20.28 | 15.67 | 15.23 |
| 19 | 19 | 10.63 | 10.51 | 10.85 | 10.25 |
| 62 | 60 | 24.81 | 25.03 | 29.06 | 28.03 |
| 31 | 31 | 17.72 | 2.03  | 22.57 | 22.58 |
| 37 | 37 | 24.81 | 24.75 | 28.46 | 27.78 |

Subj 4m

| raw | adjusted | ta   | directional | average | adjavg |
|-----|----------|------|-------------|---------|--------|
| 12  | 12       | 6.42 | 7.49        | 7.79    | 7.79   |
| 7   | 7        | 3.67 | 5.26        | 4.62    | 4.63   |
| 9   | 9        | 3.67 | 5.26        | 4.62    | 4.63   |
| 12  | 12       | 5.51 | 6.29        | 6.33    | 6.38   |
| 5   | 5        | 2.75 | 3.41        | 2.63    | 2.63   |
| 11  | 11       | 6.42 | 8.64        | 6.47    | 5.97   |
| 9   | 7        | 3.67 | 4.13        | 4.19    | 3.87   |
| 5   | 5        | 2.75 | 3.41        | 2.89    | 2.87   |
| 22  | 19       | 6.42 | 8.3         | 7.32    | 7.31   |
| 9   | 9        | 4.59 | 7.54        | 5.98    | 5.94   |
| 11  | 11       | 6.42 | 7.8         | 7.69    | 6.99   |

Subj 4t

| raw | adjusted | ta   | directional | average | adjavg |
|-----|----------|------|-------------|---------|--------|
| 19  | 19       | 8.34 | 8.77        | 9.45    | 9.15   |
| 11  | 11       | 4.77 | 4.95        | 5.75    | 5.56   |
| 10  | 10       | 4.77 | 4.95        | 5.75    | 5.56   |
| 21  | 21       | 7.15 | 7.59        | 8.5     | 8.27   |
| 9   | 9        | 3.57 | 3.78        | 3.61    | 3.51   |
| 24  | 17       | 8.34 | 6.69        | 8.38    | 7.26   |
| 10  | 10       | 4.77 | 4.44        | 5.38    | 4.76   |
| 9   | 9        | 3.57 | .38         | 4.09    | 3.71   |
| 36  | 24       | 8.34 | 7.27        | 8.85    | 8.45   |
| 12  | 12       | 5.96 | 8.41        | 7.23    | 6.91   |
| 16  | 16       | 8.34 | 8.09        | 9.48    | 8.25   |

Subj 5k

| raw | adjusted | ta    | directional | average | adjavg |
|-----|----------|-------|-------------|---------|--------|
| 44  | 44       | 16.86 | 24.99       | 26.12   | 25.09  |
| 37  | 37       | 9.63  | 15.75       | 14.63   | 14.18  |
| 39  | 37       | 9.63  | 15.75       | 14.53   | 14.18  |

|    |    |       |       |       |       |
|----|----|-------|-------|-------|-------|
| 44 | 44 | 14.45 | 25.94 | 19.65 | 18.86 |
| 18 | 18 | 7.23  | 8.64  | 7.17  | 6.93  |
| 50 | 47 | 16.86 | 23.9  | 18.19 | 17.83 |
| 24 | 24 | 9.63  | 15.75 | 12.36 | 12.34 |
| 22 | 22 | 7.23  | 8.51  | 7.59  | 7.13  |
| 70 | 58 | 16.86 | 23.57 | 21.68 | 20.97 |
| 31 | 31 | 12.04 | 14.06 | 16.35 | 15.85 |
| 34 | 34 | 16.86 | 25.46 | 23.26 | 23.19 |

Subj 5m

| raw | adjusted | ta   | directional | average | adjavg |
|-----|----------|------|-------------|---------|--------|
| 14  | 13       | 7.41 | 8.72        | 8.84    | 8.54   |
| 9   | 9        | 4.23 | 4.82        | 5.07    | 4.82   |
| 12  | 12       | 4.23 | 4.82        | 5.07    | 4.82   |
| 18  | 13       | 6.35 | 6.84        | 8.1     | 7.62   |
| 9   | 9        | 3.17 | 3.09        | 2.99    | 2.88   |
| 14  | 14       | 7.41 | 6.1         | 6.13    | 5.95   |
| 11  | 8        | 4.23 | 3.33        | 3.93    | 3.76   |
| 9   | 9        | 3.17 | 2.9         | 3.28    | 2.94   |
| 24  | 22       | 7.41 | 6.84        | 7.6     | 7.25   |
| 13  | 13       | 5.29 | 4.7         | 6.14    | 5.9    |
| 14  | 14       | 7.41 | 6.52        | 6.82    | 6.55   |

Subj 5t

| raw | adjusted | ta   | directional | average | adjavg |
|-----|----------|------|-------------|---------|--------|
| 17  | 17       | 8.28 | 9.89        | 9.58    | 9.23   |
| 10  | 10       | 4.73 | 5.41        | 5.63    | 5.57   |
| 11  | 11       | 4.73 | 5.41        | 5.63    | 5.57   |
| 13  | 13       | 7.1  | 8.08        | 8.17    | 7.8    |
| 5   | 5        | 3.55 | 2.27        | 3.24    | 3.2    |
| 18  | 14       | 8.28 | 8.78        | 7.3     | 6.49   |
| 7   | 7        | 4.73 | 7.09        | 4.91    | 4.29   |
| 10  | 7        | 3.55 | 2.58        | 4.08    | 3.81   |
| 24  | 22       | 8.28 | 7.68        | 9.22    | 8.84   |
| 13  | 13       | 5.92 | 5.48        | 7.41    | 7.28   |
| 13  | 13       | 8.28 | 7.11        | 8.68    | 7.48   |

Subj 6k

| raw | adjusted | ta | directional | average | adjavg |
|-----|----------|----|-------------|---------|--------|
|-----|----------|----|-------------|---------|--------|

|    |    |       |       |       |       |
|----|----|-------|-------|-------|-------|
| 66 | 63 | 25.17 | 41.52 | 39.28 | 39.53 |
| 42 | 42 | 14.38 | 21.49 | 21.95 | 22.09 |
| 40 | 40 | 14.38 | 21.49 | 21.95 | 22.09 |
| 48 | 48 | 21.57 | 29.2  | 31.19 | 31.44 |
| 22 | 22 | 10.79 | 12.72 | 10.43 | 10.23 |
| 55 | 55 | 25.17 | 28.58 | 22.22 | 20.97 |
| 38 | 38 | 14.38 | 21.43 | 15.28 | 14.83 |
| 30 | 30 | 10.79 | 11.77 | 10.37 | 10.02 |
| 71 | 62 | 25.17 | 38.93 | 33.79 | 33.59 |
| 41 | 41 | 17.98 | 31.43 | 27.37 | 27.4  |
| 43 | 43 | 25.17 | 29.7  | 27.02 | 25.86 |

Subj 6m

| raw | adjusted | ta    | directional | average | adjavg |
|-----|----------|-------|-------------|---------|--------|
| 22  | 20       | 10.74 | 9.1         | 10.8    | 10.16  |
| 9   | 9        | 6.14  | 6.26        | 6.53    | 6.06   |
| 11  | 11       | 6.14  | 6.26        | 6.53    | 6.06   |
| 18  | 17       | 9.21  | 10.49       | 10.47   | 9.89   |
| 6   | 6        | 4.6   | 4.29        | 4.3     | 3.97   |
| 16  | 15       | 10.74 | 8.93        | 8.49    | 8.14   |
| 10  | 9        | 6.14  | 5.24        | 5.32    | 4.98   |
| 8   | 7        | 4.6   | 4.05        | 4.19    | 3.97   |
| 35  | 24       | 10.74 | 10.18       | 10.07   | 9.51   |
| 14  | 14       | 7.67  | 8.42        | 8.33    | 7.76   |
| 20  | 17       | 10.74 | 8.07        | 8.59    | 8.14   |

Subj 6t

| raw | adjusted | ta    | directional | average | adjavg |
|-----|----------|-------|-------------|---------|--------|
| 26  | 25       | 12.16 | 14.42       | 14.16   | 12.93  |
| 19  | 19       | 6.95  | 8.76        | 8.39    | 7.81   |
| 17  | 17       | 6.95  | 8.76        | 8.39    | 7.81   |
| 29  | 29       | 10.42 | 11.64       | 12.24   | 11.6   |
| 10  | 10       | 5.21  | 6.47        | 5.48    | 5.38   |
| 21  | 21       | 12.16 | 11.93       | 10.18   | 10.06  |
| 11  | 11       | 6.95  | 8.33        | 6.69    | 6.56   |
| 13  | 10       | 5.21  | 5.92        | 5.55    | 5.35   |
| 34  | 28       | 12.16 | 12.6        | 12.14   | 11.63  |
| 19  | 19       | 8.68  | 8.94        | 9.35    | 9.24   |
| 23  | 23       | 12.16 | 11.06       | 10.5    | 10.2   |

Subj 7k

| raw | adjusted | ta    | directional | average | adjavg |
|-----|----------|-------|-------------|---------|--------|
| 51  | 51       | 34.62 | 49.72       | 44.22   | 43.23  |
| 28  | 28       | 19.78 | 21.92       | 25.33   | 25.03  |
| 25  | 25       | 19.78 | 21.92       | 25.33   | 25.03  |
| 40  | 40       | 29.67 | 30.56       | 35.69   | 35.46  |
| 15  | 15       | 14.84 | 15.88       | 12.49   | 12.61  |
| 42  | 42       | 34.62 | 30.41       | 30.17   | 29.28  |
| 28  | 28       | 19.78 | 18.55       | 18.76   | 18.19  |
| 21  | 21       | 14.84 | 19.85       | 15.2    | 14.16  |
| 64  | 62       | 34.62 | 39.85       | 39.36   | 37.57  |
| 31  | 31       | 24.73 | 38.12       | 35.81   | 33.86  |
| 35  | 33       | 34.62 | 45.53       | 35.82   | 34.48  |

Subj 7m

| raw | adjusted | ta   | directional | average | adjavg |
|-----|----------|------|-------------|---------|--------|
| 15  | 12       | 6.79 | 9.49        | 8.64    | 8.59   |
| 8   | 8        | 3.88 | 5.57        | 5.12    | 5.14   |
| 8   | 8        | 3.88 | 5.57        | 5.12    | 5.14   |
| 15  | 13       | 5.82 | 7.17        | 6.95    | 6.86   |
| 4   | 4        | 2.91 | 3.13        | 3.13    | 3.06   |
| 12  | 12       | 6.79 | 6.96        | 6.73    | 6.67   |
| 7   | 7        | 3.88 | 4.2         | 4.1     | 4.09   |
| 4   | 4        | 2.91 | 3.36        | 3.43    | 3.39   |
| 18  | 17       | 6.79 | 9.69        | 8.3     | 8.25   |
| 11  | 11       | 4.85 | 6.75        | 6.88    | 6.98   |
| 11  | 11       | 6.79 | 7.81        | 7.29    | 7.25   |

Subj 7t

| raw | adjusted | ta    | directional | average | adjavg |
|-----|----------|-------|-------------|---------|--------|
| 20  | 20       | 10.19 | 9.89        | 10.68   | 10.33  |
| 8   | 8        | 5.82  | 5.87        | 6.2     | 6.04   |
| 8   | 8        | 5.82  | 5.87        | 6.2     | 6.04   |
| 14  | 14       | 8.73  | 8.24        | 8.94    | 8.73   |
| 5   | 5        | 4.37  | 3.31        | 3.53    | 3.44   |

|    |    |       |       |       |       |
|----|----|-------|-------|-------|-------|
| 15 | 14 | 10.19 | 10.6  | 10.09 | 9.63  |
| 6  | 6  | 5.82  | 6.52  | 6.33  | 6.06  |
| 6  | 6  | 4.37  | 3.35  | 3.56  | 3.47  |
| 33 | 28 | 10.19 | 11.07 | 10.48 | 9.6   |
| 12 | 12 | 7.28  | 6.96  | 8.25  | 7.64  |
| 16 | 13 | 10.19 | 13.52 | 11.98 | 11.24 |

Subj 8k

| raw | adjusted | ta    | directional | average | adjavg |
|-----|----------|-------|-------------|---------|--------|
| 31  | 31       | 18.15 | 24.27       | 24.47   | 23.43  |
| 20  | 20       | 10.37 | 11.21       | 14.47   | 13.95  |
| 21  | 21       | 10.37 | 11.21       | 14.47   | 13.95  |
| 28  | 28       | 15.55 | 14.02       | 20.62   | 19.54  |
| 13  | 13       | 7.78  | 8.57        | 7.19    | 6.96   |
| 36  | 32       | 18.15 | 22.72       | 17.46   | 16.69  |
| 17  | 17       | 10.37 | 10.41       | 11.68   | 11.32  |
| 13  | 13       | 7.78  | 8.32        | 7.49    | 7.11   |
| 40  | 36       | 18.15 | 21.57       | 21.53   | 20.48  |
| 22  | 19       | 12.96 | 18.32       | 18.95   | 18.08  |
| 21  | 21       | 18.15 | 19.32       | 21.86   | 20.83  |

Subj 8m

| raw | adjusted | ta   | directional | average | adjavg |
|-----|----------|------|-------------|---------|--------|
| 13  | 13       | 8.04 | 8.15        | 8.87    | 8.73   |
| 8   | 8        | 4.6  | 5.74        | 5.43    | 5.32   |
| 8   | 8        | 4.6  | 5.74        | 5.43    | 5.32   |
| 14  | 14       | 6.89 | 8.12        | 8.05    | 7.89   |
| 7   | 5        | 3.45 | 3.07        | 3.21    | 3.14   |
| 15  | 13       | 8.04 | 7.12        | 6.61    | 6.54   |
| 7   | 7        | 4.6  | 4.87        | 4.24    | 4.24   |
| 5   | 5        | 3.45 | 3.2         | 3.51    | 3.42   |
| 26  | 23       | 8.04 | 8.29        | 7.71    | 7.73   |
| 13  | 13       | 5.74 | 6.59        | 6.4     | 6.42   |
| 14  | 14       | 8.04 | 6.95        | 7.06    | 7.05   |

Subj 8t

| raw | adjusted | ta   | directional | average | adjavg |
|-----|----------|------|-------------|---------|--------|
| 16  | 15       | 7.91 | 8.08        | 8.98    | 8.82   |
| 8   | 8        | 4.52 | 4.02        | 5.42    | 5.35   |
| 8   | 8        | .52  | 4.02        | 5.42    | 5.35   |
| 10  | 10       | 6.78 | 7.17        | 7.65    | 7.54   |
| 6   | 6        | 3.39 | 3.29        | 3.05    | 3      |
| 12  | 12       | 7.91 | 6.27        | 6.76    | 6.54   |
| 7   | 7        | 4.52 | 3.29        | 4.24    | 4.16   |
| 7   | 7        | 3.39 | 3.42        | 3.14    | 3.12   |
| 26  | 22       | 7.91 | 7.89        | 8.5     | 8.39   |
| 13  | 13       | 5.65 | 6.17        | 7.29    | 7.21   |
| 14  | 14       | 7.91 | 6.66        | 7.45    | 7.12   |

Subj 9k

| raw | adjusted | ta    | directional | average | adjavg |
|-----|----------|-------|-------------|---------|--------|
| 44  | 44       | 20.74 | 24.34       | 28.82   | 28.63  |
| 30  | 30       | 11.85 | 13.87       | 17.01   | 17.07  |
| 30  | 30       | 11.85 | 13.87       | 17.01   | 17.07  |
| 40  | 40       | 17.78 | 16.79       | 26.71   | 26.05  |
| 21  | 20       | 8.89  | 6.02        | 8.45    | 8.27   |
| 31  | 31       | 20.74 | 25.91       | 21.29   | 19.9   |
| 26  | 26       | 11.85 | 10.93       | 13.96   | 13.33  |
| 20  | 20       | 8.89  | 7.57        | 9.3     | 8.98   |
| 65  | 63       | 20.74 | 25.4        | 27.31   | 27.03  |
| 38  | 35       | 14.82 | 18.6        | 23.73   | 23.83  |
| 32  | 32       | 20.74 | 18.42       | 27.24   | 25.9   |

Subj 9m

| raw | adjusted | ta   | directional | average | adjavg |
|-----|----------|------|-------------|---------|--------|
| 15  | 15       | 8.39 | 11.5        | 11.67   | 11.7   |
| 10  | 10       | 4.79 | 6.83        | 6.82    | 6.84   |
| 10  | 10       | 4.79 | 6.83        | 6.82    | 6.84   |
| 15  | 15       | 7.19 | 9.69        | 9.45    | 9.54   |
| 6   | 6        | 3.6  | 4.24        | 4.12    | 4.08   |
| 13  | 13       | 8.39 | 7.08        | 7.86    | 7.66   |
| 8   | 8        | 4.79 | 5.84        | 5.5     | 5.43   |
| 7   | 6        | 3.6  | 3.8         | 4.34    | 4.32   |

|    |    |      |       |       |       |
|----|----|------|-------|-------|-------|
| 25 | 22 | 8.39 | 12.38 | 11.32 | 11.19 |
| 12 | 12 | 5.99 | 7.95  | 9.2   | 9.03  |
| 12 | 12 | 8.39 | 10.02 | 9.21  | 9.04  |

| Subj 9t |          |      |             |         |        |
|---------|----------|------|-------------|---------|--------|
| raw     | adjusted | ta   | directional | average | adjavg |
| 14      | 14       | 8.67 | 10.18       | 10.98   | 10.45  |
| 9       | 9        | 4.95 | 6.37        | 6.96    | 6.56   |
| 9       | 9        | 4.95 | 6.37        | 6.96    | 6.56   |
| 13      | 13       | 7.43 | 9.74        | 9.21    | 9.04   |
| 6       | 6        | 3.71 | 3.95        | 4.05    | 4.01   |
| 19      | 16       | 8.67 | 7.27        | 6.89    | 6.85   |
| 9       | 9        | 4.95 | 5.15        | 4.55    | 4.53   |
| 7       | 7        | 3.71 | 3.75        | 4.31    | 4.26   |
| 25      | 23       | 8.67 | 9.67        | 10.02   | 9.77   |
| 12      | 12       | 6.19 | 8.31        | 8.74    | 8.58   |
| 15      | 15       | 8.67 | 7.32        | 7.49    | 7.44   |

| Subj 10k |          |       |             |         |        |
|----------|----------|-------|-------------|---------|--------|
| raw      | adjusted | ta    | directional | average | adjavg |
| 55       | 55       | 20.56 | 34.3        | 33.83   | 29.71  |
| 34       | 34       | 11.75 | 16.15       | 19.57   | 17.25  |
| 25       | 25       | 11.75 | 16.15       | 19.57   | 17.25  |
| 35       | 35       | 17.63 | 17.96       | 27.74   | 23.8   |
| 17       | 17       | 8.81  | 6.22        | 9.75    | 8.52   |
| 40       | 40       | 20.56 | 19.47       | 21.28   | 19.56  |
| 23       | 23       | 11.75 | 11.51       | 13.88   | 12.5   |
| 21       | 21       | 8.81  | 6.17        | 10.01   | 8.68   |
| 56       | 52       | 20.56 | 17.2        | 29.05   | 25.73  |
| 30       | 30       | 14.69 | 17.68       | 22.21   | 20.37  |
| 40       | 40       | 20.56 | 21.9        | 26.47   | 23.67  |

| Subj 10m |          |      |             |         |        |
|----------|----------|------|-------------|---------|--------|
| raw      | adjusted | ta   | directional | average | adjavg |
| 13       | 13       | 9.5  | 10.17       | 11.77   | 10.78  |
| 7        | 7        | 5.43 | 6.13        | 6.41    | 6.25   |
| 8        | 8        | 5.43 | 6.13        | 6.41    | 6.25   |

|    |    |      |       |       |      |
|----|----|------|-------|-------|------|
| 15 | 15 | 8.14 | 16.68 | 10.23 | 9.18 |
| 5  | 5  | 4.07 | 3.06  | 3.22  | 3.07 |
| 12 | 12 | 9.5  | 8.74  | 8.62  | 7.87 |
| 8  | 8  | 5.43 | 4.82  | 5.85  | 5.3  |
| 7  | 7  | 4.07 | 3.55  | 3.31  | 3.22 |
| 19 | 19 | 9.5  | 10.12 | 9.63  | 9.42 |
| 10 | 10 | 6.79 | 7.22  | 7.84  | 7.78 |
| 13 | 13 | 9.5  | 9.76  | 10.7  | 9.6  |

| Subj 10t |          |      |             |         |        |
|----------|----------|------|-------------|---------|--------|
| raw      | adjusted | ta   | directional | average | adjavg |
| 25       | 25       | 8.7  | 11.12       | 10.65   | 10.85  |
| 12       | 12       | 4.97 | 5.33        | 6.41    | 6.49   |
| 10       | 10       | 4.97 | 5.33        | 6.41    | 6.49   |
| 17       | 17       | 7.46 | 9.35        | 9.81    | 9.79   |
| 6        | 6        | 3.73 | 3.25        | 3.29    | 3.31   |
| 19       | 19       | 8.7  | 7.2         | 8.43    | 7.34   |
| 8        | 8        | 4.97 | 4.78        | 5.29    | 4.81   |
| 8        | 8        | 3.73 | 3.4         | 3.54    | 3.49   |
| 30       | 29       | 8.7  | 8.22        | 8.89    | 9      |
| 13       | 13       | 6.21 | 7.75        | 6.8     | 6.89   |
| 17       | 17       | 8.7  | 11.06       | 9.38    | 8.32   |

| Subj 12k |          |       |             |         |        |
|----------|----------|-------|-------------|---------|--------|
| raw      | adjusted | ta    | directional | average | adjavg |
| 27       | 27       | 11.7  | 18.23       | 15.18   | 15.07  |
| 17       | 17       | 6.69  | 9           | 9.02    | 9.01   |
| 20       | 20       | 6.69  | 9           | 9.02    | 9.01   |
| 29       | 29       | 10.03 | 11.4        | 12.04   | 12     |
| 11       | 11       | 5.02  | 6.35        | 5.01    | 4.73   |
| 19       | 19       | 11.7  | 10.62       | 11.17   | 10.49  |
| 14       | 14       | 6.69  | 8.25        | 8.15    | 7.96   |
| 12       | 12       | 5.02  | 6.53        | 5.72    | 5.12   |
| 37       | 35       | 11.7  | 13.42       | 12.86   | 12.45  |
| 22       | 22       | 8.36  | 12.51       | 10.71   | 10.56  |
| 15       | 15       | 11.7  | 14          | 13.87   | 13.33  |

| Subj 12m |          | ta   | directional | average | adjavg |
|----------|----------|------|-------------|---------|--------|
| raw      | adjusted |      |             |         |        |
| 7        | 7        | 4.91 | 6.54        | 5.44    | 5.41   |
| 5        | 5        | 2.8  | 4.38        | 3.38    | 3.38   |
| 5        | 5        | 2.8  | 4.38        | 3.38    | 3.38   |
| 10       | 10       | 4.21 | 4.87        | 4.9     | 4.96   |
| 2        | 2        | 2.1  | 2.31        | 1.87    | 1.82   |
| 6        | 6        | 4.91 | 4.77        | 3.78    | 3.63   |
| 4        | 4        | 2.8  | 3.32        | 2.6     | 2.56   |
| 3        | 3        | 2.1  | 2.52        | 2.11    | 2      |
| 10       | 9        | 4.91 | 5.48        | 5.16    | 5.02   |
| 7        | 7        | 3.5  | 4.29        | 4.38    | 4.29   |
| 5        | 5        | 4.91 | 4.71        | 4.25    | 4.15   |

| Subj 12t |          | ta   | directional | average | adjavg |
|----------|----------|------|-------------|---------|--------|
| raw      | adjusted |      |             |         |        |
| 10       | 10       | 5.35 | 6.4         | 6.02    | 5.91   |
| 7        | 7        | 3.06 | 3.83        | 3.64    | 3.62   |
| 6        | 6        | 3.06 | 3.83        | 3.64    | 3.62   |
| 12       | 12       | 4.58 | 6.66        | 5.64    | 5.49   |
| 4        | 4        | 2.29 | 2.16        | 1.95    | 1.94   |
| 8        | 8        | 5.35 | 5.43        | 4.45    | 4.46   |
| 6        | 6        | 3.06 | 3.26        | 2.91    | 2.93   |
| 5        | 5        | 2.29 | 2.81        | 2.17    | 2.18   |
| 17       | 14       | 5.35 | 5.27        | 5.19    | 5.17   |
| 8        | 8        | 3.82 | 3.99        | 4.36    | 4.4    |
| 9        | 9        | 5.35 | 4.86        | 4.95    | 5.01   |

| Subj 13k |          | ta    | directional | average | adjavg |
|----------|----------|-------|-------------|---------|--------|
| raw      | adjusted |       |             |         |        |
| 40       | 40       | 20.64 | 35.34       | 28.8    | 27.5   |
| 23       | 23       | 11.79 | 21.64       | 18.18   | 17.34  |
| 25       | 25       | 11.79 | 21.64       | 18.18   | 17.34  |
| 41       | 41       | 17.69 | 22.77       | 22.85   | 22.18  |
| 17       | 17       | 8.84  | 8.66        | 7.98    | 7.48   |
| 33       | 33       | 20.64 | 18.76       | 18.89   | 17.57  |

|    |    |       |       |       |       |
|----|----|-------|-------|-------|-------|
| 21 | 21 | 11.79 | 12.16 | 13.09 | 12.22 |
| 20 | 20 | 8.84  | 8.13  | 8.41  | 7.72  |
| 52 | 50 | 20.64 | 32.17 | 26.11 | 24.51 |
| 30 | 30 | 14.74 | 29.07 | 22.86 | 21.66 |
| 28 | 28 | 20.64 | 25.14 | 24.36 | 22.94 |

Subj 13m

| raw | adjusted | ta   | directional | average | adjavg |
|-----|----------|------|-------------|---------|--------|
| 14  | 14       | 6.01 | 7.13        | 7.33    | 7.37   |
| 9   | 9        | 3.43 | 4.3         | 4.31    | 4.3    |
| 9   | 9        | 3.43 | 4.3         | 4.31    | 4.3    |
| 10  | 10       | 5.15 | 5.72        | 6.19    | 6.27   |
| 4   | 4        | 2.58 | 2.58        | 2.58    | 2.59   |
| 9   | 9        | 6.01 | 5.32        | 5.53    | 5.57   |
| 7   | 7        | 3.43 | 3.98        | 3.64    | 3.66   |
| 6   | 6        | 2.58 | 2.62        | 2.76    | 2.75   |
| 19  | 17       | 6.01 | 7.63        | 7.01    | 7.01   |
| 8   | 8        | 4.29 | 5.63        | 5.59    | 5.58   |
| 9   | 9        | 6.01 | 6.19        | 6.27    | 6.35   |

Subj 13t

| raw | adjusted | ta   | directional | average | adjavg |
|-----|----------|------|-------------|---------|--------|
| 15  | 15       | 8.75 | 9.56        | 9.76    | 9.38   |
| 9   | 9        | 5    | 5.95        | 5.87    | 5.6    |
| 11  | 10       | 5    | 5.95        | 5.87    | 5.6    |
| 15  | 15       | 7.5  | 8.4         | 9.38    | 8.94   |
| 6   | 6        | 3.75 | 4.5         | 3.6     | 3.53   |
| 13  | 13       | 8.75 | 8.27        | 7.42    | 7.22   |
| 9   | 9        | 5    | 5.57        | 4.79    | 4.72   |
| 6   | 6        | 3.75 | 4.21        | 4.14    | 3.86   |
| 21  | 19       | 8.75 | 9.86        | 9.4     | 9.12   |
| 11  | 11       | 6.25 | 8.38        | 7.65    | 7.53   |
| 18  | 18       | 8.75 | 8.61        | 8.19    | 8.09   |

Subj 14k

| raw | adjusted | ta | directional | average | adjavg |
|-----|----------|----|-------------|---------|--------|
|-----|----------|----|-------------|---------|--------|

|    |    |      |       |       |       |
|----|----|------|-------|-------|-------|
| 40 | 38 | 18.2 | 17.91 | 20.61 | 20    |
| 25 | 25 | 10.4 | 10.78 | 12.49 | 11.82 |
| 25 | 25 | 10.4 | 10.78 | 12.49 | 11.82 |
| 36 | 36 | 15.6 | 19.65 | 19.22 | 18.97 |
| 13 | 13 | 7.8  | 4.88  | 6.67  | 5.99  |
| 34 | 34 | 18.2 | 11.95 | 14.49 | 13.16 |
| 21 | 21 | 10.4 | 11.87 | 10.24 | 9.54  |
| 14 | 14 | 7.8  | 5.87  | 6.65  | 6.23  |
| 51 | 49 | 18.2 | 21.41 | 20.33 | 19.16 |
| 29 | 29 | 13   | 16.96 | 18.31 | 17.06 |
| 27 | 27 | 18.2 | 15.55 | 17.38 | 15.7  |

Subj 14m

| raw | adjusted | ta    | directional | average | adjavg |
|-----|----------|-------|-------------|---------|--------|
| 14  | 13       | 10.38 | 9.35        | 10.79   | 10.21  |
| 8   | 8        | 5.93  | 5.68        | 6.71    | 6.26   |
| 8   | 8        | 5.93  | 5.68        | 6.71    | 6.26   |
| 16  | 16       | 8.9   | 9.42        | 10.36   | 9.56   |
| 5   | 5        | 4.45  | 3.26        | 3.68    | 3.48   |
| 13  | 13       | 10.38 | 7.43        | 8.41    | 8.08   |
| 7   | 7        | 5.93  | 4.25        | 5.62    | 5.31   |
| 5   | 5        | 4.45  | 3.01        | 3.97    | 3.74   |
| 20  | 17       | 10.38 | 9.76        | 9.66    | 9.29   |
| 9   | 9        | 7.42  | 7.63        | 8.03    | 7.63   |
| 13  | 11       | 10.38 | 11.36       | 9.41    | 9.09   |

Subj 14t

| raw | adjusted | ta   | directional | average | adjavg |
|-----|----------|------|-------------|---------|--------|
| 11  | 11       | 8.07 | 8.57        | 8.72    | 8.59   |
| 8   | 8        | 4.61 | 4.68        | 5.17    | 5.03   |
| 9   | 9        | 4.61 | 4.68        | 5.17    | 5.03   |
| 13  | 13       | 6.92 | 6.8         | 7.3     | 7.32   |
| 5   | 5        | 3.46 | 3.08        | 2.91    | 2.85   |
| 11  | 11       | 8.07 | 7.51        | 6.88    | 6.83   |
| 4   | 4        | 4.61 | 3.78        | 4.23    | 4.17   |
| 6   | 5        | 3.46 | 2.91        | 2.98    | 2.93   |
| 25  | 23       | 8.07 | 6.57        | 7.79    | 7.6    |

|    |    |      |      |      |      |
|----|----|------|------|------|------|
| 12 | 12 | 5.76 | 6.11 | 6.2  | 5.99 |
| 13 | 13 | 8.07 | 7.23 | 7.55 | 7.56 |

## Vita

Born to Delmar and Janet Chase in Bowlinggreen, KY, the author spent the first ten years of his life in several different southern states. At the age of eleven, the author moved with his family to his father's hometown of Lewisburg, WV. Here he remained until graduating from Greenbrier East High School and entering the computer science program at Virginia Polytechnic Institute and State University.

After graduating from Virginia Tech with a B.S. degree in computer science, the author went to work for NCNB corporation in Charlotte, NC. After moving from programmer to systems planning officer over a period of two years, the author returned to Virginia Tech to pursue his master's degree. During his two years in the master's program, he taught one semester as a graduate teaching assistant and spent the remaining year and a half as the system manager for the Human-Computer Interaction Laboratory in the Industrial Engineering Department at Virginia Tech. It was during this interaction with the Industrial Engineering Department that the seed for this current research was germinated.

The author plans to remain at Virginia Tech in pursuit of a Ph.D. degree in computer science. Upon completion of that degree,

the author would like to pursue a career in research and teaching at a college or university in the mid-Atlantic region of the country.