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Perceptual-Motor Control in Human-Computer Interaction

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This report isolates and examines some of the emergent perceptual-motor issues raised by the new style in human-computer interaction. It concerns the use of a mouse to select commands from menus. Herein, I describe the physical and perceptual characteristics of the menus and selection procedures to be studied. I also cover research from both the motor-control and the human-computer interaction literature that applies to perceptual and motor aspects of menu selection.

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CHAPTER 1
INTRODUCTION

The manner in which people interact with computers underwent a dramatic change in the 1980's. Before 1980, small computer screens displayed information using only alphanumeric characters or primitive graphics constructed from letters, numbers and symbols. Now, large screen bit-map displays present information in many forms and at many locations on the screen. People used to send commands to the computer by typing letter combinations or words memorized from a command language. Commands are recognized and selected today from a list of options presented to the user in command menus. Increasingly, the selection of information does not require keyboards, but involves other selection devices, such as a mouse, trackball, joystick, or touchscreen, which allow direct manipulation of objects on the screen.

The new interaction style has changed many of the psychological issues that are important for understanding and modelling human-computer interaction. The old style emphasized memory processes and keystrokes associated with recalling commands and entering them with a keyboard. The new interaction style places a much greater emphasis on the perceptual/motor features of interaction, locating and selecting information on the screen.

The scope of relevant motor-control issues has also been greatly expanded by non-keyboard selection devices. With keyboard entry, the only significant limb movement is the pressing of keys. The range of physical actions required by the new selection devices is much broader, including reaching to and grasping objects that are in different spatial locations, moving the selection device in two or three dimensional space, and coordinating actions for selection and movement.

The range of possible tasks using computer technology is vast and is increasing steadily. One challenge for conducting research in this field is to choose a small set of tasks that representative of the current technology, and that will be relevant to future developments.

Menu-selection with a mouse incorporates two of the three innovations in interface design, namely menu displays, and spatial positioning, that Lewis (1990) identifies as central for the decade of the 1990's. Menu-selection has become a primary method for entering commands on new and emerging computer systems. Menu-selection is also a generic task independent of the software being used, so the findings of this research should have general applicability to a wide range of situations.

Overview of Dissertation

This dissertation isolates and examines some of the emergent perceptual-motor issues raised by the new style in human-computer interaction. It concerns the use of a mouse to select commands from menus. The rest of this chapter describes the physical and perceptual characteristics of the menus and selection procedures to be studied here. Chapter 2 then reviews research from both the motor-control and the human-computer interaction literature that applies to perceptual and motor aspects of menu selection. In Chapter 2, predictive performance models of computer-based tasks and their application to menu selection are also discussed. Chapters 3 through 6 present a series of empirical studies that test hypotheses about perceptual and motor aspects of menu selection. They focus on understanding the mechanisms that underlie the major findings. Chapter 7 summarizes the results and discusses the implications of the research for both theory development and interface design.

Menus Used in the Experiments

Many different styles of mouse-activated menus are currently implemented on computer systems (Callahan et al., 1988). These include pull-down, click-open, walking, and pie menus all of which involve very different perceptual features and action sequences. Little empirical research has been done to suggest which style is best. One possible research approach would be to compare performance for all the menu styles in one set of tasks.

However, such an ambitious undertaking has a problem. Because there are many differences in the physical arrangements and actions associated with menu styles, it would be difficult to determine which attributes are responsible for any performance differences. The studies in this dissertation have reduced the potential complexity by comparing two styles of menus that are perceptually equivalent but require different physical actions to select displayed options from them. To be specific, we will focus on click-open and walking menus.

Click-open and walking menus are two popular styles of "pop-up" menu used in advanced graphical workstations (e.g., Sun, Next). Pop-up menus are invisible when a person enters information that does not require the menu; yet they can be quickly accessed by a single button press. When the button of a mouse is depressed, a linear list of menu items appears or "pops up" at the location of the cursor on the screen.

The next section provides detailed descriptions of click-open and walking menus. Figure 1.1 shows the physical actions required for a two-level menu-selection using both menu styles.

Comparison of Action Sequences For Different Menu Styles

Click-Open Menus

Click-open menus are accessed by clicking (pressing and releasing) a mouse button on a computer display. Once the menu is visible, the cursor is located just above the upper left corner of the menu (five pixels in from the edge) and then moved to the desired menu item. A command is selected with a click of the mouse button anywhere in the box containing the menu item. Upon pressing the mouse button, the next menu level appears. Submenus are aligned with the selected higher-level menu item, overlapping ten pixels. Once the mouse button is clicked in the final menu, it disappears and the command is executed. A selection can be aborted by clicking outside the menu region.

Two defining features of click-open menus are: (1) all menu items are selected with a click of the mouse button, and (2) the cursor is moved with the mouse button released until a sequence of selections is completed or the button is clicked outside the menu region.

Walking Menu

For walking menus, a menu selection is initiated by pressing and holding the mouse button down, bringing up the first menu level. The

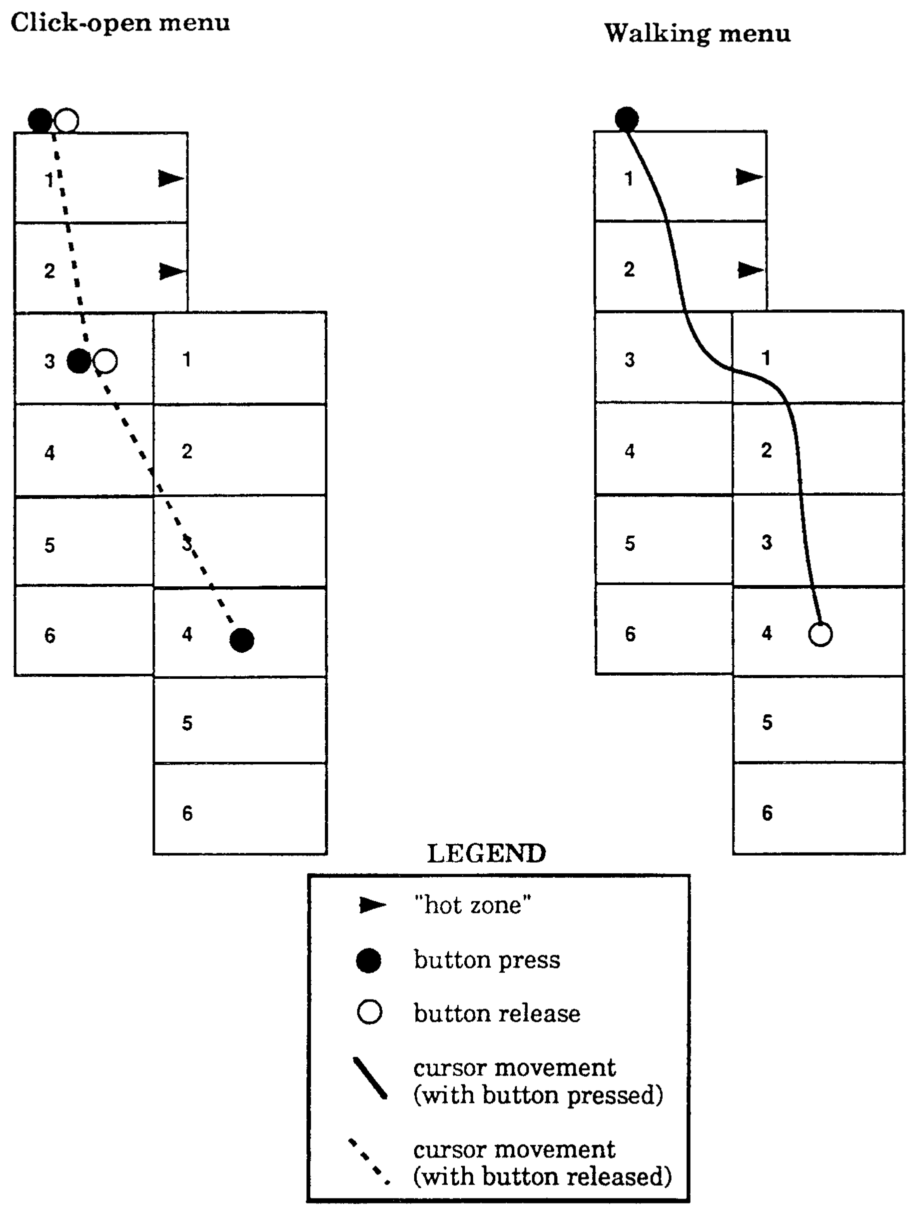

Figure 1.1 Physical actions required by menu styles for two-level selections.

cursor is located exactly as in the click-open menu, and is then moved to the desired menu item. A command is selected by moving the cursor into a "hot zone" located at the extreme right of the menu item. The "hot zone" is a rectangular area ten pixels wide, running from the top to the bottom of the menu. Perceptually, the "hot zone" is identified by a rightward arrow that is aligned with the left edge of the zone. As soon as the cursor crosses into this region, the next menu level appears, aligned with the selected menu item, overlapping ten pixels. Selection from the final menu is made by releasing the mouse button anywhere in the selected menu item. Upon release of the button, the menu disappears, and the command is executed. A selection can be aborted by releasing the mouse button outside the menu region.

Three defining features of walking menus are: (1) Higher-level menu items are selected by moving the cursor into a "hot zone"; (2) the cursor is moved with the mouse button depressed; (3) final-level menu items are selected by releasing the mouse button.

As Figure 1.1 shows, the physical actions required by these two menu styles are quite different. Click-open menus require a click (i.e., a button press and release) to bring up the first menu, and an additional click for selection at each menu level. Walking menus require a single press (and hold) to bring up the first menu, followed by a single button release at the end, regardless of the number of menu levels. This comparison of the number of button presses favors the walking menu, since it involves fewer button actions than are required with a click-open menu. On the other hand, a walking menu imposes some severe movement-path constraints: The horizontal movement from the first-level menu to the second must stay within the boundaries of the menu box or else the wrong second-level menu will be opened. In contrast, with the click-open menu, once the button is clicked to bring up the second-level menu, any path to the next item is allowed. Consequently, these two menu styles present an interesting trade-off between the minimization of button presses and the reduction of path constraints. This dissertation assesses the relative costs of these design features. Also, it quantifies the impact that they have on the complexity of planning and the difficulty of executing the task of menu selection.

CHAPTER 2
LITERATURE REVIEW

Introduction

In this chapter, I cull earlier research for insights about the information-processing demands, research paradigms, and models relevant to understanding menu selection. The studies reviewed in this chapter come from two quite distinct research areas: human motor control, and human-computer interaction. Although the subject matter and research approaches of these disciplines differ, they all contribute insight into the task of menu selection. This review is organized around three major topics: (1) the control of aimed movements, (2) visual search of menus, and (3) performance models of computer-based tasks. Research from various literatures will be intermingled as they pertain to these topics.

The Control of Aimed Movements

Using a mouse involves a strong motor-skill component with coordination of highly practiced finger, hand, and arm movements. One area of research relevant to this component is included in the field of human motor control. Since the turn of the century, psychologists and physiologists have studied how people plan and control movement (Woodworth, 1899). The findings and experimental methods developed in these studies may help in understanding the menu-selection task and may provide tools to explore these tasks with scientific rigor. In particular, the literature on motor control includes two lines of research relevant to the study of menu-selection: (1) studies of the speed and accuracy of aimed movements, and (2) studies of the planning and execution of response sequences. These are briefly reviewed here with special emphasis on issues that they raise about the menu-selection task.

Movement Speed and Accuracy

The use of a mouse to select commands from a computer menu involves speeded movements. The user's goal is to position a display cursor at the menu item by moving the mouse. Movements like this have been studied extensively in the field of human motor control (e.g., Meyer et al., 1988).

The oldest, and probably best understood aspect of human motor control deals with the relationship between the speed and accuracy of aimed movements. Woodworth (1899) was one of the early researchers to report an inverse relationship between movement speed and accuracy. He found that as movement speed increases, accuracy decreases.

Another major breakthrough in understanding the relationship between movement speed and accuracy came with a formal mathematical description of the speed-accuracy trade-off (Fitts, 1954). Fitts had subjects move a stylus back and forth between two target regions as quickly as possible while keeping their error rate (target misses) low. He discovered that the average movement time was a logarithmic function of the distance between the targets divided by their widths. Known as Fitts' law, the function is:

$$\text{Movement Time } (MT) = a + b \log_2 [2D/W]$$

where, D is the distance between the centers of the targets, W is the width of the target regions toward which the subject moves, and a and b are constants. The quantity $\log_2 [2D/W]$ is called "the index of difficulty" (ID).

Fitts' law is a good description of movement time for a wide variety of situations. For example, Fitts and Peterson (1964) demonstrated that it applies when a subject makes a discrete movement to a target. Langolf, Chaffin and Foulke (1976) verified Fitts' law for tiny finger movements under microscopic conditions. Fitts' law also accounts for movement times with a mouse used in text selection (Card, English, & Burr, 1978) and for graphical editing tasks (Epps, 1986, 1987). A major emphasis of the present research is to use Fitts' law for understanding menu selection.

Device-Comparison Studies

One reason for considering the mouse as a selection device is that many empirical studies have shown it to be a good one. A prevalent approach to research on selection devices in the field of human-computer interaction is the comparative study. Here, a benchmark movement task (or small set of tasks) is selected, and several selection devices are used to accomplish the task(s). The main independent variables are the sizes of the movement targets, the distances to them, and the type of task. The main dependent variables are movement times, error rates, and user preference ratings. Typical analyses include ANOVA's for determining the effects of the independent variables, calculation of the learning curve for each device, and a regression analysis based on Fitts' law to model the asymptotic performance for the applicable devices. The weight of evidence indicates that the mouse is an optimal or near optimal device in terms of both learning and performance measures. Three illustrative demonstrations of this include an early study by Card, English, and Burr (1978) and two recent ones by Epps (1986, 1987) which represent the best published work to date.

Card, English and Burr (1978) chose text editing of a document as their benchmark task. Subjects were told to locate a word on a display screen and to select that word by positioning a cursor over it as quickly as possible. The experiment compared performance with four different selection devices (step keys, joystick, mouse, and text keys), using a within-subjects design. Subjects were given extensive practice with each device. Performance with the mouse exhibited the steepest learning curve, and the fastest movements once learning had stabilized. The overall speed advantage of the mouse was accompanied by the lowest error rate (5%). The highest error rate was found for step keys (13%). Movement times for the mouse were well modeled by Fitts' law:

$$MT = 1030 + 96\ ID,\ r^2 = 0.83 \quad \text{(time in msec).}$$ [1]

Epps (1986) chose a target-acquisition task as his benchmark. Square targets of varying sizes and screen distances were selected through one of six devices in a within-subjects study. The devices were two touchpads, two joysticks, mouse, and trackball. Analyses of the selection-time data showed that the mouse and track ball were optimal devices, while the two joysticks yielded the worst performance. Movement times for each of the devices were well modelled by Fitts' law. The formula for the mouse was:

$$MT = 108 + 392\ ID,\ r^2 = 0.70 \quad \text{(time in msec).}$$

In a follow-up study, Epps (1987) compared performance with the same six selection devices in a set of seven graphics editing tasks (e.g. line drawing, object selection, object resizing). While this study did not manipulate the size and distance of the targets sufficiently to represent the

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[1] For the calculation of ID, Card et al. used Welford's (1968) correction. For comparisons sake, all ID calculations reported in this dissertation will also be based on Welford's correction, which is MT= a + b(D/W + .5).

times with Fitts' law, Epps is one of the few investigators to have looked at performance in more than one benchmark task. His data indicated that across the various tasks, subjects performed best with the trackball and mouse, worst with the two joysticks. The trackball and mouse were also subjects' favorite devices, while the absolute touchpad was least favored.

Application of Fitts' Law to Menu Selection

It seems plausible that the task of menu selection with a mouse would also be well described by Fitts' law. If so, then we may predict menu-selection times and guide the design of menus to speed menu access and reduce errors. If Fitts' law fits, do different menu styles have the same or different parameter values? If they are different, then knowing the values of the slope and intercept for various menu styles will allow trade-off analyses to determine which is best under different conditions.

A pilot study with walking menus has yielded some evidence that movement times for the menu-selection task accord well with Fitts' law (Walker, Smelcer, & Nilsen, 1988). The time to select the first item in a two-level walking menu is given by the following equation:

$$MT = 303 + 185\ ID,\ r^2 = 0.92 \quad \text{(time in msec)}.$$

This result is encouraging, but such research should be extended to a wider variety of menu styles to determine how robust the trade-off relationship is.

Special Features of the Menus

Two aspects of the menus examined in the present research are not ordinarily studied in experiments on Fitts' law: (1) movement along a constrained path, and (2) movement with constrained finger/hand postures.

In most experiments on Fitts' law, the major independent variables are the target width and distance. The movement path (i.e., the trajectory) between the starting point of the movement and the target is not physically constrained, but is assumed to be a straight line. This latter assumption appears in the calculation of the target width and distance. On the other hand, walking menus involve significant path constraints and curvilinear movements in going from one menu level to the next. We want to determine whether this path constraint will change the parameters for Fitts' law or invalidate it altogether?

The motor-control literature contains only one set of studies that examines Fitts' law for movements with path constraints of the type that occur in walking menus (Kvalseth, 1973, 1975). These studies involved moving a ball-point pen back and forth between two targets as fast as possible while trying to keep the movement within certain spatial bounds. Various kinds of bounds were included. The one most like that of the menu-selection task involved movement through a slot of various heights situated between two targets (e.g.). Based on his results, Kvalseth proposed a modification of Fitts' law that adds another parameter. Kvalseth's equation was:

$$MT = -139.38 + 31.50\ ID + 25.83\ [1/V],\ r^2 = 0.94 \quad \text{(time in msec)}.$$

The first two terms of this equation are identical to those in Fitts' law. The "*V*" here is the height of the center slot. Kvalseth found a good fit for his equation in the slot condition.

Unfortunately, he did not report the fit of the simpler version of Fitts' law, which is needed to see how much improvement was made by adding another parameter to it. If the times for the walking menu deviate greatly from Fitts' law, Kvalseth's equation may be a good candidate for a replacement. However, if Fitts' law provides a reasonable fit to the data, it would be preferred on grounds of parsimony.

A second salient feature of the present menu styles is that they involve constrained versus free finger/hand position. This feature entails a comparison between different effector systems for movement. It could have a significant effect. Langolf, Chaffin, and Foulke (1976) compared the parameters of Fitts' law for movements of the fingers, the wrist, and the whole arm. They found that the more muscles involved in the movement, the slower the movement and the steeper the slope in Fitts' law (parameter b). Their results would imply that longer selection times should occur for walking menus, because they require keeping the button depressed during the movement.

A recent study in the field of human-computer interaction addressed this possibility for the task of selecting text using a mouse. Gillan et al. (1990) examined Fitts' law for point-click and point-drag sequences. The point-click sequence consisted of moving the mouse with the button released, while the point-drag sequence involved moving the mouse with the button depressed. Gillan et al. (1990) varied the distance and the width of the targeted text. They found that the point-click sequence was significantly faster than the point-drag sequence, for all combinations of distance and width. The point-click sequence was influenced by the width of the text, while the point-drag sequence was not. Apparently, for the point-click sequence, the effective target width depended on the entire text target while for the point-drag sequence, it depended on the left edge of the text. Fitts' law accounted quite well for both the pointing and the dragging segments of the selections (r^2 ranging from 0.88 to 0.99 for the best fitting regressions).

Though the task of Gillan et al.'s subjects was not menu-selection, the findings from it do have implications for the current study. They suggest that moving with a mouse button depressed is more complex to plan and time consuming to execute than moving with the button released. The parameters in Fitts' law may vary with the physical characteristics of the movement. This dissertation examines how these single components combine in the task of menu selection.

Planning Response Sequences

This dissertation also deals with the phase in which mouse movements are planned. Research done on the planning of response sequences can provide a guide toward the understanding of the planning phase of menu selection. A central concept in motor control is the idea of a "motor program". A motor program is "a set of muscle commands, structured before a movement sequence begins, which allows the entire sequence to be carried out uninfluenced by peripheral feedback" (Keele, 1968). According to conventional wisdom, a portion of the planning time for a movement is used for specifying and loading the muscle commands into the motor program, which then automatically controls the movement.

Since motor programming is assumed to take place before the movement begins, studies of is focus on factors that influence the reaction-time interval. Two kinds of reaction-time (RT) paradigms have been used to study the planning of movements: simple and choice. In this dissertation, the user always has advance knowledge of the item to be selected; so only research with the simple RT paradigm is discussed here.

In simple reaction time (SRT) studies, a single response is prepared on each trial, and execution of the movement is signaled by a reaction signal. This allows for complete and unambiguous planning of the movement. The SRT represents the time to load or otherwise prepare an already constructed motor program, and to mobilize the muscles to begin the movement. Any aspect of the movement that lengthens the SRT is attributable to the effort needed to prepare a motor program. Varying the nature of the required movements and examining the effects of those changes on the reaction time can uncover the basic unit of movement in menu selection.

One factor that affects SRT is the complexity of the movement. Complexity can be defined as the number of goal-oriented segments in a movement (Henry & Rogers, 1960). Research on various classes of movements has shown that SRT increases with the number of different segments in the response. For example, this response complexity effect occurs for grasping and hitting (Henry & Rogers, 1960), keypressing (Klapp, 1977), speech and typing (Sternberg, Knoll, Monsell & Wright, 1978) and tapping movements (Fischman, 1984).

The Fischman study is most relevant to menu selection with a mouse. In it, subjects used a stylus to tap a series of metal disks (ranging from one to five targets) arranged either in a straight line, or in a staircase that required a 90° change of direction between each target. The movement trajectories in the change-of-direction condition were very similar to those in selection from multi-level pop-up menus. The number of different targets (disks) also corresponded nicely to the number of menu levels in a hierarchical menu.

Fischman found that SRT increased linearly with the number of target disks, for both the straight line and the change-of-direction conditions. This complexity effect was strongest for the one and two target conditions. Changes in movement direction did not affect SRT. The implication here is that adding movement segments increases the complexity of a prepared motor program, but changing direction does not.

Replicating Fischman's findings in a menu-selection task would have important implications for menu design (e.g., increasing the depth of multiple level menus can only be achieved at the cost of longer planning time). The greatest cost may occur between one and two menu levels, with lesser but significant effects up to five menu levels. However, the relative impact of the complexity effect could differ for menu-selection tasks and depend on menu style. If the change of direction does not matter, then for experienced users who know the location of the menu items (and hence can prepare a complete motor program), the spatial layout of the submenus will not matter in planning of the movement. Of course, these suggestions must be viewed in the context of other aspects of menu selection, such as execution time and visual scanning.

What are the dimensions of complexity that influence the reaction time for mouse movements? Possible candidates include number of changes of direction, distance to be moved, number of movement segments, and path restrictions during the movement. Manipulating the depth of the menu hierarchy (number of menu levels) can influence extent, changes in direction, and number of movement segments in the response sequence. The comparison of click-open and walking menus will provide information about the influence of the number of movement segments and path restrictions on the stage of response programming.

Visual Search Of Menus

Another body of research relevant to this dissertation deals with the visual-search process in menu selection. A hallmark study by Card (1983) concluded that search is random for command menus. This conclusion is based on the findings that (1) there are no differences in the search times for items at different positions in the menu, (2) eye movements are both downward and upward instead of consistent in direction and (3) the cumulative probability of locating a target as a function of time is best fit with an unsystematic random-sampling model.

Other researchers (MacGregor, Lee & Lam, 1986; MacGregor & Lee, 1987) have challenged Card's conclusion, showing that his empirical results are consistent with a non-random model incorporating redundant, exhaustive, serial search. Another experiment (Perlman, 1984) produced a serial-position effect for menus of letters and numbers, which suggests a serial search from either the beginning or end of the menu. In yet another study (Somberg, Boggs & Picardi, 1982) a serial, top-to-bottom, self-terminating search was found for categorical information in a menu. The issue of random versus systematic search is not yet settled.

Nevertheless, researchers agree that the nature of the search process changes with the experience of the user. Novice or occasional users will take a long time to search menus. With increased familiarity, users move towards a strategy of "direct search" where they fixate immediately on the desired menu item (Card, 1983; MacGregor & Lee, 1987). Once the user becomes familiar with the menus, the time for visual search is greatly reduced and becomes constant in the predictive model. It is very important to understand the influence that visual search has in the menu-selection task for users with different knowledge of the menu contents.

An unanswered question concerns when visual search occurs in the process of menu-selection. Many of the above studies used keypresses to select information from a menu. When a selection is made by a single keypress, visual search may be completed before the movement is initiated, since information from the visual search is needed in order to know which key to press. However, when a selection is made using a mouse, the movement can begin before the visual search is completed, on the basis of partial information. Alternatively, one can move the cursor while searching for the correct item to select.

Previous studies have assumed that visual search and physical selection are independent processes. One example of this assumption comes from a study of various ways to deal with menu items that are only appropriate in certain situations (Francik & Kane, 1987). In the authors' conclusion they state that

> "the results ... suggest that faster selection has an important visual search component. Hence deleting inactive items from menus should help users select items more rapidly, regardless of whether the selection is made with a cursor key, a letter, or another input device such as a mouse."

Their assumption that the visual-search component is clearly separable from the input device seems tenuous at best. The physical actions used to make the selection could influence the search process. For example, typing a letter may not change the display until the menu item is selected, and it provides little proprioceptive feedback until the key is depressed. In contrast, moving a mouse changes the position of the cursor on the display and provides rich proprioceptive feedback before the selection is completed. The differences in visual and proprioceptive feedback for these two input devices could result in very different search strategies. This dissertation tests this possibility by exploring whether altering the physical actions in menu selection influences the search process.

Performance Models Of Computer-Based Tasks

Below is a description of two performance models in the field of human-computer interaction that can be applied to the task of menu selection and that make predictions about users' performance in menu-selection tasks.

Keystroke-Level Model

One candidate is the Keystroke-Level Model of Card, Moran, and Newell (1980, 1983). It predicts the amount of time that a skilled user would take in performing a computer-based task, based on the mental and physical operations required to execute the task. By applying a series of cognitive and motor operators to each of the steps in the task, the model generates a total-time prediction for that task. The operators in the Keystroke-Level Model that are relevant to the menu-selection tasks in the present study are listed below:

P Pointing to a target on the screen with a mouse, 1100 msec.

k Pressing the mouse button, 200 msec.

M Preparing mentally for a physical action, 1350 msec.

The time parameters for these operators were estimated from empirical studies of people using text editors, graphical editors and some operating-system commands. By using a set of heuristic rules to determine which operators are involved in a task, this analysis successfully accounted for over 90% of the variance in the total task times (Card, Moran, & Newell, 1983). With the addition of a perceptual-scanning operator, the Keystroke-Level Model accurately predicted the execution time for a set of spreadsheet tasks (Olson & Nilsen, 1988).

However, a number of questions arise when applying the operators of the Keystroke-Level Model to the task of menu selection with a mouse. In multi-level menu selections, should each level of the menu be considered a target on the screen and assigned a P operator, or should the entire menu traversal be considered as a single pointing operation? Depending on the answer to this question, very different time predictions will emerge. For a two-level menu selection with a click-open menu, the relevant physical operators include two button presses (at 200 msec each) and either one or two mouse pointings (at 1100 msec. each) yielding a time estimate ranging from 1.5 to 2.6 sec. For the walking menu, the relevant physical operators include a single button press, and either one or two mouse pointing operators for a range of 1.3 to 2.4 sec using the average P operator.[2]

Another question concerns the placement of the M operators. Where in the process of menu selection does mental preparation occur? Is mental preparation required for traversing each level of a multi-level menu (to retrieve the target item from memory or acknowledge that the correct item has been reached), or does a single mental preparation at the outset of a menu selection suffice for preparing the entire movement? Depending on the answer, the above estimates might be wrong, because they assume that all mental preparation occurs before the menu is accessed, which is why the M parameter does not appear in the calculations.

There are obviously some parameters missing from the Keystroke-Level Model that may be relevant to selection for the menu styles under

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[2]By applying Fitts' law, which underlies the P operator, the range for the click-open menu increases from 1.2 to 3.4 sec, and for the walking menu 1.0 to 3.2 sec.

study. The model includes no perceptual operator to represent the visual-search process. However, in a recent review article of cognitive-engineering models, Olson and Olson (1990) recognized this shortcoming and added a perceptual operator of 230 msec for a saccadic eye movement and an operator of 100 msec for simple perception and recognition, based on previous empirical studies. These parameters were gleaned from research on specialized component tasks and have not yet been verified in combination for HCI-relevant tasks.

The model also has no parameter to account for the cost of path constraints in movement. This exclusion, along with the inclusion of the button press parameter (k), results in a prediction that selection from walking menus will always be faster than selection from click-open menus. Futhermore, this difference should increase with the number of menu levels. This increase is a testable prediction that will reflect on the efficacy of the Keystroke-Level Model.

A more basic question regarding the Keystroke-Level Model is whether its assumption of seriality fits the task of mouse-based menu selection. The model assumes that the total selection time is the sum of a number of subcomponent times. This assumption may be valid, but another alternative is that the perceptual, cognitive, and motor processes involved in menu selection are parallel. For example, as discussed earlier in the section on visual search of menus, searching for a command and moving the cursor down the menu may take place simultaneously. The exact relationship between the two processes could depend on the knowledge and experience of the user. When the user does not know the location of the correct command, the search time might overshadow the motor movement time. However, for experienced users who know the exact identity and location of the commands, the search time would be minimal, and the motor time would determine the speed of performance. Other parallel processes may also be involved in menu selection. If a task involves substantial parallel processes, a serial model would overestimate the time to accomplish the task.

Critical-Path Analysis

One approach to modelling both serial and parallel processes is critical-path analysis, a technique borrowed from operations research called (Malcolm, Roseboom, Clark, & Fazar; 1959). This technique treats the different processes used to accomplish a task (perceptual, cognitive, and motor) as potentially serial or parallel. By specifying the time that each process takes to execute, and identifying the sequential dependencies between processes, the method generates a total-time estimate for the task. The total-time estimate is reached by summing the duration of all processes that take place serially and only the longest duration of any processes executed in parallel. The shorter processes not on this critical path are executed for free as long as some other process does not delay their onset or lengthen their duration. This framework is ideal for analyzing the influence of a users' knowledge and experience on the relationship between searching and moving in a menu.

Several psychological studies have used critical-path analysis in reaction-time experiments. It has been applied to model the effect of response compatibility in the Stroop task (Schweickert, 1978), to explain negative interactions between figure-ground contrast and response difficulty in a lexical-decision task (Hardzinski, 1980), and to account for the pattern of results from various stimulus-response compatibility tasks

(John, 1988).

John and her colleagues have successfully used critical-path analysis to model the overall execution time for a variety of computer-based tasks ranging widely in complexity and length. Tasks to which she has applied her model include transcription typing (John, 1988), and processing of long distance calls (Gray, John, & Atwood, 1991).

Not enough is known yet about the task of menu-selection to propose a fully specified critical-path model for it. If the serial Keystroke-Level Model proves inadequate to predict the timing of menu selection, the current research will reveal some of the sequential dependencies and timing parameters that would contribute to specifying such a model.

Summary

The present review of the literature(s) has generated a large number of questions, and several specific predictions regarding the perceptual and motor factors that might affect the task of menu selection. These can be summarized in a small set of central questions. The next chapters will attempt to address them as follows:

(1) Is the speed and accuracy of menu selection sensitive to changes in the physical actions required by different menu styles? If so, which aspects of selection are affected by the difference?

(2) How are the applicability and parameter values of Fitts' law affected by the subjects' advance knowledge about the location of menu items?

(3) Is visual search random or systematic in mouse-based menu selection?

(4) Are visual search and movement serial, independent processes, as assumed in the literature on menu selection?

(5) Is menu selection with a mouse best characterized by a serial or a parallel model?

CHAPTER 3
EXPERIMENT 1

Rationale

This experiment was designed to identify the principal perceptual and motor factors that determine performance in menu selection with click-open and walking menus. Regarding motor processes, it explores the trade-off between multiple button presses and constraints along the path of movement. The effect of button status (pressed or released) during the major movement phase is also explored. These two motor factors are intentionally left confounded in this initial study to approximate current menu designs. Finally, the applicability of Fitts' law to these styles of menu is tested.

The perceptual process explored here is visual search. We examine how visual search changes with different levels of information regarding the location of menu items. The current experiment includes two extremes of this continuum, complete advance location information, and no advance location information. As a result, it may be determined whether visual search is best described as an random or systematic process under these conditions.

Finally, Experiment 1 was designed to examine the relationship between the search and motor processes. It concerns another interesting question. Are they independent processes as previous studies have assumed, or do the actions involved in menu selection and the process of searching the menus interact?

Method

Subjects

Twenty-three right-handed University of Michigan students served as paid subjects.[3] They had no apparent motor deficiencies. All of them had experience using a mouse. Each subject was paid $12 for three, 1 hr sessions, plus bonuses based on performance.[4]

Procedure

The procedure involved self-initiated, speeded selection from two-level menus. At the beginning of each trial, subjects were shown two numbers that identified the selection targets from each of the menu levels for that trial. When they had memorized the numbers, they depressed the mouse button to display the first level of the menu, and then they made their selections as fast as possible while minimizing errors.

The sequence of events during a trial is shown in Figure 3.1. At the beginning of each trial, subjects placed the cursor in a small "go" box in the upper left-hand corner of the screen. A precue appeared directly above the box. The precue consisted of the menu items to be selected on each menu level, separated by commas. Subjects were told to take as much time as they

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[3]Twenty-four subjects were run in the study, but the data for one subject were lost because of a computer failure. Of the remaining subjects, twelve used the click-open menus, and eleven used the walking menus.

[4] The bonuses were based on performance and calculated for each block of trials. Money was awarded to the subjects based on the average selection time for a block of trials. One cent was added to the bonus for every 100 msec under four seconds for the average selection time. For every error trial in a block, 5 cents were deducted regardless of the selection time. Thus, an average correct selection time of 2.5 sec with no errors earned 15 cents, while the same time with two errors earned 5 cents. Subjects were told that the bonus could not take away from their base pay rate. In actuality, all subjects received positive bonuses of at least $5 over the course of the experiment. The bonus system was explained to subjects before the experiment began.

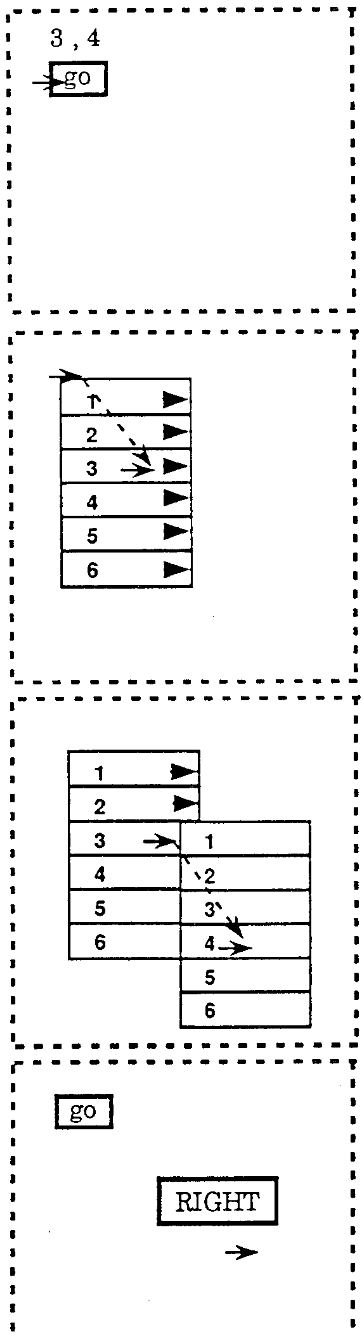
needed to memorize the precues, and to begin the menu selection when they were ready. Upon clicking or pressing the mouse button in the "go" box, the

<u>Screen One</u>
When cursor is moved into "go" box the precues appear above the box. Subjects take as much time to memorize the precues as they want.

<u>Screen Two</u>
When the subject is ready he clicks/presses in the "go" box. The precues disappear and the menu pops up. He then moves the cursor to the first menu item specified in the precue.

<u>Screen Three</u>
Upon selecting a first-level menu item, the second level menu pops up adjacent to the first menu item. The subject moves to the second menu item.

<u>Screen Four</u>
Upon selecting a second-level menu item (or selecting a region outside of the menu), the menu disappears and the trial is over. A box containing accuracy feedback is displayed and a new "go" box appears in the top right corner of the screen.



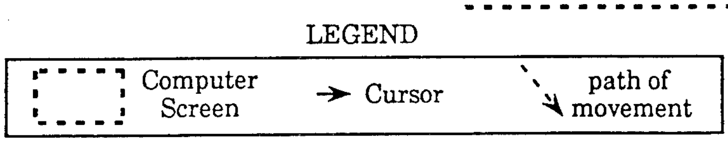


Figure 3.1 Sequence of events on an experimental trial.

numbers disappeared and the subjects made their menu selections as fast as possible. Upon completing the selection, accuracy feedback was flashed on the screen, and the "go" box appeared for the next trial.

Design

The twenty-three subjects were divided into two groups (of twelve and eleven). Each group made menu selections from a single style of pop-up menu (click-open or walking). All subjects selected from menus having two different heights (ten pixels and twenty-five pixels per item) and two different organizations (normal and random). A block of trials always consisted of a single combination of menu height and menu organization. The four combinations seen by each subject are shown in Figure 3.2. Each menu level consisted of the digits one through six for a total of thirty-six distinct menu selections. A block of trials consisted of two practice trials followed by one of each of the thirty-six menu combinations repeated until they were selected correctly. At the end of a block of trials, subjects were shown the average total selection time for correct trials, the number of error trials, and the bonus that they had earned based on their performance.

Each subject participated in three sessions held on consecutive days. The first session involved training the subjects on the menu style that they would use, followed by two blocks of trials for each of the height by organization combinations. None of the data from the first day are included in the analysis of results. The first day served strictly as a familiarization and practice session. The second and third sessions were for data collection. The organization of menus was counterbalanced across days. Menu height was alternated within a session, and five blocks for each menu height were completed.

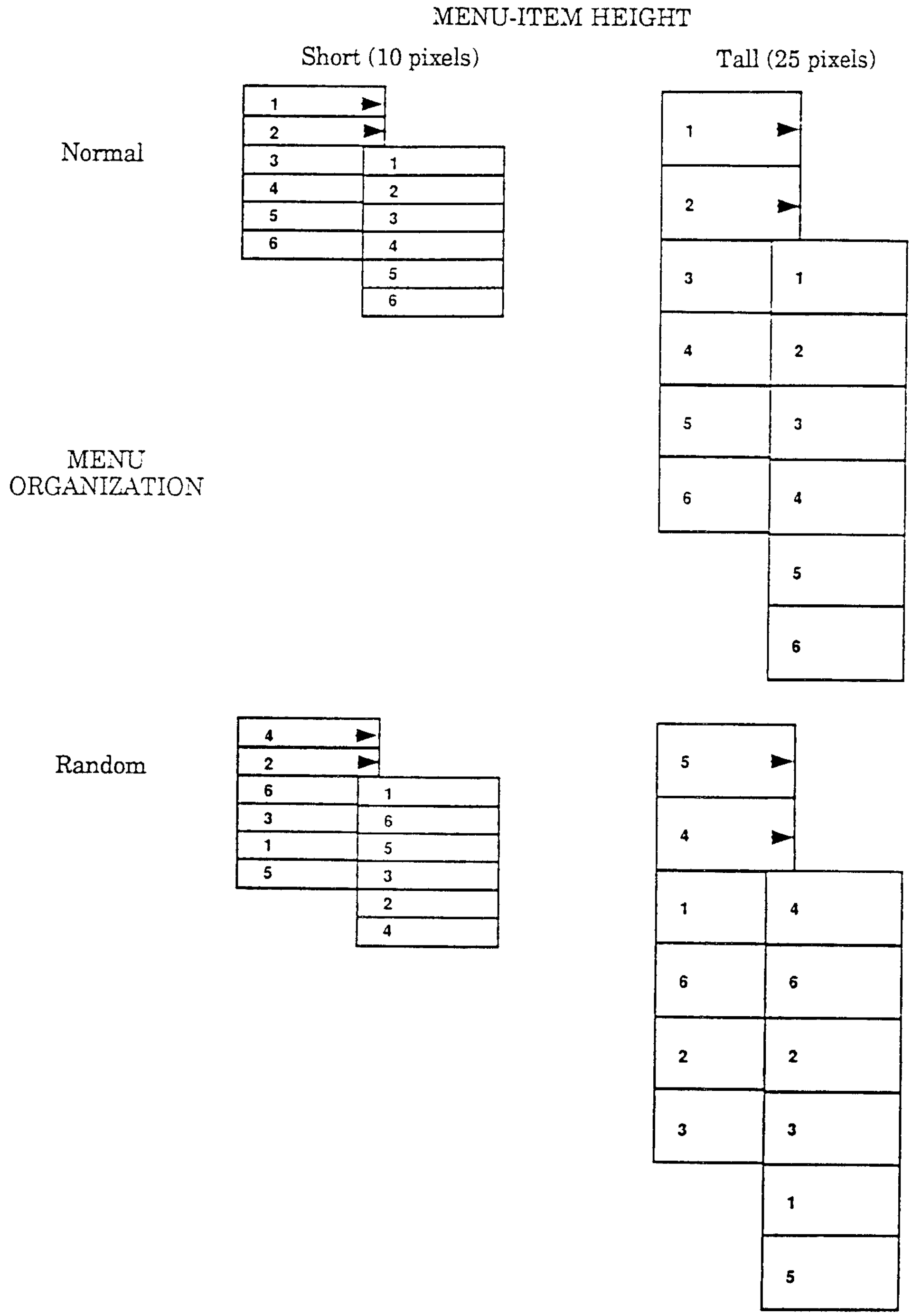


Figure 3.2 Menu height by menu organization combinations for Experiment 1.

Results

The results from this experiment are presented in four sections: (1) errors in menu selection; (2) total selection time; (3) selection times for various phases of movement; and (4) selection times based on the serial position of the first menu selection.

Errors in Menu Selection

There are two kinds of errors possible in multi-level menus. Upon selecting a wrong first-level item and detecting the mistake, it is possible to recover and select the correct first-level item. This is called an "inefficiency error". Use of the click-open menus produced a much lower rate of inefficiency errors (0.71%) compared to the walking menus (6.2%) [$F(1,21) = 31.63$, $p < .0001$]. The cost in time for these is also quite high: Selections containing an inefficiency error took 1.1 sec longer on average than did correct selections.

When a subject selects a wrong item at the final level of the menu, or fails to notice an incorrect first-level selection, or selects a region outside of the menu, then the menu disappears. This precludes recovery and is, therefore, a fatal error. The rates of fatal errors were very low for both click-open (1.6%) and walking menus (2.3%). They did not differ significantly from each other [$F(1,21) = 3.39$, $p > .05$].

In the following sections for the time results, only error-free trials are included.

Total Selection Time

Total time for correct menu selections is operationally defined as starting with the action that brings the menu on the screen (click or press) and ending with the action that completes the selection, causing the menu to disappear. For each subject, the mean selection time was calculated for each combination of menu organization, menu size, and block. A repeated measures analysis of variance (ANOVA) was performed on the mean selection time using these three within-subject variables and menu style as a between-subject variable.

Each menu-style by organization by menu-size combination was repeated in five blocks of trials during the data collection sessions to assure that the subjects had reached asymptotic performance. ANOVA results showed that there was a block effect [$F(4,84) = 5.53, p < .001$]. The range of times was fairly small (1780 msec to 1728 msec). Subsequent analyses indicated that the block effect on time was not systematic; it remained after eliminating the first three blocks of trials. More importantly, eliminating early blocks did not change the results. Subsequent analyses, therefore, include all blocks. A summary of the actual times and significance levels for the variables of interest, by movement phase, is shown in Table 3.1.

Selection times were significantly faster for click-open menus (1680 msec) than for walking menus (1832 msec) [$F(1,21) = 12.81, p < .001$]. Selecting from tall menus displayed a 45 msec speed advantage over selecting from short menus [$F(1,21) = 24.44, p < .0001$]. Not surprisingly, menu organization had the largest effect on the selection times, with selections from normally-organized menus occurring 664 msec faster than those from randomly-organized menus [$F(1,21) = 1087, p < .0001$]. The only significant interaction was a menu-style by organization interaction; selecting from the random organization was especially slow for the walking menus [$F(1,21) = 7.43, p < .01$]. The effect of random versus normal organization was 111 msec less for click-open menus than for walking menus. Figure 3.3 shows the menu-style by organization interaction.

Table 3.1 Selection times by movement phases for Experiment 1.

EFFECTS	MOVEMENT PHASES: Total Selection Time	Start-Up	First-Level Execution	Second-Level Selection
Menu Style	$p < .001$	$p < .01$	**n.s.**	$p < .0001$
Click-open	1,680	45	781	854
Walking	1,832	97	752	983
Menu Height	$p < .0001$	$p < .05$	$p < .01$	$p < .0005$
Tall	1,730	65	760	905
Short	1,775	74	774	927
Menu Organization	$p < .0001$	$p < .0001$	$p < .0001$	$p < .0001$
Normal	1,421	33	624	764
Random	2,085	106	911	1068
Menu Style by Menu Organization	$p < .01$	**n.s.**	**n.s.**	$p < .01$
Click Normal	1,374	15	642	718
Click Random	1,986	74	921	991
Walk Normal	1,471	53	604	815
Walk Random	2,193	141	899	1152

All times in milliseconds

Selection Time for Movement Phases

The total selection time was divided into three movement phases: start-up, first-level execution, and second-level selection. A verbal description of these movement phases is given at the beginning of each section. A more detailed operational definition of the movement phases is given in Appendix B. The ANOVA's for these phases were identical in form to the one for the total selection time. The three significant main effects and one interaction in the total selection times will be examined for each movement phase. No additional interaction effects were found to be significant for any of the movement phases. These results are also summarized in Table 3.1

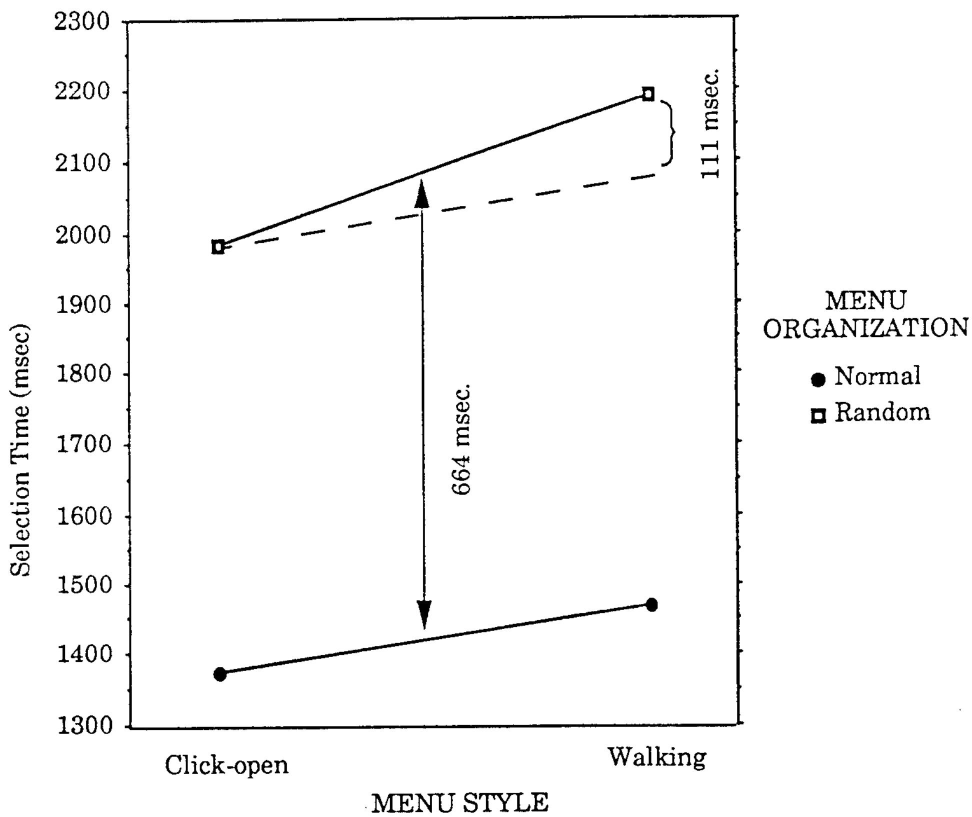


Figure 3.3 Menu style by organization interaction for total selection time in Experiment 1. (Dashed line is parallel with the normal organization line)

Start-Up Phase

The start-up phase begins following the action to bring up the first-level menu[5] (button click for click-open, and button press for walking), and

[5]The initial button press to display the first menu level is not included in the analyses. Instead, the event timing begins when the menu appears on the screen. Likewise, the end of the selection is defined as the button action that makes the menu disappear (button press for click-open, button release for walking menus).

ends when intentional movement[6] of the mouse begins. This is not a typical reaction-time measure because menu selection is self-initiated, instead of being a response to some externally generated signal. It is best understood as representing the amount of programming effort required to shift from the initial button press to initiating the movement of the entire mouse. The pattern of results for this start-up phase mimics the total selection times (see table 3.1).

The start-up times for click-open menus were much faster than for walking menus [$F(1,21) = 8.99$, $p < .01$]. Both the times for click-open menus (45 msec) and walking menus (97 msec) are considerably faster than a typical reaction time.

Tall menus had slightly faster start-up times than did short menus [$F(1,21) = 4.94$, $p < .05$]. The magnitude of the difference is 9 msecs, which is 13% of the overall mean start-up time of 70 msec

Once again, menu organization had the largest impact on the duration of the start-up phase, with start-up times being 73 msec. faster for normally-organized menus than for randomly-organized menus [$F(1,21) = 28.27$, $p < .0001$].

The menu-style by organization interaction failed to reach significance for the start-up phase [$F(1,21) = 1.11$, $p > .30$]. The mean times ranged from only 15 msec for beginning to move in normally-organized click-open menus to 141 msec for randomly-organized walking menus. High between-subject variability in the start-up times for the randomly-

[6]The data files for this experiment include an entry only when the mouse moves. Occasionally the first entry is very fast and followed by a significant pause before the next entry. This is caused by muscle tremor, or unintentional mouse movement which accompanies the pressing of the mouse button. To overcome this, the movement start is operationally defined as the first of three consecutive recordings in the data file each of which have a duration of less than 40 msec. This ensures that the movement is sustained and intentional.

organized menus suggests that individuals adopted different strategies, with some subjects beginning to move immediately, and others visually searching before beginning to move the mouse.

First-Level Execution Phase

This movement phase commences when the subject begins intentional movement of the mouse, and ends when the first menu item is selected, bringing up the second menu level. For the click-open menu, the termination point is a button press anywhere in the target menu item; for the walking menu, it is signalled by moving the cursor into the "hot zone" region at the right of the menu item. (Refer to Figure 1.1 for a visual comparison of these actions.)

The first-level execution is the only movement phase for which no difference occurred between click-open and walking menus [$F(1,21) = 1.28$, $p > .25$]. In fact, the trend is in the opposite direction to that of the other movement phases.

The first-level execution was 14 msec faster for tall menus than for short menus [$F(1,21) = 7.82$, $p < .01$]. This result is interesting because Fitts' law predicts that the times should be the same, since the ID values were identical.[7]

The organization effect is highly significant in the expected direction [$F(1,21) = 262$, $p < .0001$]. Selecting from normal menus was 287 msec faster than selecting from random menus.

The menu-style by organization interaction is not evident in the

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[7]One interesting feature of many menus is that the distance of the menu items and their size are perfectly correlated. If the menu items are of equal size in a linear list, as they are in the menus under study, the ID is equivalent regardless of the height of the items. Knowing the serial position of the item is all that is needed to calculate the ID. The ID values for this experiment range from 0 for the first menu item to 2.59 for the sixth menu item.

first-level execution phase [F(1,21) < 1]. As in the start-up phase, the pattern is similar to the one found for the overall selection time.

Second-Level Selection Phase

This movement phase begins with the appearance of the second-level menu, and ends with the action that completes the menu-selection (button press for click-open, and button release for walking). It is the longest, and the most complex movement phase in terms of information-processing demands. Here subjects must verify that the correct first-level menu item was selected, search for the second-level menu item, move to it, verify that the entire menu selection is complete, and finally execute the button action that will finish the trial.

The pattern of results for the second-level menu selection duplicates the total selection time in both significance levels and magnitude of the effects. Selecting from click-open menus was 129 msec faster than selecting from walking menus [$F(1,21) = 69.83$, $p < .0001$]. Selecting from tall menus was 22 msec faster than selecting from short menus [$F(1,21) = 12.03$, $p < .005$]. Selecting from normally-organized menus was 304 msec faster than selecting from randomly-organized menus [$F(1,21) = 773$, $p < .0001$]. The menu style by organization interaction is also evident, with walking menus being more affected by the random organization (160 versus 97 msec) than were click-open menus [$F(1,21) = 8.57$, $p < .01$].

Serial-Position Functions

Examining the selection times in terms of the serial position of the menu items is required to evaluate both the visual search and Fitts' law for the motor component of menu selection. The start-up and first-level execution phases are combined in the analyses of the serial-position functions for several reasons. It is necessary that the tests concerning visual search and Fitts' law be based on the same data in order to uncover any perceptual-motor interactions. For visual search, the shape of the serial-position function indicates whether the search process is systematic (selection time increases with serial position) or unsystematic (no difference in selection time with serial position). The index of difficulty for Fitts' law is determined by the size and distance of the targets, which is correlated with the serial position of the menu items.

Comparing the serial position functions for normally and randomly-organized menus also reveals the relationship between visual search and movement. A comparison of the shapes of the functions reveals how positional uncertainty in the randomly-organized menus affects visual search and movement. As mentioned earlier, high between-subject variability for the start-up times suggests that some individuals started to search the menu before moving the mouse and others started to search after. Thus, to capture the entire search process, both the start-up and first-level execution phases are examined.

The first-level execution phase comes closest to being a discrete movement to a bounded target with advance information of the target location. Adding the start-up phase increases the intercept and has minimal effect on the slope of Fitts' law. Since the slope parameter reflects the motor complexity of the movement, the start-up phase is included for the present test of Fitts' law.

The second-level selection phase is more complicated. As noted earlier, this phase has many information-processing tasks embedded in it. Also, the beginning point of this phase is very different for the click-open and walking menus. At the appearance of the second-level in the click-open menu, the cursor is typically located outside the second-level region and stationary. For the walking menu, the cursor is already in the second-level region and moving when the second-level appears. Thus, the purest examination of the perceptual and motor interactions involve analyzing the combined start-up and first-level menu execution times.

Figure 3.4 shows the serial-position functions for the four combinations of menu style and menu organization. Here the functions are grouped according to menu organization. Not surprisingly, the selection times are always slower for the random menu than for the normal menu items. The shapes of the functions are quite different for the normal and random menus. Each must be examined separately to determine the regression function that best characterizes the pattern of selection times.

The data for the normally-organized menus are well characterized by Fitts' law regardless of menu style.[8] The regression lines and equations are shown in Figure 3.5.

The slope is slightly shallower for the click-open menus MT = 395.7 + 116.7(ID), r^2=.98 (time in msec), than for the walking menus MT = 361.6 + 148.3(ID), r^2=.96 (time in msec). These two functions suggest that for normally-organized menus, the selection time is dominated by motor processes, with direct visual search adding a constant increment.

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[8]For the calculation of the index of difficulty (ID), the straight line vertical distance is measured. The width is calculated as the vertical height of the menu item. ID's were calculated in the same manner for both walking and click-open menus even though the target for the walking menus could be considered to be the "hot zone" at the right edge of the menu item (see Figure 1.1), suggesting a distance measure of the diagonal distance and a width calculation along the axis of primary movement. The rationale for using the simpler vertical calculations of ID for both menu styles is two-fold. First, from a software designer's perspective, the calculation of vertical ID is much simpler. Secondly, it really doesn't make a great deal of difference in the relative values of the ID's, whether the vertical or the diagonal distance is used so the parsimonious vertical calculation is preferred. If Fitts' law does not hold for the walking menus, the diagonal measure of distance will be used.

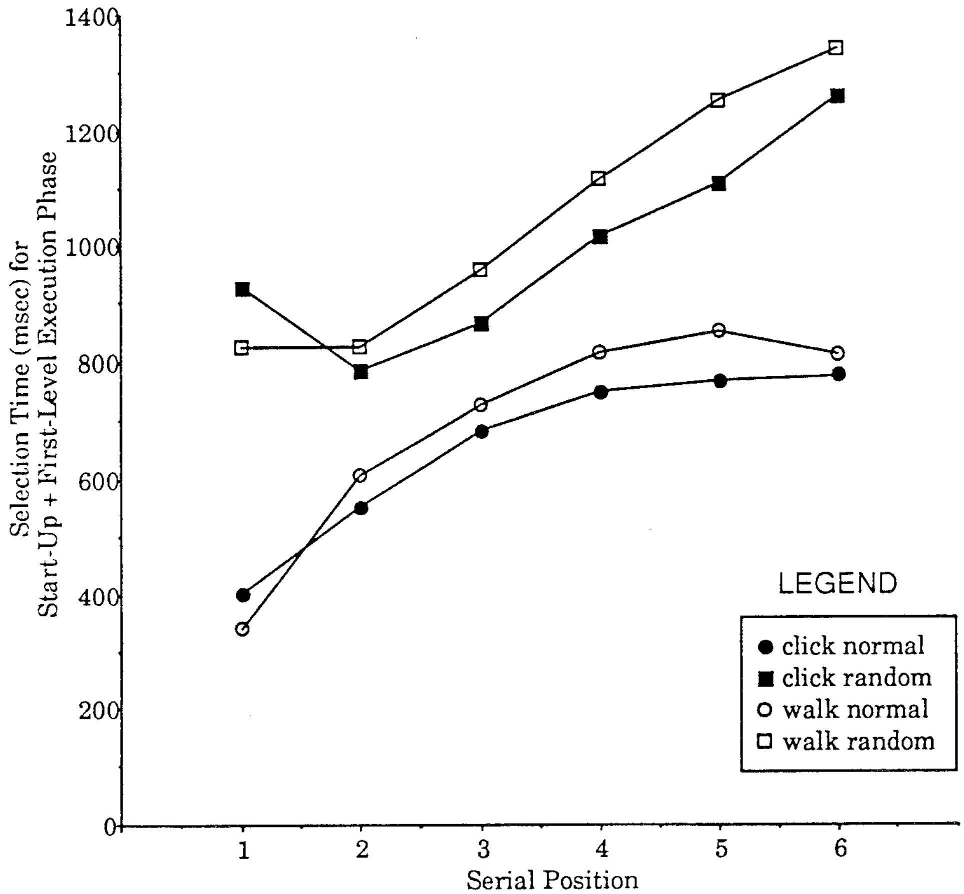

Figure 3.4 Serial-position functions for Experiment 1 separated by menu style and menu organization.

The best function for the randomly-organized menus is linear with serial position as the regressor (Figure 3.6). Excluding the first menu item results in a very good fit for both the click-open MT = 534.2 + 118.3(menu item), r^2=.99 (time in msec) and walking [MT = 571.4 + 131.4(menu item), r^2=.99 (time in msec) menus. This suggests that a systematic, top-to-bottom, visual search governs the selection time for the randomly-organized menus. Apparently the motor processes involved in moving the mouse are not affecting the selection time, since the curve obtained for the normally-organized menus does not hold for the random menus.

The selection time for the first item of random menus is longer than

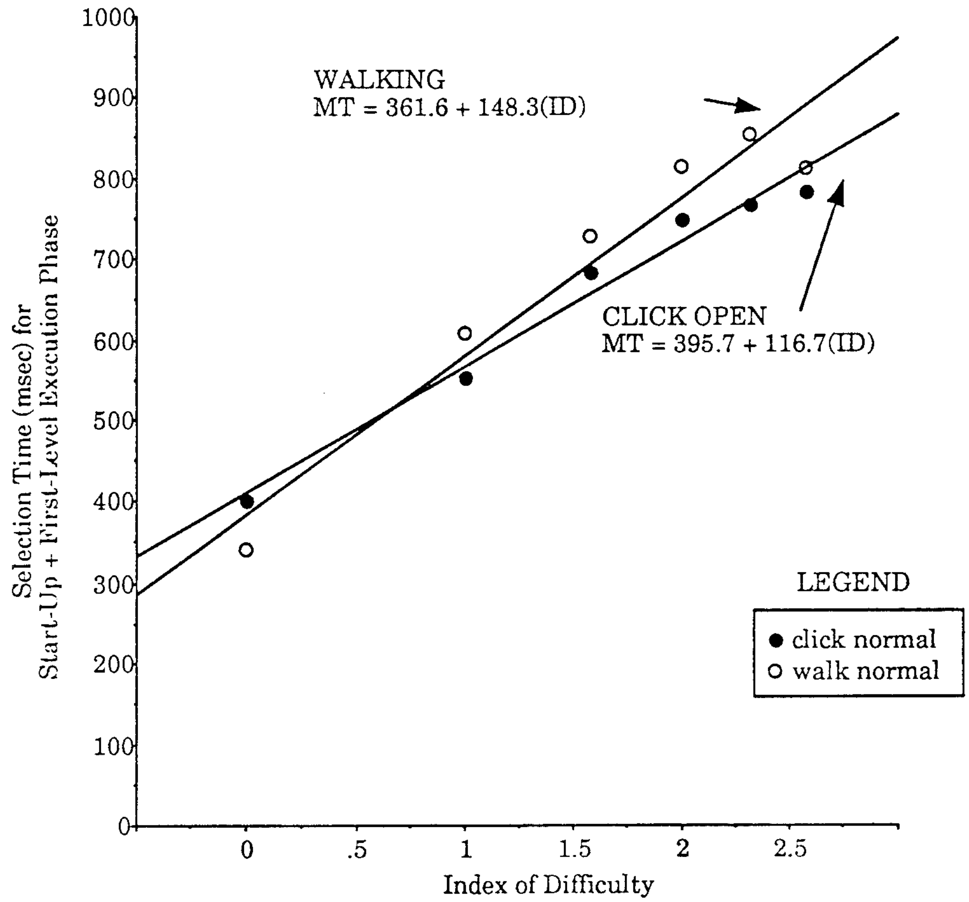

Figure 3.5 Fitts' law for normally organized menus in experiment 1 separated by menu style.

predicted by the search function. One plausible explanation for this is that the visual search and movement are initiated in parallel. Since the visual search takes longer than the mouse movement in random menus, the subject will frequently have moved the cursor past the first menu item by when he has identified it as the target item. This results in a corrective measure, yielding a longer time to select the first menu item.

Discussion

The results of Experiment 1 clearly show that the current understanding of mouse-based selection from hierarchical menus is incomplete and flawed in some respects.

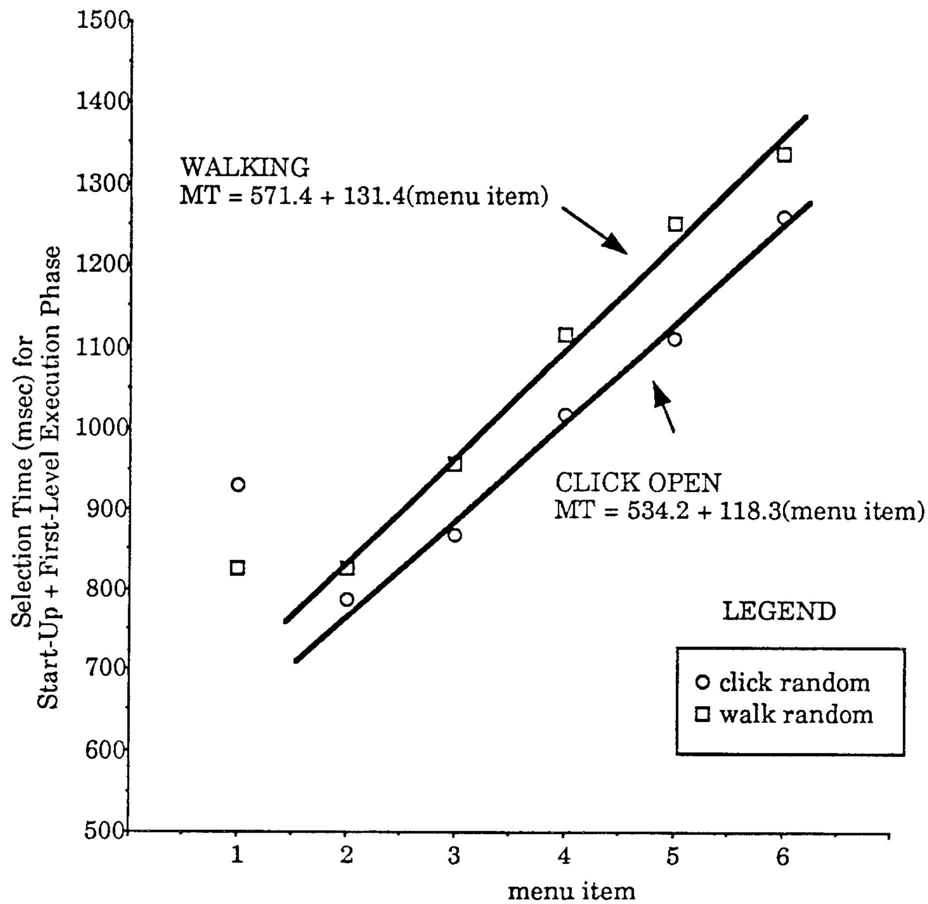

Figure 3.6 Linear functions for the randomly organized menus in experiment 1 separated by menu style. (Excluding the first menu item)

First, selections from the click-open menu are faster than from the walking menu; this disagrees with the prediction of the Keystroke-Level Model outlined in Chapter 2. Our data, thus far, indicate that making selections by moving through a spatially-constrained path with the mouse button depressed is slower and more error-prone than making selections by moving through unconstrained paths and clicking at the beginning (or end) of each movement segment. Current models quantify the effect of the number of button presses and unconstrained movement to bounded targets. No existing model addresses either the button status while moving, or spatial constraints along the path of movement. However, both of these warrant further exploration, based on the results of this experiment.

The present subjects selected items slightly faster from tall than from short menus, contrary Fitts' law. Since target size and distance are perfectly correlated in linear menus such as those of Experiment 1, Fitts' law predicts identical selection times for all menu heights. In Experiment 1, however, subjects paid more attention to target size than target distance. This may have happened because the menu items were embedded in a set of similar targets, not isolated as in many Fitts studies. The most salient common feature of the targets was the size of the menu items, which might bias the subjects' performance.

The effects of the independent variables in this experiment do not seem to be clearly localized in any one phase of the menu-selection process. Rather, they seem to occur in every phase of the movement to varying extents. The largest effects appear in the second menu-selection phase, which has the greatest number of information processes, including evaluation of first-level selection, planning, search, and execution of the second-level selection followed by evaluation of the entire menu-selection.

The organization of the menus proved to be the strongest determinant of selection time. This factor also revealed the most about the process of visual search in menu selection. It also helped manifest the relationship between search and motor processes used in the selection.

The significant interaction between menu style and menu organization gives evidence for the non-independence of the search and motor processes. According to Sternberg's (1969a) additive-factor logic, factors that affect different processes in a serial-stage model should have additive effects on reaction times for discrete responses. Generalizing this logic to selection times, the interaction in Experiment 1 suggests one of two possibilities: (1) visual search and motor processes in the menu-selection task occur during a common stage of processing, or (2) a serial model is not an adequate characterization for the task of menu selection.

The serial-position functions (Figure 3.4) support the second of these possibilities. The linear functions for the selection from the random menus is well explained by a systematic, serial-search model with seemingly little or no influence of the motor processes except for a small constant time added in selecting from the walking menus. In contrast the log-linear functions for the normal menus, which obey Fitts' law, suggest a fast direct search that adds a constant to the selection time. The divergence of these functions is evidence for the non-seriality of perceptual and motor processes.

A serial model predicts that the shape of the serial position curve for the normally-organized menus would be reflected in the curve for the randomly-organized menus. The time for the visual search required by the randomly-organized menus would add to the motor time for the selection. The shape of the curve for the randomly-organized menus depends on the nature of this search process. Given a random search process, found by Card (1983), the curves for the random menus would have the identical shape as the curves for the normal menus. The visual search adds a constant to the selection time, regardless of the serial position of the menu item. Given a systematic search process, the serial position function for the random menus would be steeper than the function for the normal menus, but still curved. A serial model that would account for the present data would have to posit an exponentially growing search function which is an exact mirror image of Fitts' law found for the normally-organized menus.

Such a function is implausible for visual search. The alternative explanation of concurrent motor and search processes is preferred.

Experiment 1 has revealed new insights into the nature of visual search and the control of aimed movements in mouse-based menu selection. We have obtained evidence of search and movement functions that are highly dependent on the amount of advance location information available to the user. This outcome counters the claim that the time for visual search and selection are independent of the motor processes involved in the menu selection. The empirical evidence refutes one example of a serial stage model of menu selection (Keystroke-Level Model) and points toward a the need for a process model with both serial and concurrent processes (Critical-Path Model). The subsequent experiments in this dissertation will explore these conclusions in greater detail.

CHAPTER 4
EXPERIMENT 2

Rationale

The data from Experiment 1 showed that click-open menus were superior to walking menus in terms of movement speed and errors. However, some questions remain unanswered.

One question concerns what is the underlying motor mechanism for the speed difference. The two-level menus in Experiment 1 varied on two motor factors: the trade-off between the number of button presses and path constraint,[9] and the status of the mouse button during movement. The results of Experiment 1 did not reveal which of these factors play a role in the selection-time difference since both of them are varied there.

Experiment 2 addresses this question by varying only button status during movement while eliminating the path-constraint factor. This is accomplished by using single-level menus. With only a single level, there is no path constraint for either click-open or walking menus, the size and location of the movement targets are identical (the entire menu item), and the number of button actions is equal (one action to display the menu, and one to select the menu item). The only difference between the menu styles involves the mouse being moved with the button either released (click-open)

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[9]This is a tradeoff because the two menu styles minimize one of these factors at the expense of the other. Walking menus minimizes the number of button actions required for selection (one press and one release regardless of the number of menus levels), while adding a path constraint for moving between menu levels. Click-open menus eliminate all path constraints at the cost of requiring extra button presses for each menu level.

or depressed (walking).

If the difference between click-open and walking menus is replicated in Experiment 2 it will support the hypothesis that holding the mouse button down slows menu selection. If no difference occurs, it will suggest that the trade-off between button presses and path constraint is a primary contributor and should be the focus of further work.

A second question raised by Experiment 1 concerns the nature of the visual search that occurs in mouse-activated menu selection. The data suggest that this search is best modeled as a systematic, top-to-bottom, process. What remains unanswered is whether the search is self terminating, exhaustive, or some combination of the two.

This question will be addressed by varying the number of items on the menu. With a strictly self-terminating search, the number of items in a menu should not affect the serial-position function. An identical, monotonically increasing function should be found for each menu size. In contrast, a strictly exhaustive search would yield a flat serial-position function with the y-intercept increasing as the number of items on a menu increases. A search process combining self-terminating and exhaustive components would predict a monotonically increasing serial-position function, where additional menu items increase the selection time for each location on the serial-position function.

Varying the number of items in the menu may also give insight into the nature of the motor processes underlying menu selection. For example, it increases the range of ID values available to evaluate the robustness of Fitts' law for the normally-organized menus. Also, the serial-position curves for the normally-organized menus may reveal if increasing the total number of movement targets on the screen slows the movement.

Method

Subjects

Eight right-handed University of Michigan students served as paid subjects. They had no apparent motor deficiencies. All of them were experienced mouse users. Each subject was paid $15 for two, 1 1/2 hour sessions, plus bonuses based on performance.

Procedure

The procedure involved self-initiated, speeded selection from single-level menus. At the beginning of each trial, subjects were shown a digit that identified the target item for that trial. When they had memorized the digit, they depressed or clicked the mouse button to display the menu, and then made their selection as fast as possible while minimizing errors.

Design

Each of the eight subjects used both styles of pop-up menu (click-open and walking). Menu style was varied across days. All subjects selected from menus having different lengths (three, six, or nine items) and different numeric organizations (normal or random). Each block of trials consisted of a fixed combination of menu style, menu length, and organization. The six combinations seen by each subject are shown in Figure 4.1. A block of trials consisted of two practice trials followed by three with each of the menu items repeated until each was selected correctly. Each combination of menu length by numeric organization was presented in six blocks during the course of the experiment.

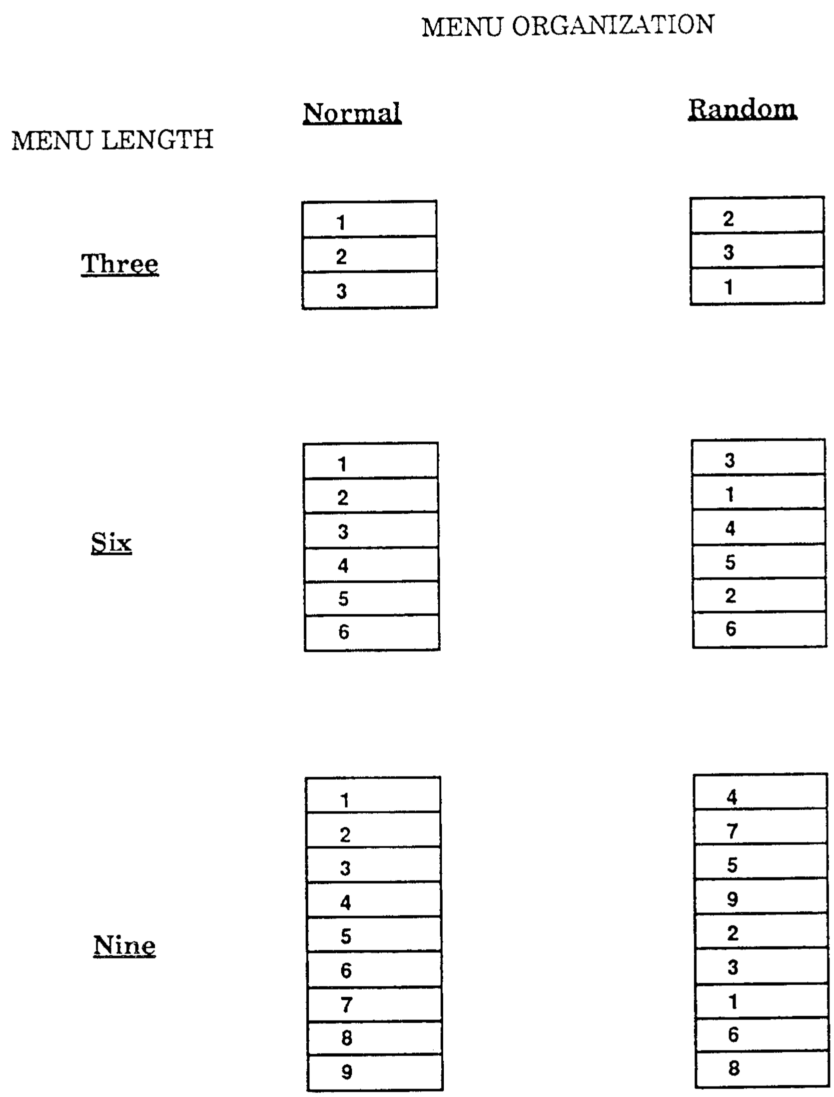


Figure 4.1 Menu organization and menu length combinations used in experiment 2.

Results

The results of Experiment 2 are presented in four sections: (1) errors in menu-selection; (2) total selection time; (3) selection times for various phases of movement; and (4) serial-position functions for menu selection.

Errors in Menu Selection

When selecting from single-level menus, every error is fatal, whether it involves selecting a wrong menu item or stopping outside the entire menu region. The error rates were low for both click-open (4.77%) and walking menus (4.16%); they did not differ significantly [$F(1,7) < 1$]. As in the first experiment, only error-free trials are included in the following analyses.

Total Selection Time

Total selection time is operationally defined as starting with the action that first displays the menu on the screen, and ending with the action that completes the selection to make the menu disappear. For each subject, the mean selection time was calculated for each combination of menu style, menu organization, menu length, and block. An ANOVA was performed on the mean selection time as a function of these four within-subject variables.

Each combination of menu style, organization, and length was repeated in six blocks of trials to assure that subjects reached asymptotic performance. There was a significant block effect [$F(5,35) = 5.01, p < .001$]. Removing the first block of trials from the analysis eliminated the block effect [$F(4,28) < 1$]. Therefore, all analyses are performed on blocks two through six to examine asymptotic performance. A summary of the actual times and attained significance levels for the variables of interest, separated by movement phase, is shown in Table 4.1.

Selecting from click-open menus was faster than selecting from walking menus [$F(1,7) = 7.26, p < .05$]. The average selection time for click-open menus was 743 msec compared to 819 msec for the walking menus, a

Table 4.1 Selection times by movement phases for Experiment 2.

EFFECTS	Total Selection Time	Start-Up	First-Level Execution
	MOVEMENT PHASES		
Menu Style	p < .05	**n.s.**	**n.s.**
Click-open	743	61	682
Walking	819	90	730
Menu Length	p < .0001	**n.s.**	p < .0001
Three	567	66	501
Six	788	72	717
Nine	988	88	900
Menu Organization	p < .0001	p < .01	p < .0001
Normal	580	26	554
Random	982	124	858
Menu Length by Menu Organization	p < .0001	p < .05	p < .0001
Menu Style by Menu Organization	**n.s.**	**n.s.**	**n.s.**

All times in milliseconds

difference of 76 msec (almost exactly half of the menu-style effect for two-level menus in Experiment 1). Selecting menu items was slower with the button depressed than with the button released. Selection times were 402 msec faster with normal menus than with random menus [$F(1,7) = 185.18$, $p < .0001$]. Menu length also had a strong effect on selection times [$F(2,14) =$

165.42, $p < .0001$]. This is not surprising, since the average movement distance increases with menu length. There was a significant interaction between menu organization and length in the data [$F(2,14) = 55.61$, $p < .0001$]. As menu length increased, the difference in selection time between normal and random menus increased as well. Also, the interaction between block and menu organization was borderline in significance [$F(4,28) = 2.64$, $p=.055$]. Normal menu-selection times exhibited a small but consistent decrease over the course of the experiment (from 611 to 553 msec), while random menu-selections varied unsystematically across blocks. The interaction between menu style and organization found in Experiment 1 did not occur here [$F(1,7)<1$]. There was no evidence that the button status while moving the mouse differentially influenced the visual search in single-level menus. All other interactions failed to reach significance.

Selection Time for Movement Phases

The total selection time was divided into two movement phases: the start-up phase and first-level execution phase. A verbal description of these movement phases is given at the beginning of each section. A more detailed operational definition of the movement phases is given in Appendix B. ANOVA's for these phases were identical to those for the total selection time.

Start-Up Phase

As in Experiment 1, the start-up phase began after the action to display the first-level menu (button click for click-open, and button press for walking), and it ended when intentional movement of the mouse began.

Only the main effect of menu organization reached significance for the start-up phase [$F(1,7) = 12.67$, $p < .01$]. Both the menu-style and menu-length effects were in the expected direction but not significant. The start-up time for click-open menus was 61 msec compared to 90 msec for walking menus [$F(1,7) = 3.97$, $p > .05$]. For the menu-length effect the average start-up times for the 3, 6, and 9 item menus were 66, 72, and 88 msec respectively [$F(2,14) = 3.58$, $p > .05$]. The only significant interaction involved menu organization by length [$F(2,14) = 4.53$, $p < .05$]. It paralleled the results on total selection time; the difference between normal and random menus increased with the longer menus.

First-Level Execution Phase

This movement phase starts when the subject begins intentional movement of the mouse and ends when the menu item is selected. The termination event is a button press anywhere in the menu item for the click-open menus, and a button release anywhere in the menu item for the walking menus. The results for this movement phase were identical to those found for the total selection time, except that no significant menu-style effect occurred.

The difference between selecting from click-open (682 msec) and walking menus (730 msec) was not statistically significant for the first-level execution phase [$F(1,7) = 4.21$, $p > .05$]. Selecting from normal menus was 304 msec faster than selecting from random menus [$F(1,7) = 176.85$, $p < .0001$]. Menu length also had a significant effect on selection times [$F(2,14) = 155.62$, $p < .0001$]. There was a significant interaction between menu organization and length [$F(2,14) = 32.67$, $p < .0001$]. As menu length increased, the difference in selection time for normal versus random menus increased as well. There was one additional significant interaction between menu-organization and block [$F(4,28) = 2.96$, $p < .05$]. Normal menu-selections showed a small but consistent improvement over the course of the experiment, (from 568 to 533 msec), while the time for selecting from random menus varied unsystematically across blocks.

Serial-Position Functions

As in Experiment 1, the cleanest examination of the perceptual and motor interactions involve analyzing the serial-position functions for combined start-up and first-level menu-selection times.

Figure 4.2 shows the serial-position functions for the four combinations of menu style and menu organization in Experiment 2. As in Experiment 1 with two-level menus, the selection time was always slower for the random menu items than for the normal menu items. The shapes of the functions are also very similar to those from Experiment 1. Additionally, the magnitude of the effects are similar across experiments, as shown in Figure 4.3.

The data for the normally-organized menus are well characterized by Fitts' law. With click-open menus $MT = 289.6 + 177.1(ID)$, $r^2=.98$ (time in msec); with the walking menus $MT = 328.9 + 206.8(ID)$, $r^2=.99$ (time in msec). These functions suggest that the selection time with normal menus is dominated by motor processes. Both the slope and the intercept are lower for the click-open menus than for the walking menus, which reinforces the conclusion that selecting from the walking menus is more complex motorically.

The data for the random menus appear to be a linear function of serial position. If the first menu item is excluded from the data, linear functions fit the remaining results well for both the click-open $MT = 515.8 +$

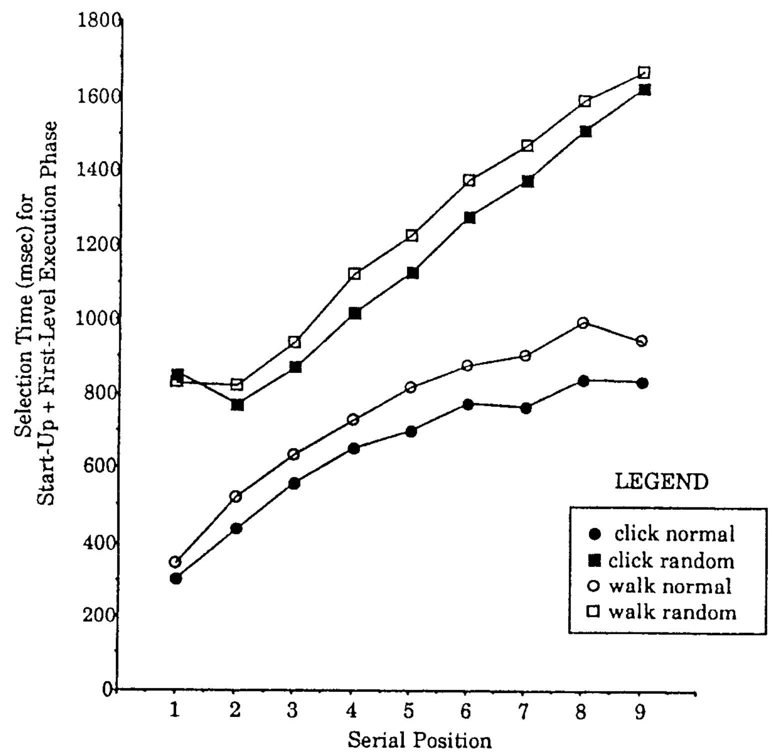


Figure 4.2 Serial-position functions for Experiment 2 separated by menu style and menu organization (includes 3, 6, and 9 item menus).

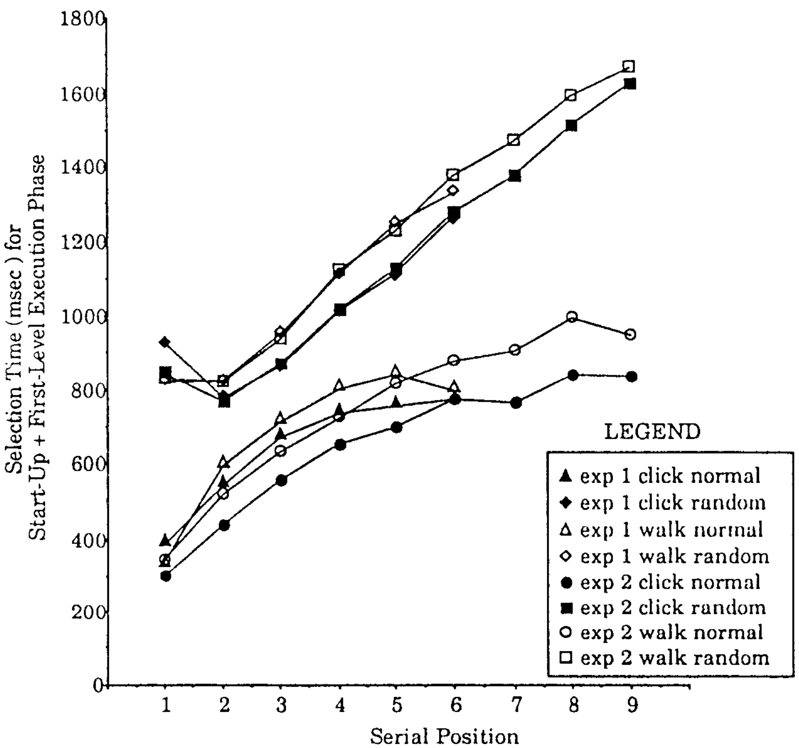


Figure 4.3 Comparison of the serial-position functions from Experiments 1 and 2 separated by menu style and menu organization.

116.7(menu item), r^2=.99 (time in msec) and walking menus MT = 597.2 + 123.6(menu item), r^2=.99 (time in msec). These functions suggest that a systematic, top-to-bottom, visual search dominated the selection time for the random menus.

The serial-position functions for each menu length collapsed across menu style (Figure 4.4) reveal more about the visual search in menu selection.

Looking first at the random menus, there is a clear increase in selection time with more menu items. The first three serial positions show a steady increase in selection time with menu length. This indicates an exhaustive component of the search. The monotonically increasing

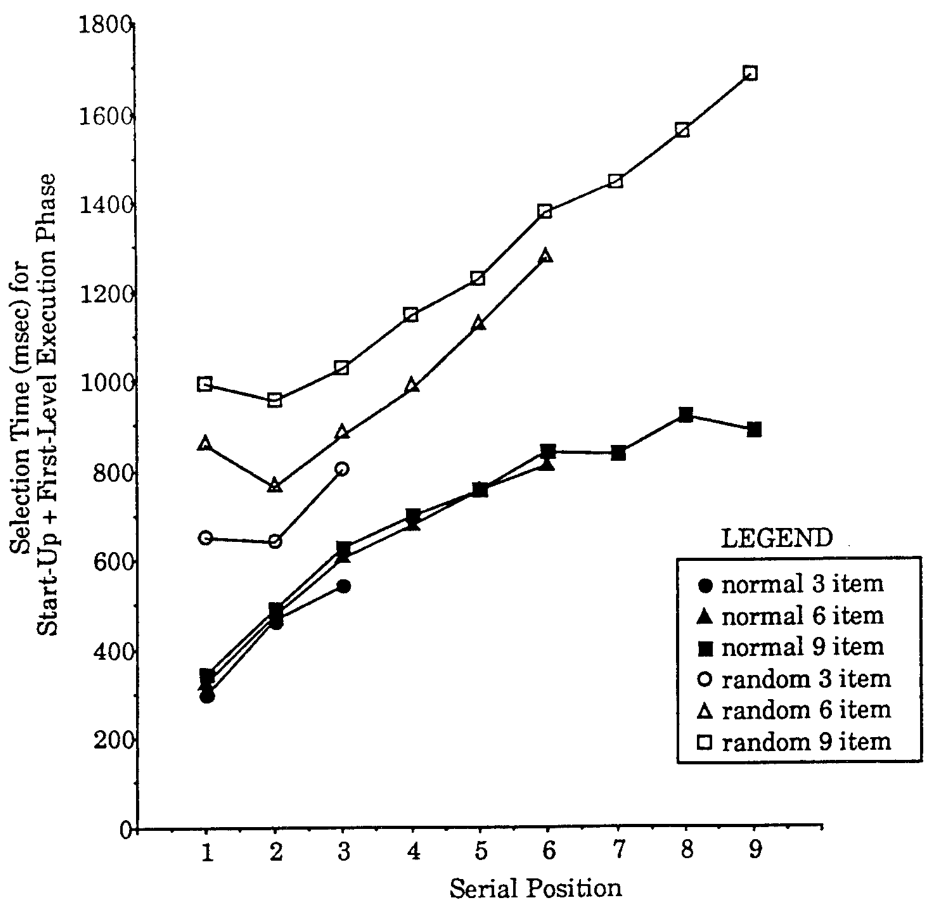


Figure 4.4 Serial-position functions separated by menu length for Experiment 2.

functions for all three menu lengths indicates a self-terminating component of the search as well. The evidence points to a visual search combining exhaustive and self-terminating processes.

The serial-position curves for the normal menus are qualitatively different. Here the menu length has little or no impact on the selection time. This agrees with the suggestion from previous research on the visual search of menus that a single saccadic eye movement to the menu item is possible when the user knows the location of the menu item in advance.

Another feature of the serial-position curves for normal menus is that they have the same shape regardless of menu length. This means that Fitts' law applies equally well to menus of differing lengths.

Discussion

Interpretation of Results from Experiment 2

The results of Experiment 2 suggest that the difference in selection time between click-open and walking menu depends on the status of the mouse button during the selection movement. However, the present analysis of the movement phases does not isolate this effect in a single phase. In general, the pattern of results for each movement phase was similar to the pattern for total selection time, though the effect was generally weaker during the movement phases. Notably, menu style did not affect either movement phase, but the trend favored the click-open over the walking menu. These borderline results may stem from the high degree of between-subject variability in the duration of the movement phases. This variability may be caused by subjects adopting different strategies concerning when they commence visual search and when they begin moving the mouse.

Examination of the serial position functions separated by menu length, indicates that the search process for random menus has an exhaustive component. A strictly self-terminating search cannot account for the observed menu length effect. The lack of a menu length effect for the normal menus supports the finding from previous research that the search process is minimized with advance location information.

Comparison of Results for First and Second Experiments

The difference in error rates between the menu styles, which was present in the first experiment with two-level menus was absent in the second experiment with one-level menus. This suggests that the additional errors on walking menus in Experiment 1 were caused primarily by the path constraint on moving from the first to the second level. This constraint was eliminated in Experiment 2 and the differences in error rates disappeared as well.

Another result found in the first but not second experiment is the interaction between menu style and menu organization. For single-level selections, walking menus were not more affected by the random organization of menu items than were click-open menus. This suggests that the interaction between search and movement is related to the added complexity of moving along a constrained path (from level to level) rather than being related to the button status during the movement.

Turning to some commonalities, the serial-position functions were qualitatively and quantitatively similar across the two experiments. Selection times for randomly-organized menus were best fit by a linear function in which each menu item was scanned in approximately 125 msec. Selection times for normally-organized menus were well characterized by Fitts' law in the range of three through nine menu items. Moreover, the parameters of all the functions did not depend on either the total number of menu levels in the selection or on whether menu style was a between or within-subjects variable. This is reassuring as it demonstrates the robustness of the findings across experimental conditions.

CHAPTER 5
EXPERIMENT 3

Rationale

The results from Experiment 2 show that one important factor in the speed of mouse-based menu selection is the state of the mouse button. From a software designer's perspective, the study might well end here with a conclusion that clicking is faster than dragging for menu selection as well as for other computer-based tasks (Gillan et al., 1990). However, from a psychological perspective, there is still one important question to address. What is the mechanism responsible for this difference?

Experiment 3 was designed to test two alternative hypotheses about what causes the observed difference between moving with the mouse button depressed and moving with the mouse button released. One possibility is that the difference might be caused by some central-processing demands. Alternatively, it might be caused by some purely peripheral, physical aspect of the movements. These hypotheses may be expressed in more detail as follows:

1) The difference for dragging versus clicking stems from a greater load on working memory. This is because one must remember when to keep the button depressed and when to release it in walking menus, but not in click-open menus.

2) The difference stems from increased friction between the mouse and the pad caused by the continuous pressure on the depressed button.

The task chosen to manipulate the load on working memory involved memory search of short lists (Sternberg, 1969b). In the standard version of this task, the subject memorizes a set of letters or numbers, is shown a probe letter (or number) that may or may not be a member of the memorized set, and then has to determine as quickly as possible if the target belongs to the set, and respond accordingly. For this task, numerous studies have shown that reaction time increases linearly with the set size. The empirical evidence suggests that the search through working memory is serial and exhaustive. The memory-search task has been used in many studies as a measure of mental workload (Wickens, 1986).

For present purposes, the memory-search task was modified slightly to fit with our menu-selection task. Two-level menus were included here. The first-level menus were numeric, and identical to those used in Experiment 1. The second-level menus were alphabetic, and each menu item was identified by a different letter. All selections were made from randomly-organized menus in order to preclude users from associating numbers with spatial menu positions. The precues for the numbers were the same as the menu item to be selected, just as in the previous experiments. However, the precues for the letters consisted of one, two, or four letters that constituted a memory set. One and only one of the letters appeared on the second-level menu, constituting a memory probe. The subjects had to select the correct first-level menu item, and then find the letter in the second-level menu that had been a member of the memory set. All trials had a member of the memory set in the second-level menu.

Examples of the menus and precues in this experiment are shown in Figure 5.1.

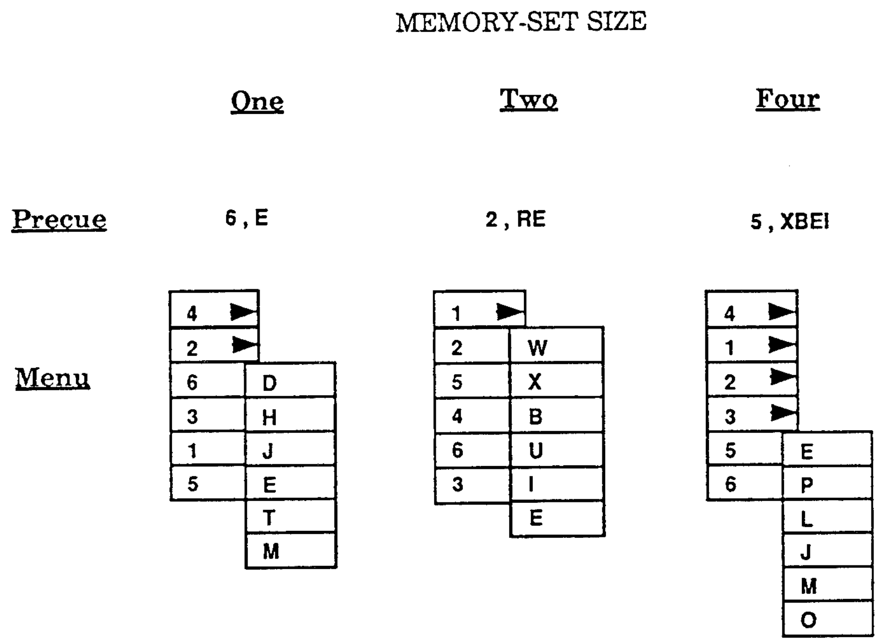


Figure 5.1 Examples of menus with different memory-set sizes used in Experiment 3.

One expected result is that selection time should increase with the size of the memory set. Additionally, if selecting from the walking menus does involve extra working memory capacity, and if the memory-search task sufficiently occupies that capacity, then an interaction between menu style and set size should occur. Increasing set size should degrade performance more for walking menus than for click-open menus.

In order to vary a peripheral factor separate from memory load, friction between the mouse and the surface on which the mouse moved was varied. This was accomplished by having half the menu selections performed on the cloth side of a mouse pad, and the other half on the rubberized backing of the pad; the rubber backing of the mouse pad had a much greater level of friction than did the cloth side.

If friction is a major determinant of movement speed, then selection times should be significantly slower on the high-friction surface. Additionally, if pressing the mouse button raises the friction level more for the walking menus than for the click-open menus, an interaction between menu style and friction level should occur. With menu style, memory set size, and friction level as the main independent variables, Experiment 3 was run to test these two hypotheses.

Method

Subjects

Twelve right-handed University of Michigan students served as paid subjects. The subjects had no apparent motor deficiencies. All of them were experienced mouse users. Each subject was paid $10 for a two hour session, plus bonuses based on performance.

Procedure

The procedure involved self-initiated, speeded selection from two-level menus. At the beginning of each trial, subjects were shown precues consisting of a single digit for the first-level selection, and a set of one, two, or four letters as a precue for the second-level selection. When they had memorized the precues, subjects depressed the mouse button to display the first-level menu, and proceeded to make their two selections as fast as possible while minimizing errors.

Design

The twelve subjects were divided into two groups. Each group made menu selections at a single friction level (high or low). Subjects selected from both styles of menu (click-open and walking), and they received all memory-set sizes (one, two, and four). All menus were randomly organized for each trial. A block of trials always consisted of a single combination of menu style and memory-set size. First-level targets were identified by single digits 1-6, and second-level targets were identified by single letters, requiring a total of 36 distinct two-level menu selections. A block of trials consisted of two practice trials followed by each of the 36 menu combinations, each of which was repeated until a correct selection from it occurred.

The first half of the experiment involved selecting from either click-open or walking menus; following a break, subjects selected from the other menu style for the remainder of the session. At the beginning of each half, subjects were instructed about the particular menu style for that half, and they were given one practice block to familiarize themselves with it. Following practice, each memory-set size was presented in three blocks of trials.

Results

The results are presented in three sections: (1) errors in menu selection; (2) total selection time; and (3) selection time for movement phases.

Errors in Menu Selection

As in Experiment 1, recoverable efficiency errors and nonrecoverable fatal errors were possible in this two-level menu selection. Inefficiency errors occurred more often with walking (1.8%) than with click-open (0.5%) menus [$F(1,10)=32.9$, $p < .001$]. Fatal errors were more frequent than inefficiency errors. The average fatal-error rate was significantly greater for click-open menus (3.1%) than for walking menus (2.3%) [$F(1,10)=13.88$, $p < .005$]. Only error-free trials are used in the following time analyses.

Total Selection Time

There were three experimental factors in this study: menu style, memory-set size, and friction level. The actual times and attained significance levels for these factors are shown in Table 5.1.

Selecting from the click-open menus (2,248 msec) was 169 msec faster than selecting from the walking menus (2,417 msec) [$F(1,10)=11.09$, $p < .01$]. The size of the memory set had a significant effect on selection time [$F(2,20)=5.209$, $p < .05$], with the average selection time increasing linearly with the size of the memory set. Surprisingly, friction level did not affect the speed of selection [$F(1,10) < .01$]. One possible explanation for this is that by chance, subjects in the high-friction condition were more skilled than those in the low-friction condition. Another possibility is that subjects compensated for the higher friction without much cost or difficulty. The only significant interaction occurred between menu style and block [$F(2,20)=5.3$, $p <.05$]. The selection times for the click-open menu exhibited a small but consistent improvement from block one to block three. The walking-menu selections were fastest for the second block and slower for the final block of trials.

Table 5.1 Selection times by movement phases for Experiment 3.

EFFECTS	MOVEMENT PHASES: Total Selection Time	Start-Up	First-Level Execution	Second-Level Selection
Menu Style	p < .01	p < .005	n.s.	p < .05
Click-open	2,248	98	942	1208
Walking	2417	173	977	1267
Friction Level	n.s.	n.s.	n.s.	n.s.
Low	2,341	158	987	1197
High	2,324	113	933	1278
Memory Set Size	p < .05	n.s.	n.s.	p < .05
1	2,138	130	951	1057
2	2,323	136	974	1212
4	2,537	141	954	1443
Menu Style by Block	p < .05	n.s.	n.s.	p < .05
Click Walk				
1 1	2,271 2,478			1,225 1,273
2 2	2,260 2,371			1,227 1,243
3 3	2,213 2,403			1,173 1,285

All times in milliseconds

Two critical interactions that would have differentiated between the alternative hypotheses were not present here. The interaction between menu style and memory-set size, which would have supported the central memory-load hypothesis, was not significant [F(2,20)=1.6, p >.2]. The interaction between menu style and friction, which would have supported the peripheral motor hypothesis, was also absent [F(2,20)<1].

Selection Time for Movement Phases

The total selection time was divided into three phases: start-up, first-level execution, and second-level selection. The operational definitions for the movement phases were the same as those for Experiment 1 (see Appendix B for details). The ANOVA's for these phases were identical in form to that used for the total selection time. Only the significant results are presented below.

Start-Up Phase

The only significant effect in the start-up phase came from menu style [$F(1,10) = 12.67$, $p < .01$]; the average start-up time for click-open menus was 98 msec compared to 173 msec for walking menus.

First-Level Execution Phase

None of the factors in the experiment affected this phase of movement significantly, although the absolute time comparisons favor the click-open menu (942 msec) over the walking menu (977 msec).

Second-Level Selection Phase

In this experiment, selecting from the second-level menu was clearly the most complex phase. The subjects had to search the randomly organized letters in the menu, and then match them with the letters that they had memorized at the beginning of the trial.

The pattern of results for the second-level selection phase is very similar to the total selection time. Selecting from click-open menus (1208 msec) was faster than selecting from walking menus (1267 msec) [$F(1,10) = 5.04$, $p < .05$]. The size of the memory set also affected the selection time

[$F(2,20) = 5.05$, $p < .05$]. The friction level did not significantly affect the time [$F(1,10)<1$]. Finally, the interaction between menu style and block found in the total selection time is also evident in this phase of movement [$F(2,20) =4.22$, $p < .05$].

Discussion

Most results of Experiment 3 are not surprising. Selecting from click-open menus was faster than selecting from walking menus, thus confirming the results from the previous two experiments. The magnitude of the difference is similar for simple two-level numeric menus (152 msec) and two-level menus involving a memory search (169 msec). The motor differences between click-open and walking menus are not overwhelmed by adding a modest amount of cognitive complexity to the menu selection. In terms of critical-path analysis, the button-depression effect remains on the critical path when a memory search is added. The addition of the memory-search task did affect the second-level menu selection as expected. No evidence was found for the added complexity influencing earlier phases of menu selection.

It is puzzling that friction level did not affect either selection times or error rates. Because of the small sample size and between-subject design, it is tempting to attribute this result to the vagaries of random assignment. If the same null effect was found in a within-subject design, or with a much larger sample size, it would suggest that people can easily adjust their muscular force to accommodate externally imposed difficulties.

Unfortunately, this experiment did not reveal the mechanism for the slower selection times associated with button depression. Adding both central and peripheral complexity to the task did not differentially affect selection times in the case of click-open or walking menus.

CHAPTER 6
ISOLATION OF THE BUTTON-DEPRESSION EFFECT

Two Motor Hypotheses About the Button-Depression Effect

No clear evidence was found for either the central memory-load hypothesis or the peripheral friction hypothesis in Experiment 3. We now consider two additional hypotheses for what causes the slowness in moving the mouse while the button is depressed. These hypotheses attribute the slowness to neuromuscular factors and are presented below:

1) The difference stems from increased neuromuscular complexity and postural awkwardness when moving with the mouse button depressed.

2) The difference stems from a greater difficulty of coordinating the end of the arm movement with a button release, relative to coordinating the movement end with a button press.

These hypotheses can be distinguished by which portion of the movement exhibits the slowness. If the first hypothesis is correct, the difference should appear throughout the main phase of movement, perhaps including response preparation. If the second hypothesis is correct, then the slowness should occur at the end of the menu selection. Here, the difficulty is presumed to be in making the transition from moving the mouse to initiating the button action that confirms the menu selection.

To test the hypotheses, new analyses of the data from Experiment 2 were conducted. This involved parsing the movement records into phases that correspond to response preparation, mouse movement, and confirmation. Here response preparation is measured as the start-up phase previously defined. Mouse movement and confirmation are measured by partitioning the first-level execution phase of the movement into two segments: mouse movement begins with intentional movement and ends when the cursor (and the mouse) stops moving; confirmation begins with the halt of the cursor and finishes with the button action that terminates the selection. More detailed operational definitions for the movement phases is given in Appendix B.

New Movement Parsing of Single-Level Selections

As in the previous analyses for Experiment 2, the following ANOVA's were conducted on data from error-free trials from blocks two through six. These analyses differ from those reported thus far in one respect. Selections of the first menu item were excluded. The rationale for this is given below.

In order to compare hypotheses, we must have distinct movement segments. Examination of the log files revealed that subjects often did not move the mouse when selecting the first menu item. This happened because it was often possible to select the first item by simply pressing (or releasing) the button. Even when subjects did move, the distance was very small. These circumstances, which are unique to the first menu item, making the button action for the walking menu be a single click of the mouse button. Similarly, selecting with the click-open menu is changed to a double button-click. As a consequence, the same time value is often attributed to the start-up, movement, and confirmation phases for first-item selections. This confounding is avoided by eliminating the first menu position from the analysis. All remaining selections have an unambiguous start-up phase, a significant movement phase, and a clear confirmation phase at the end.

Results

The present menu-style manipulation bears directly on the hypotheses being tested by these analyses. Therefore, for the sake of brevity, only significant results involving menu style are reported here. None of the other effects give any new insight into the menu-selection task.

Start-Up Phase

The effect of menu style almost reached significance for the start-up phase [$F(1,7) = 5.0$, $p \approx .06$]. Click-open selections (58 msec) were 31 msec faster than walking menu selections (89 msec). No other effects involving menu style approached significance [all p's $>.20$].

Mouse-Movement Phase

Moving the mouse was 57 msec faster for the click-open (button-up) menus than for the walking menus [$F(1,7) = 7.99$, $p > .05$]. Click-open averaged 650 msec compared to 707 msec for walking menus. No other effects involving menu style approached significance [all p's >.20].

Confirmation Phase

There was virtually no effect of menu style on the time for the final button action to confirm the menu selection [$F(1,7)=0.05$, $p < .80$]. Click-open selections (69 msec) were a mere 3 msec faster than walking-menu selections (72 msec). There were, however, two significant interactions involving menu style. The interaction between menu style and menu length was highly significant, with the walking menu being much more affected by menu length than was the click-open menu [$F(2,14)=16.28$, $p > .001$]. The three-way interaction involving menu style, length, and organization [$F(2,14)=12.07$, $p > .001$] further suggests that the randomly-organized walking menus have the greatest increase in confirmation time as a function of length.

Discussion

The new analyses of Experiment 2 finally give some insight into the mechanism for the slowness of moving the mouse with the button depressed. The evidence suggests that the selection-time difference is caused by increased postural complexity when moving with the mouse button depressed. The difference appears in the mouse-movement phase, which suggests that moving with the button depressed is more awkward than moving with the button released.

There was no evidence of difficulty in synchronizing the end of the mouse movement with the final button action. Click-open and walking menus yielded the same duration for the final button action.

The interaction effects involving menu style and menu length in the confirmation phase are intriguing. The disadvantage of selecting from a walking menu increases with the number of items on the menu. This is especially true for the randomly-organized menus. The click-open confirmation times were relatively unaffected by the length and organization of the menus. This indicates that at least for longer menus, the final confirmation phase is different with click-open and walking menus. The confirmation phase for walking menus may include a search of the entire menu. The confirmation phase for the click-open menu may involve a local search which is not influenced by the length or organization of the menu.

CHAPTER 7
GENERAL DISCUSSION

Summary of Major Findings

At the end of chapter two, several questions were raised about mouse movements and menu selection in HCI. We may now proceed to answer these questions as follow:

(1) Is the speed and accuracy of menu selection sensitive to changes in the physical actions required by different menu styles? If so, which aspects of selection are affected by the difference?

The answer to the first part of this question is unequivocally yes. Selecting from click-open menus is faster and more accurate than selecting from walking menus. The difference in accuracy appears to stem from the path constraint imposed by walking menus. Without such constraints (e.g. one-level menu selections, final-level selections in multi-level menus), there is no appreciable difference in accuracy between the two menu styles. The position of the mouse button during the movement contributes to the difference in speed. Moving the mouse with the button depressed is appreciably slower over the entire movement phase than moving the same distance with the button released.

While the findings about total selection time are clear, our attempt to isolate the effect of menu style in specific phases of the movement had mixed results. In two-level menu selection, the strongest effects appeared to occur during the second-level selection phase, the most complex phase of movement. Both Experiments 1 and 3, showed that the pattern of results for the second-level execution phase mimics the total selection times. The start-up time was also influenced by the menu style for two-level menu selections. Initiating movements was faster with click-open menus than with walking menus. One-level menu selections exhibited the same trend, but it was not significant.

Analyses of the start-up phase failed to uncover clear dimensions of response complexity. One possible dimension mentioned in Chapter 2 is the number of movement segments required by a selection. If the number of movement segments is a dimension of response complexity, the start-up time should be shorter for one-level selections than for two-level selections. However, comparing the results for Experiment 2 (one-level menus) and Experiment 1 (two-level menus) reveals that the start-up time increased slightly for walking menus (90 to 97 msec), but it actually decreased for click-open menus (61 to 45 msec) when selecting from one and two-level menus, respectively. This suggests that number of movement segments may not be a complexity dimension for menu selection.

Moreover, the first-level execution phase is somewhat influenced by menu style. For one-level selections, the trend went in the expected direction, with selections from click-open menus (682 msec) taking 48 msec less than did selections from walking menus (739 msec). Further parsing of the execution phase reveals that the mouse-movement phase, not the final button action, mediated the observed difference between the two menu styles.

(2) How are the applicability and parameter values of Fitts' law affected by the subjects' advance knowledge about the location of menu items?

Fitts' law applies quite well when subjects know the location of the menu items in advance and do not have to search extensively for them (Figure 3.5). It does not apply when substantial visual search is required to locate the target menu item, as in the randomly-organized menus. A linear function, based on the serial position of the menu item, provides the best fit for the randomly-organized menus (Figure 3.6).

For the normally-organized menus, Fitts' law applies equally well to both menu styles ($r^2 > .95$), even when ID is calculated in terms of the vertical distances to the menu items. The parameters are similar for the two menu styles with walking menus tending to yield steeper slopes (Figure 3.5). Fitts' law is not altered by the number of items in a menu (Figure 4.4) or the number of menu levels (Figure 4.3). This stability bodes well for the generalizability of the present results to other menu-selection tasks.

(3) Is visual search random or systematic in mouse-based menu selection?

There is clear evidence that for numeric menus, the search process is systematic when the menu items are randomly-organized. The serial-position functions for the randomly-organized menus indicate a serial top-to-bottom search with a rate of approximately 125 msec per item (Figure 3.6). The linearly increasing serial-position function also indicates that the visual search is predominantly self-terminating. However, Experiment 2 showed that the total number of items in the menu influences the selection time for random menus (Figure 4.4), whereas a strictly self-terminating search would not be influenced by the length of the menu. This result suggests that there is an additional exhaustive component of visual search.

On the other hand, for the normally-organized menus, the evidence indicates a fast, direct search process. This is seen in the relatively fast selection times and the smaller serial-position effect characterized by Fitts' law for movement time. The lack of a length effect in normally-organized menus suggests that here the search is either self-terminating or faster than other concurrent processes.

(4) Are visual search and movement serial, independent processes, as assumed in the literature on menu selection?

The interaction between menu style and menu organization in Experiment 1 provides evidence that the search and movement processes are not independent (Figure 3.3). Click-open and walking menus differ only in the physical actions required to make the selections. Menu organization (normal or random) changes only the amount of visual search required to make the selections. Therefore, if search and movement were serial independent processes, then the difference in selection times between normally and randomly-organized menus should be equal for the two menu styles (Sternberg, 1969a). However, this does not happen here. The physical actions associated with selecting from two-level walking menus adversely affected the selection times for randomly-organized menus. Examining the amount of time taken right before the final button action for one-level menu selection, suggests that an extra exhaustive search may occur at the end of the selection process for randomly-organized walking menus.

(5) Is menu selection with a mouse best characterized by a serial or a parallel model?

The present results point to major problems with the Keystroke-Level Model. It overestimates the menu-selection times by a significant amount. This is not too surprising given that the model was validated originally on naturalistic tasks and is meant hold for a wide range of tasks. More problematic is that the model's predictions were directly opposite of the results of the present study.

Part of the problem with the Keystroke-Level Model is that its parameters do not embody certain salient features of the menu-selection task (e.g., path constraints and button status while moving the mouse). Adding more parameters to the model should improve its fit. One such parameter, derived from the present studies, is the added time for moving with the mouse button depressed (76 msec per menu level). Analysis of the final button action in one-level menu selection adds another parameter value of 70 msec for the time to press or release the mouse button.

A more fundamental problem is the Keystroke-Level Model's assumption of exclusively serial processing. The shape of the serial-position functions show that adding more parameters to the Keystroke-Level Model cannot explain the data. The serial position functions are better explained in a framework that provides for serial and concurrent processes, as under the Critical-Path Model (CPM). Although the experiments in this dissertation are not sufficient to fully specify such a model, they do provide information relevant to developing one. The divergent serial-position curves suggest that search and movement are concurrent processes. To be specific, one variable that affects which processes are on the critical path is the menu organization. The two Critical-Path Models shown in Figure 7.1 illustrate possible relationships between perceptual and motor processes for a one-level menu selection from normal and randomly-organized click-open menus. In these models, each process necessary to complete the task is represented as a box with a duration (e.g., a saccade takes 230 msec (Olson & Olson, 1990). The durations for searching and moving are taken from the serial-position functions of Experiment 1. The numbers in the boxes represent the positions of the menu items. Sequential dependencies between processes are represented by lines connecting the boxes (e.g., the final button press does not begin until both the eyes and the cursor have been moved to the target menu item). There are no lines between the search and move boxes. This indicates that they are independent, concurrent processes. The critical path (thick, shaded boxes) is the set of processes whose duration contributes to the total task time. The total task time is calculated by summing the durations of the processes on the critical path. Processes off the critical path are not time critical and have flexibility in when they are executed.

Figure 7.1 shows that the critical path changes substantially as a function of menu organization. For normally-organized menus, the mouse movement determines the overall time. For randomly-organized menus, the visual search determines the overall time. This is a result of the parallel-processing assumption of the Critical-Path Model. It explains the shape of the serial-position curves quite well. Identical models for the walking menus can be formulated by replacing the values for the move and search processes with the appropriate values from the walking-menu serial-position functions.

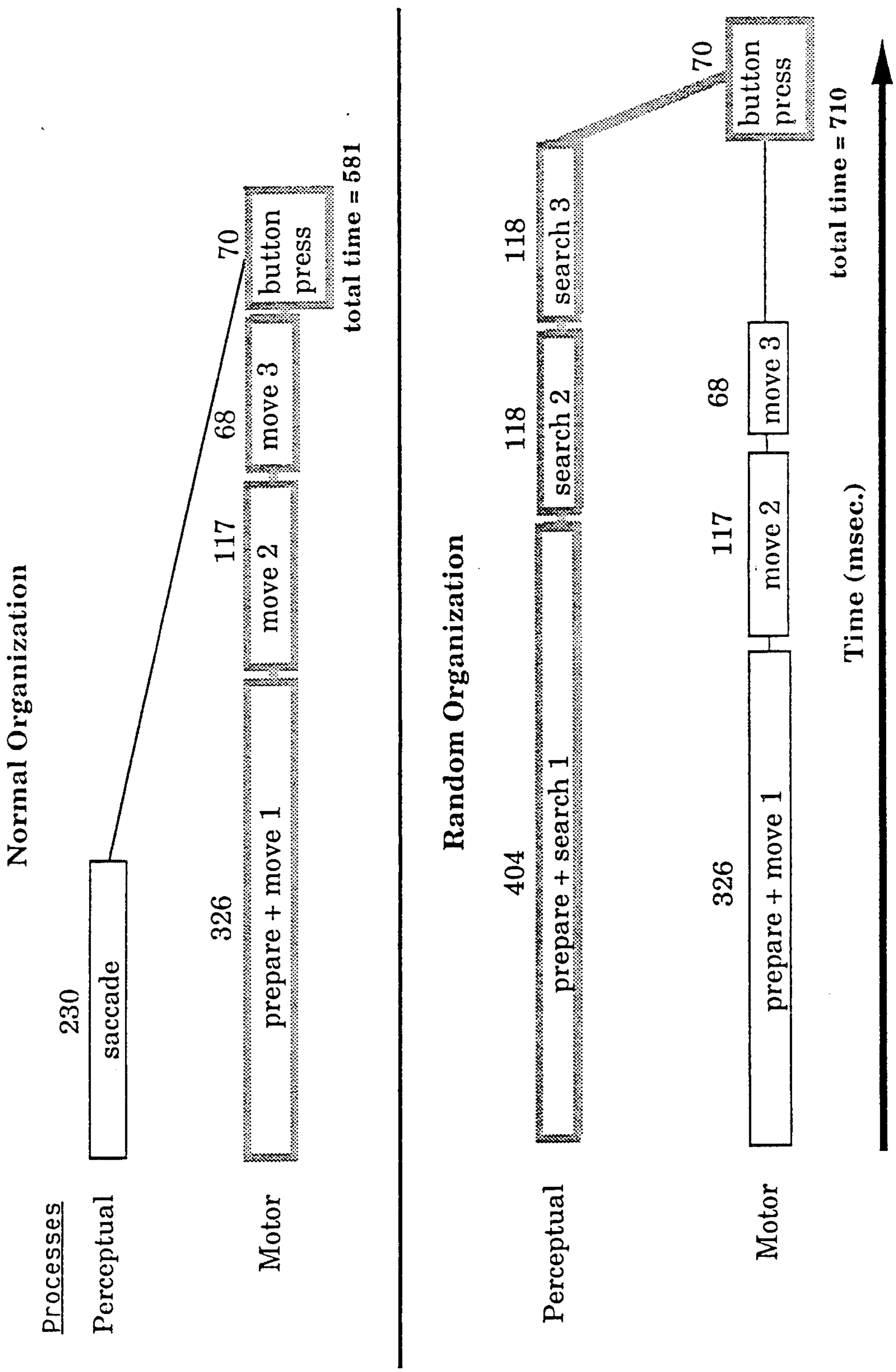


Figure 7.1 Critical-path models for selecting the third item from normally and randomly organized, click-open menus.

The longer times for the first serial position in the randomly-organized menus can also be explained by looking at the random-organization CPM. If the search and move begin at the same time, then after the search of item one is completed, the cursor will have already moved to item two, requiring an extra movement back to item one when it is the target menu item. This prediction is supported by examining the movement trajectories from single-level selections in Experiment 2. In the randomly-organized menus, 40% of the movements to first menu items were overshoots, compared to only 5% overshoots in the normal menus.

Of course, a few difficulties may arise in developing a CPM model for menu selection. It is not clear how to treat a process whose duration is stochastic. Extant CPM models assume all processes take constant amounts of time, unlike the models in Figure 7.1. It is also not clear how to handle errors and error recovery with a CPM model. Finally, determining the placement of the sequential dependencies is not obvious. There are several alternative models that lead to the same critical path as in Figure 7.1. Much more work is needed therefore to generate a definitive CPM model for menu selection.

Implications for Interface Design

It is a large step from a laboratory study with simple, numeric menus to complex real-world interfaces. Nevertheless, the findings of this dissertation, do have implications for existing and emerging human-computer interfaces.

The implications for menu selection are readily apparent. We have found that click-open menus are superior to walking menus on measures of speed and accuracy. Moving a mouse with the button depressed is more awkward than moving it with the button released. This bears on the Next computer system, which provides both of these menu styles. The present research implies that with experience, Next users should use the click-open menu predominantly.

The implications also go beyond menu selection. Moving the mouse with the button depressed is a feature of many tasks on current systems. On the MacIntosh, for example, many actions (e.g., selecting, moving, resizing, animating) performed on many objects (e.g., files, icons, windows, graphical objects, text objects, scroll bars) involve moving with the mouse button depressed (dragging). While the time costs of these operations may be relatively small, as in the current study, their ubiquity and frequency means that replacing them with clicking operations, where appropriate, should be considered.

Future Directions

There are three future directions that this research can take. One logical next step would be to investigate the other main motor factor found in these menu styles, path constraint during movement. We can pursue this by introducing a new, hybrid menu style into the investigation, a button-up walking menu. This menu style resembles walking menus with respect to how submenus are accessed by moving through a constrained "hot zone", but it is similar to click-open menus in that the movement occurs with the mouse button released. Comparing the button-up walking menu with existing menu styles will provide a way to study the influence of path constraint more fully.

Another direction for future research is to understand the factors that influence the suitability of Fitts' law in various HCI tasks. One shortcoming of previous work on HCI is the over-generalization of Fitts' law to mouse movements. It is incorrect to state that Fitts' law applies in general to mouse movements, and to then use that statement as a design guideline. Current studies indicate that the applicability of Fitts' law depends on the advance information that a user has about the location of the target.

Even when Fitts' law does apply, as for normally-organized menus, its slope and intercept depend on the nature of the selection task. This is shown in Figure 7.2 which outlines Fitts' law for three computer-based selection tasks with a mouse.

MOVEMENT TARGETS	EQUATION FOR FITTS' LAW (all times in msec)
Words Embedded In Text (Card, English, & Burr, 1978)	MT = 1003 + 96 ID, $r^2 = 0.83$.
Numeric Walking Menus (Current Study, Experiment 2.)	MT = 329 + 207 ID, $r^2 = 0.99$.
Simple Graphical Targets (Epps, 1986)	MT = 108 + 392 ID, $r^2 = 0.70$.

Figure 7.2 Fitts' law for three computer-based tasks.

As figure 7.2 indicates there is a systematic change in both the slope and the intercept across these three tasks. Two factors that vary across these selection tasks might account for the difference in these parameters. They are (1) the complexity of the target, and (2) the context in which it is embedded.

For the text-selection task (Card, English, & Burr, 1978) the target is very complex, and reading is required as part of recognizing the target. The target is also embedded among many other words with semantic content. As a result, Fitts' law has a relatively large intercept and a shallow slope. Its form may stem from the slower cognitive processes reducing the impact of motor processes.

At the other extreme, for the graphical-selection task (Epps, 1986), the targets are simple shapes, with little semantic content, isolated from other possible targets on the screen. Here Fitts' law has a steep slope and a small intercept. The much larger effect of ID on selection time in this task may occur because of the isolation of the targets, the lack of semantic content, or both.

Relative to these preceding cases, menu selection is intermediate both in complexity of target and context. In menus, the set of command names are more limited than in written text, but they do have semantic content. The menu items are imbedded in the context of other similar targets in the same area of the screen. The slope and intercept parameters for menu selection are between those for embedded text selection and isolated graphical selection.

An integrated set of studies that manipulate the semantic and spatial context of aimed movements in the domain of HCI will provide a way to specify task conditions where Fitts' law applies. It will also give some indication of the approximate parameter values for Fitts' law, based on a task analysis of the characteristics that affect those parameters.

A third direction that future research must take is to make the menu selection more realistic by adding more cognitive processing to the task. This can be accomplished by changing the menu items and the precues in a systematic fashion. Words must be added to the menus, with identical precues, as in the current studies. Another level of complexity will involve using synonyms or class inclusion precues, thus requiring subjects to make a semantic match in order to complete the selection. Next up the ladder of realism would be to have the precues represent procedural goals that are matched with the menu options. It will be interesting to see how the results of the current investigation are altered by these suggested modifications in the menu-selection task. Perhaps some of the perceptual/motor factors will continue to have an effect in the presence of more cognitive processes. Also, certain factors may be overwhelmed by the higher-order processes.

In summary, further efforts must be made to specify processes that are important for real-life menu selection. This dissertation serves as an existence proof of concurrent information-processing in HCI tasks. It remains to be seen whether the concurrent nature of processing in the menu-selection task will generalize to other, more realistic, menu-selection tasks.

APPENDIX A

COMPUTER PROGRAM FOR DATA COLLECTION

A computer program was developed to run the experimental sessions and collect the data. It is called the Mice and Menus Program (MMP), and runs on an IBM AT compatible computer with a Microsoft mouse as the selection device. MMP presents menus on the screen of the computer, tracks the movement of the cursor to select from the menus, and collects fine-grained timing and position data.

The program allows the experimenter to name and organize the items in a hierarchical menu ranging from one to three menu levels, with one to nine items at each menu level. The experimenter can also control which menu items are to be selected in an experimental session and how many practice trials are included at the beginning of each block of trials.

The appearance of the menus can be manipulated by specifying the width and height of the menu items, the ordering of the menu items within a menu, and whether or not non-target items appear on the menu. The actions for using the menu can also be controlled by choosing one of the supported menu styles (currently click-open, walking, and button-up walking).

MMP generates three data files for each subject. A short data file (appended with ".x") shows information at the block level including the number of practice trials, the average correct selection time for the block of trials, the number incorrect trials, and the name of the file that contains the information about the characteristics of that block. A second data file (appended with ".o") gives information for each trial, including the style of menu, the target menu items, the menu items selected, and the timing and position of the total selection time. The third long data file (appended with ".l") contains the same information as the second data file along with a record of the cursor position, mouse-button status, and elapsed time from the beginning of the trial. The timing resolution of the data files are 5 msec.

APPENDIX B

OPERATIONAL DEFINITIONS FOR MOVEMENT PHASES USED IN THE EXPERIMENTS

Many of the analyses in this dissertation are based on segmenting the total selection time into various movement phases (e.g., start-up, first-level execution, second-level selection, mouse movement, confirmation). This appendix will give detailed operational definitions for the movement phases as well as describing the parsing algorithms that were used to extract the times from the data files produced by MMP (the data collection program described in Appendix A).

The long data files (appended with ".l") were used to identify the movement phases. These files contained a record of the cursor position in x and y coordinates, mouse-button status (up or down), and elapsed time from the beginning of the trial. This information was obtained by using an interrupt provided by the Microsoft Mouse software (*Microsoft Mouse Programmer's Reference*, 1989) that reported the information whenever a "mouse event" occurred. A "mouse event" is defined as a change in the position of the mouse of at least one "Mickey" (approximately 1/200 of an inch), or a change in the status of the mouse button. The interrupt is strictly event-driven, only reporting when a "mouse event" occurs. The maximum resolution of the interrupt is 5 msec. Any events that happen in a 5 msec interval are reported as a single entry in the data file.

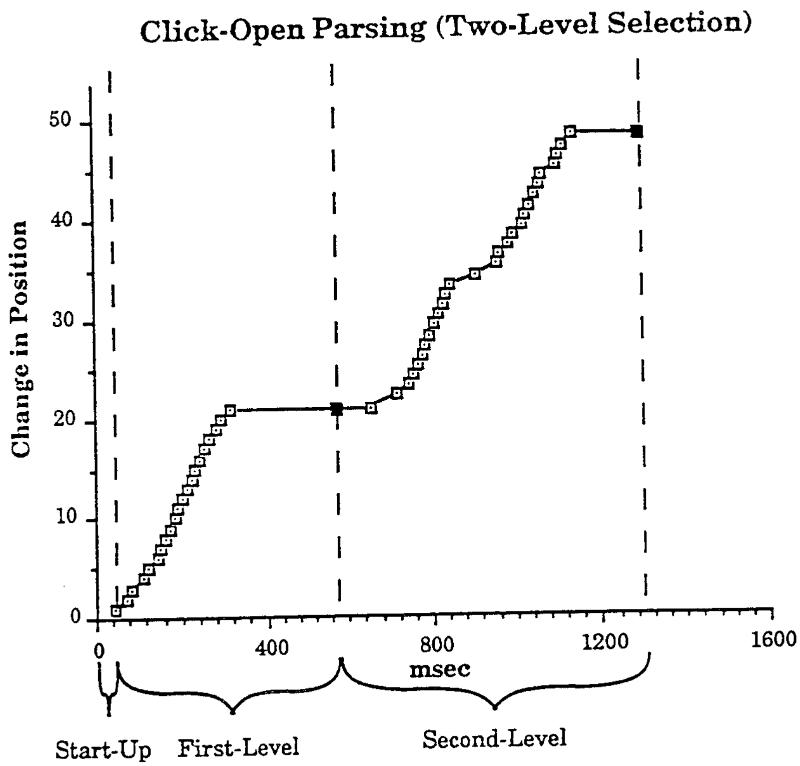
Two-Level Menu Selection

Explanation of Phase-Parsing Graphs

In Experiment 1 and 3 subjects selected from two-level menus. The total selection time was divided into three movement phases: start-up, first-level execution, and second-level selection. Figure B.1 shows how these movement phases were determined from sample trials using click-open and walking menus. The x-axis on these graphs represent the elapsed time (in msec) for a trial. The zero point is determined when the first menu-level appears on the screen. Each tick mark represents 40 msec. The y-axis represents the movement of the cursor.

While the data file records the absolute position of the on-screen cursor in x and y coordinates, it is difficult to represent both these dimensions and time in a two-dimensional graph. Also, the parsing algorithms are not dependent on the direction of movement, but rather on the detection of movement in <u>any</u> direction, changes in mouse button status, and movement through specific screen coordinates. Therefore, these graphs increment the value on the y-axis for every time period that <u>any change</u> in position is detected. The "Change in Position" axis is an ordinal scale and does not represent the distance or the direction of the movement. It is, however, highly correlated with the principal direction of movement. Since it differentiates between periods of rapid movement and pauses in the movement trajectory, it is sufficient for our needs to parse the interval into segments.

Each box on the graphs corresponds to a change in either mouse position or button status that is detected by the data collection software. The connecting lines show the time delay between events. A slightly sloping



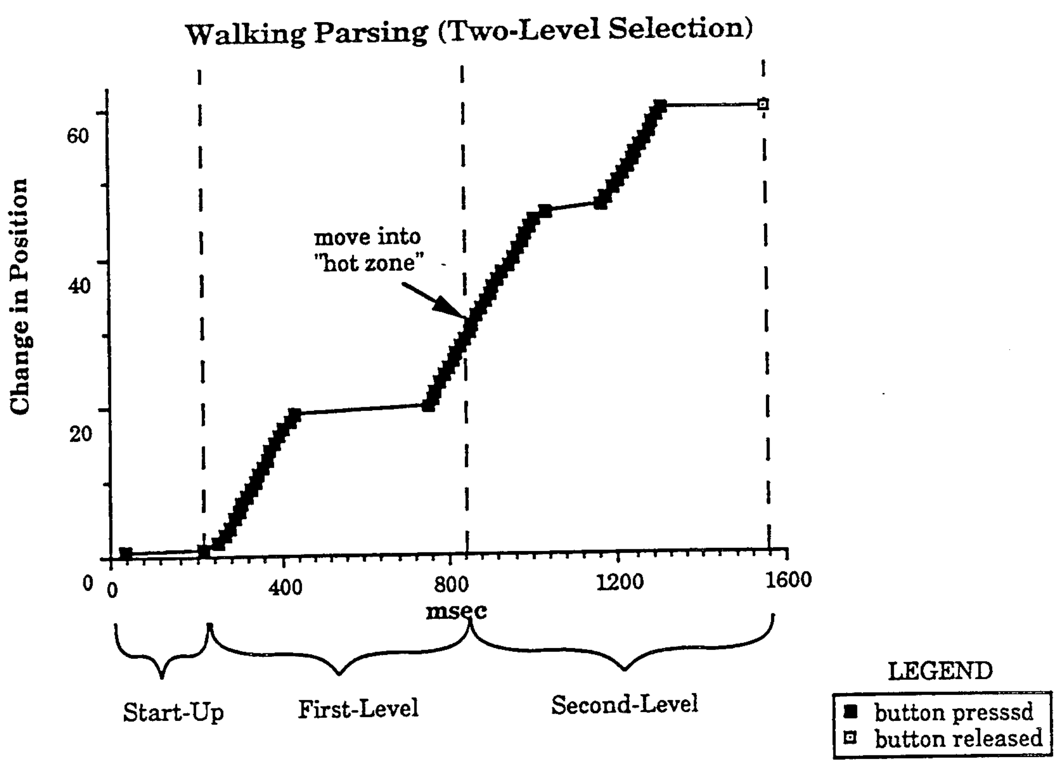


Figure B.1 Examples of Movement Phase Parsing for Two-Level Menu Selections (Experiments 1 & 3).

line between boxes of the same color represents a pause in the movement, followed by a change in position. A horizontal line between boxes of different colors represents a change in button status with no movement of the mouse. Finally, the vertical dashed lines, show the demarcations between the various movement phases. The rationale for determining these phases will be described in the next section.

Parsing Rationale for Movement Phases

Start-Up Phase

The operational definition for the start-up phase is identical for both click-open and walking menus in all of the analyses in this dissertation. It begins following the action to bring up the first-level menu (button click for click-open, and button press for walking), and ends when intentional movement of the mouse begins. A majority of the time, the ending point is the very first entry in the data file as shown in the click-open parsing example (top graph in Figure B.1).

Occasionally the first entry is very fast and followed by a significant pause before the next entry as seen in the walking parsing example (bottom graph in Figure B.1). This is caused by muscle tremor, or unintentional mouse movement which accompanies the pressing of the mouse button. To overcome this, the movement start is operationally defined as the first of three consecutive movements, each of which have a duration of less than 40 msec. This ensures that the movement is sustained and intentional. In the example at the bottom of Figure B.1, the first entry is considered to be in the start-up phase since it is followed by a pause greater than 40 msec. The second entry is identified as the end of the start-up phase since the two following entries occur in rapid succession.

First--Level Execution Phase

This movement phase commences when the subject begins intentional movement of the mouse, and ends when the second menu level is visible on the screen. The action which marks the end of this movement phase is different for the two menu styles. For click-open menus, the termination point is a button press anywhere in the target menu item, as shown in Figure B.1. For walking menus, it is signalled by moving the cursor into the "hot zone" region at the right of the target menu item. For these experiments the edge of the "hot zone" has an x coordinate of 51. The first entry in the data file which is in the target menu item and has an x coordinate of 51 or greater is specified as the end of the first-level execution phase.

Second-Level Selection Phase

This movement phase begins with the appearance of the second-level menu, and ends with the action that completes the menu-selection and causes the menu to disappear (button press for click-open, and button release for walking). The end of this movement phase is always the last entry in the data file for that trial.

Single-Level Menu Selection

Experiment 2 subjects selected from single-level menus. Figure B.2 shows how these movement phases were determined from sample trials using click-open and walking menus. These graphs are identical in form to those in Figure B.1. The determination of the start-up phase is also the

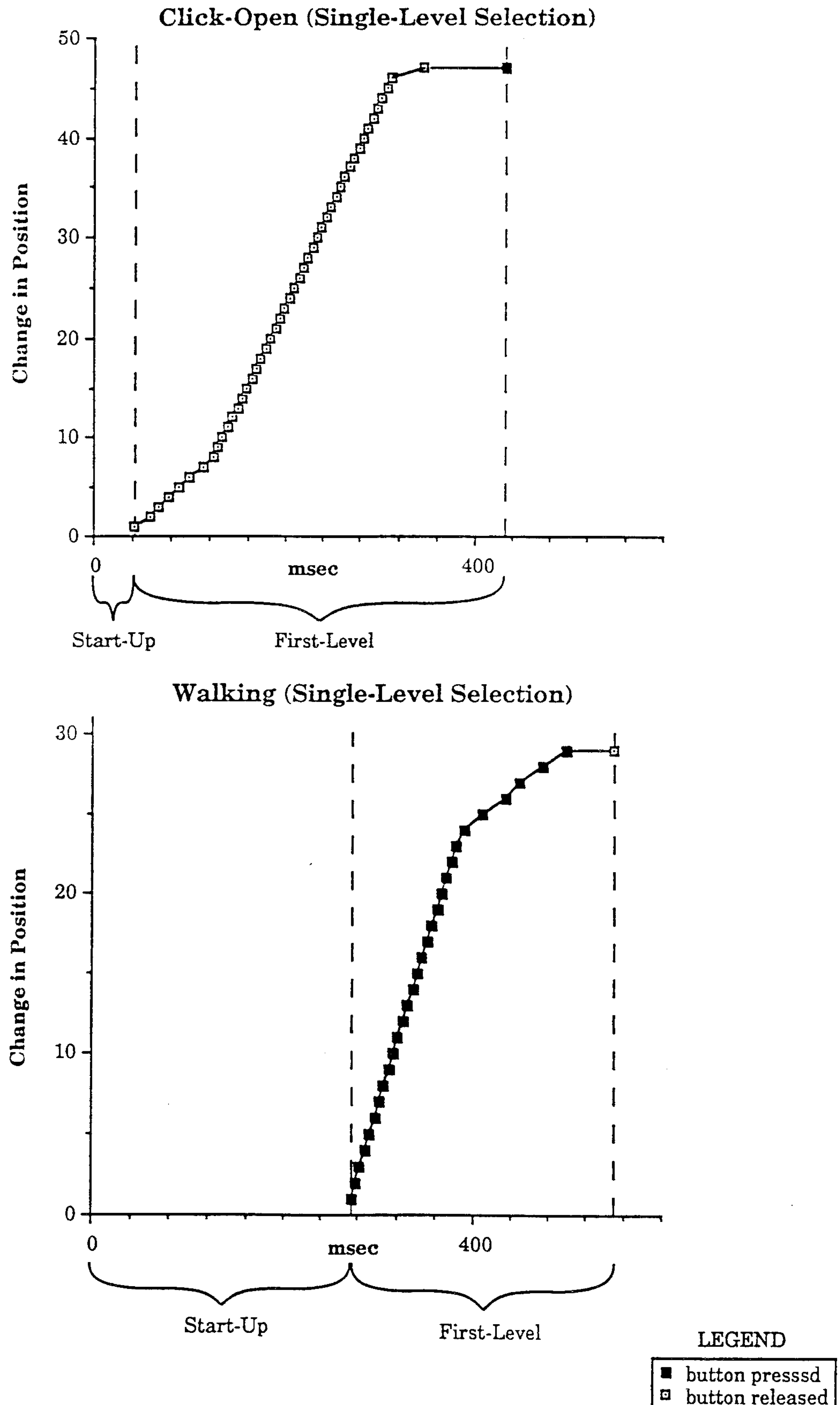


Figure B.2 Examples of Movement Phase Parsing for Single-Level Menu Selections (Experiment 2).

same as for two-level selections. The first-level execution phase, however, is different for single-level selections. This movement phase commences when the subject begins intentional movement of the mouse, and ends when a menu item is selected, causing the menu to disappear. The action which ends the selection is a button press anywhere in the menu item for the click-open menus, and a button release anywhere in the menu item for the walking menus. This action is always the last entry in the data file for a particular trial, as shown in Figure B.2.

New Movement Parsing for Single-Level Selections

In order to discriminate between two motor hypotheses for the button-depression effect, it was necessary to obtain a more detailed parsing of the single-level menu selections from Experiment 2. This was accomplished by taking the first-level execution phase, described in the previous section, and dividing it into two movement segments; the mouse movement phase, and the confirmation phase. This new movement parsing is shown in Figure B.3.

Here, the start-up phase is defined as in the previous analyses. The mouse-movement phase is identical for both click-open and walking menus. It begins with intentional movement and ends when the mouse movement ceases immediately before the final button action. This is always the second to the last entry in the data file and has the same x-y coordinates as the final button action. The confirmation phase is the time between the last mouse movement and the final button action (button press for click-open, and button release for walking). This is always the difference between the last and the second to last entry in the data file.

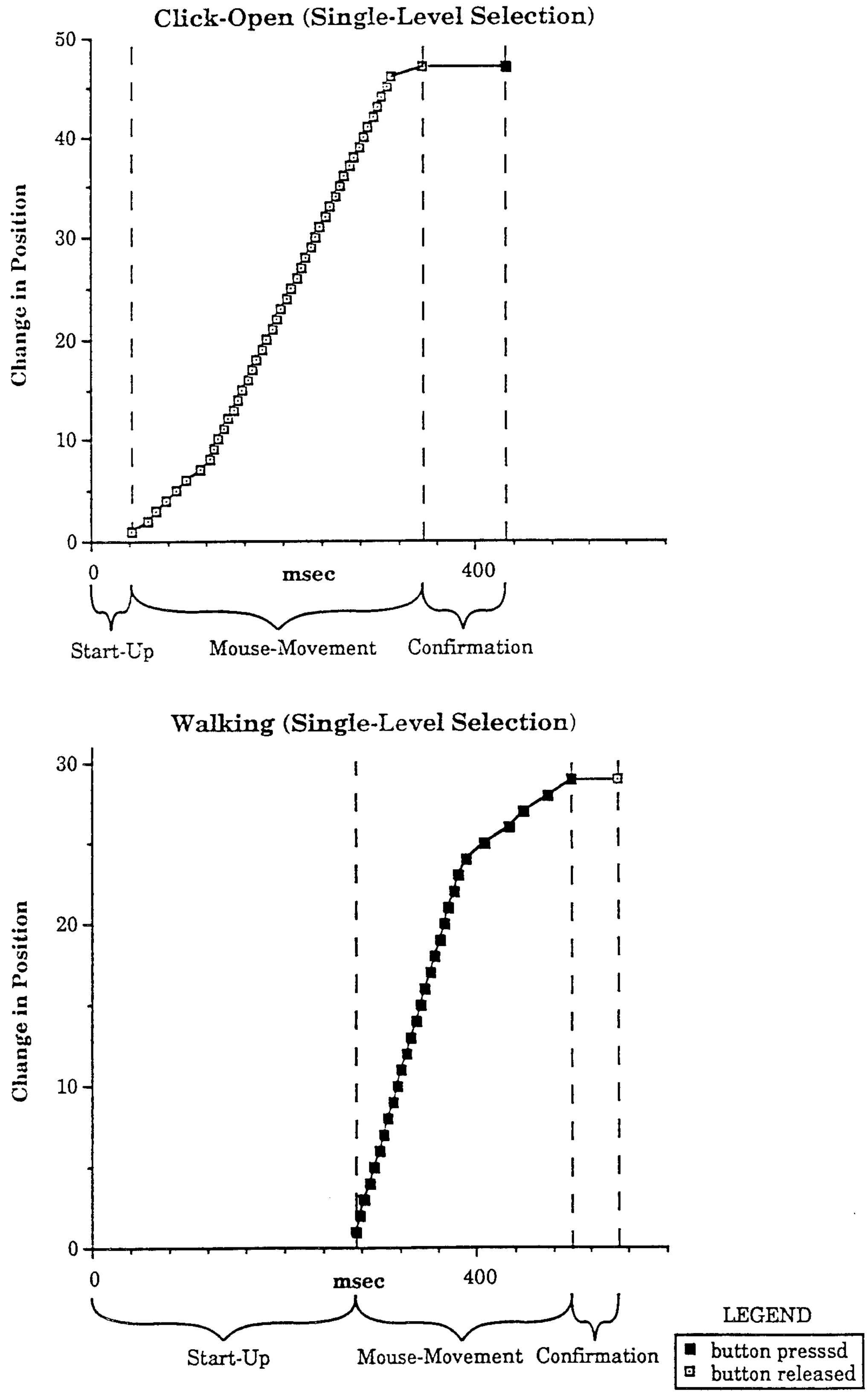


Figure B.3 New Movement Parsing for Single-Level Menu Selections (Chapter 6, Experiment 2).

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