Sc.D. DISSERTATION PROPOSAL

COMPLETION TIME PREDICTIONS FOR SECONDARY TASKS IN NON-STATIONARY ENVIRONMENTS

By

MARTIN J. SCHEDLBAUER

B.S. COMPUTER SCIENCE, UNIVERSITY OF LOWELL

M.S. COMPUTER SCIENCE, UNIVERSITY OF LOWELL

DEPARTMENT OF COMPUTER SCIENCE
UNIVERSITY OF MASSACHUSETTS LOWELL

April 28, 2005

Dissertation Advisor:

Dr. Jesse M. Heines, Department of Computer Science, University of Massachusetts Lowell

Dissertation Committee:

Dr. Giampiero Pecelli, Department of Computer Science, University of Massachusetts Lowell

Dr. Holly Yanco, Department of Computer Science, University of Massachusetts Lowell

Dr. Robert Pastel, Department of Computer Science, Michigan Technological Institute

ABSTRACT

COMPLETION TIME PREDICTIONS FOR SECONDARY TASKS IN NON-STATIONARY ENVIRONMENTS

Martin J. Schedlbauer

Computers are increasingly being used as assistive tools in settings away from the desktop. Examples of such computer systems include in-vehicle navigation systems, maritime electronic navigation systems, personal digital assistants, and mobile telephones, among others. Interacting with these computing systems is different in that the interaction task is not the user's primary task, but rather a secondary task to which less attention is paid and which is of less importance. In addition, the interaction frequently happens in a non-stationary environment, *i.e.*, one where the user and the computing device are moving.

The proposed research intends to investigate the questions whether completion time for a secondary task differs from that of a primary task and whether the activation of on-screen controls through manual input devices, such as a trackball, joystick, or touch screen, is unchanged when the environment is not stationary. Specifically, the proposed study seeks to determine if the present models for predicting task completion time still apply to secondary tasks in non-stationary environments. Due to the distractions of the environment, we hypothesize that the cognitive and motor performance of human operators are negatively affected and consequently total task completion time of the secondary tasks increases. We further conjecture that the motion of the environment requires that the quantitative models for predicting completion time, such as the Fitts and Hick-Hyman Laws, will need to be revised to provide an accurate estimate. The hypotheses will be investigated through a series of context-aware field and lab experiments which we hope will lead to a new engineering model.

The results of the research are expected to provide user interface designers of mobile computing platforms a set of heuristics for designing usable interfaces.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF EQUATIONS

1. INTRODUCTION

1.1 Motivation

This research was first considered when, in 2001, the author drove a rental car with a Garmin In-Vehicle Navigation System (IVIS) through Ohio. While the system proved very useful in guiding the driver, the interaction with a set of arrow buttons for destination entry was error prone, awkward, and frustrating to use while the vehicle was in motion. Clearly, the technology had significant potential, but usability was lacking.

Shortly after the above incident, the author experienced similar issues when using a newly developed interactive navigation system aboard his boat. Subsequently, the author conducted informal interviews that produced additional insights into the usability of interactive navigation systems and the findings presented further impetus for the proposed research. The boat was equipped with a Sea Ray Navigator (Maptech, 2003) navigation system. The Sea Ray Navigator is an embedded computer system that runs an electronic chart and information display (ECDIS.) Furthermore, it allows for interactive piloting of the yacht by simply point at destinations on the chart (see Figure 1). The Sea Ray Navigator is connected to a GPS antenna which provides the operator with real-time position information. The position of the vessel is plotted on the chart giving instant information as to the present location of the boat.

Over the span of two years, the author asked five experienced professional captains and four recreational boaters about their experiences with the Sea Ray Navigator while piloting various near-coastal routes along the U.S. East Coast aboard the author's boat. The Sea Ray Navigator (see Figure 1) installed on the boat had a 10" touch-sensitive display, although newer models employ a 12" display. A more sophisticated user interface notwithstanding, the Sea Ray Navigator was similar in functionality to the In-Vehicle Navigation System mentioned above. Likewise, similar operational issues surfaced when in actual use.

All of the interviewed subjects liked the intuitive nature of the touch-screen interface and much preferred it over the traditional key-button interface. In addition, everyone liked the clear display of the charts and the ease with which the charts could be panned by swiping ones finger across the screen. None of the subjects reported difficulty in learning the use of the system after a short tutorial. The chief complaints centered on the inaccuracy of the touch screen inputs, in particular during the selection of menu choices.

While none of the subjects expressed difficulty in entering waypoints (destination coordinates expressed as latitude and longitude) while at dock, several of the subjects indicated great difficulty in accurately entering waypoints while underway. In particular, they found that they had to concentrate for long periods of time on the display to make certain that they entered the coordinates correctly. The Sea Ray Navigator INS does not provide any tactile, visual, or auditory feedback during touch input. Furthermore, the current Sea Ray Navigator interface uses standard text fonts for menu items that are perceived to be too small leading to many selection errors.

Almost all of the subjects used their pointing finger to interact with the touch screen. One of the subjects, as well as the author personally, experimented using a pen as a stylus instead of their finger and found that input accuracy increased. However, while underway, the stylus was still too inaccurate in hitting targets as the vessel was simply too unstable. The difficulty in interacting with the Sea Ray Navigator as well as the Navman GPS, a second GPS with a simpler button interface instead of a touch-screen, was exacerbated during periods of heavy seas. Similar findings are reported by Husick (2003). During several voyages the subjects reported that they simply couldn't concentrate long enough on the screen to make sure that they entered the correct waypoints. Subsequently, they resorted to visual and compass steering instead of using the electronic navigation system.

Figure 1. Maptech Sea Ray Navigator with 10” screen. The navigation menus are at the extreme right edge. The bottom of the display contains navigational data, including speed, current vessel position, and depth under keel.

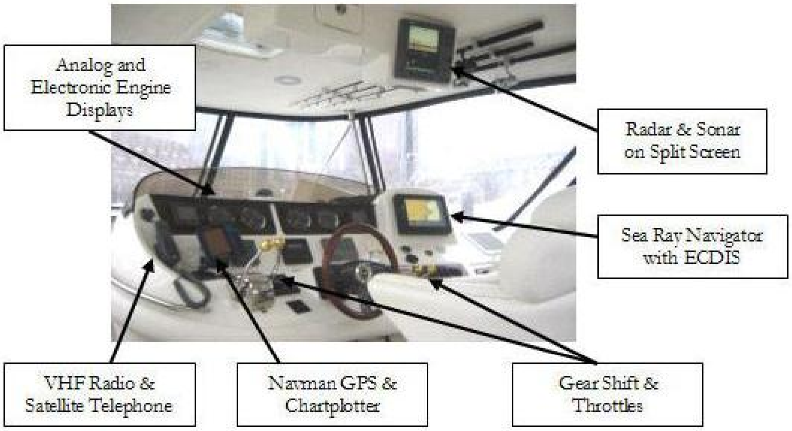


Figure 2. Helm configuration of the small craft on which the survey was conducted. The Sea Ray Navigator is located to the right of the helm center. The overhead console contains a multi-function display with Radar and Sonar. The Navman GPS is installed to the left of the helm center.

1.2 Problem

The experiences presented in Section 1.1 lead to several questions. First, do the input mechanisms presently used in integrated navigation systems work in randomly moving condition, such as heavy seas, rocky terrain, or limited visibility? In particular, how does the predominant use of touch screen interfaces impact usability and performance? In regard to this question, the study and applicability of currently accepted predictive models (Shneiderman, 2004; Jacko and Sears, 2004; Carrol, 2003; Hinckley, Jacob, & Ware, 2004) for input are important. Much of the published research pertains to environments where the operator (user) and the display are stationary, which would not be the case aboard a moving vessel or in an automobile? However, some research has been done in the context of mobile systems, such as PDAs and mobile phones (Pascoe, Ryan, & Morse, 2000.) Second, what impact does the size and layout of user interface controls have on total task completion time for common interactive tasks, such as destination entry or command selection? Furthermore, are keyboard, button, or dial interfaces easier to use in moving conditions compared to touch-screens that do not provide any tactile feedback? Finally, how does the task of driving distract from interacting with the navigation system and does this cause increased completion time?

2. PROBLEM ELABORATION

2.1 Research Question

The research considered in this dissertation effort looks at the question whether the accepted predictive models for estimating completion time of an interactive task apply to environments where the operator and the interactive application are not stationary, as would be the case aboard a moving vessel or in a moving vehicle? To further that point, is there a predictive model that provides estimates for how long an interaction with a system in a non-stationary environment will take given a particular input device?

2.2 Research Boundaries

The focus of the research will be on interactions in non-stationary environments, such as a moving vehicle, a boat, or even a walking user. Due to the lack of research in marine navigation systems, special attention will be paid to those interactions and the non-linear, near random motion of a small marine craft. Small marine craft are those that are small enough to be operated by a single person and do not employ active stabilization systems, which generally implies craft up to 65 feet in length. In addition to interactions on boats, the research will also consider interactions with wearable or hand-held systems, such as Personal Digital Assistants (PDA) or MP3 players, that are used while walking. While the movement pattern for walking is different from standing in a moving environment, the experiments are easier to control and the results can be used as a starting point for research in more complex motion environments.

Furthermore, the system interactions to be investigated by this study are restricted to manual input devices. Eye tracking or voice recognition interfaces are explicitly excluded from the study as those are much less likely to be employed in ubiquitous and mobile settings. For instance, voice input on a boat or even in a car is not practical due to the significant ambient noise.

2.3 Applicability

This research has the potential to provide a design methodology and empirical performance model for the design of computer systems for a variety of non-stationary environments. It holds the promise for an engineering model that, when applied by interface designers, increases the usability of the systems, reduces interaction errors, and therefore increases task completion time. Additionally, a predictive model for estimating movement and task completion time can be useful to application developers when designing graphical user interfaces for mobile and ubiquitous computing systems.

2.4 Organization of the Proposal

The proposal is organized into five main chapters: survey of input methods and devices, literature search of relevant research in human-computer engineering models for estimating interaction time, description of interactive systems for vehicle and boat navigation and their associated interaction patterns, a statement of the research hypotheses, and lastly an overview of the planned experiments.

3. SURVEY OF MANUAL INPUT DEVICES

3.1 Input Technologies

Users of computers must be able control and interact with application through user interfaces. The interactions can be categorized as either command selection, command response, or data input. Input is commonly in the form of alphanumeric characters, selection of an on-screen object through a pointing device, activation of a button, or environmental information from a sensor, such as temperature. An input device gathers physical information and translates the analog signal into a digital one for interpretation by the computer application. In some cases, the input device supports output and may provide tactile, haptic, visual, or auditory feedback to the user.

This chapter reviews the current state of manual input devices that are frequently deployed in mobile computing platforms and have the most potential for embedded system applications (Hinckley, 2003). Buxton (2005) maintains an online list of commercially available input devices.

3.1.1 Properties of Input Devices

The characteristics of the different input devices can be summarized by the set of properties described in Table 1.

Table 1. Characteristics and properties of input devices with accompanying definitions.

Property	**Explanation**
Sampling rate	The sampling rate determines how often measurements from the physical sensors embedded in the input device are taken and sent to the computer system. Increased sampling rates produce finer control over the input. Rates of 80 – 100 Hz. are common (Hinckley, 2003.)

Property	**Explanation**
Resolution	Resolution is a metric of the number of unique measurements the input device can send to the computer.
Latency	Latency, or lag, is the time that elapses between the physical actuation of the input device and the resulting on-screen feedback. Latency above 100 msec. interferes with cognitive performance and leads to increased error (MacKenzie and Ware, 1993.)
Noise	Noise is the result of sensing errors due to hardware malfunctions or design inadequacies. Increased noise leads to sampling problems and loss of accuracy.
Position mode	The position mode can be either absolute or relative. For an absolute input device, each position on the sensing surface corresponds to a specific location on the screen. In relative positioning mode, each input is a functional translation from the current point. A touch screen is an example of an absolute input device, whereas a mouse is a relative input device.
Gain	Gain is also referred to as the Control-Display (C-D) ratio. C-D is the ratio of the distance that the on-screen cursor moves in relation to the physical movement of the input device. An increased gain allows for a smaller footprint, *i.e.*, less space is necessary for the input device since a small movement of the input device causes a large movement of the on-screen cursor. The function that controls the gain (C-D ratio) is frequently configurable through software. Studies have shown that there is no optimal setting for gain (Accot and Zhai, 2001) and that increased gain frequently leads to higher error rates (MacKenzie, 1995.)
Physical property measured	Every input device measure one or more physical properties. The value of the measurement is translated into a digital signal by a transfer function. The sensed physical properties are

Property	**Explanation**
	commonly absolute position on a sensing surface, velocity, or force in one or more dimensions.
Degrees of freedom	Degrees of freedom is a measure of the number of dimensions that the input device senses.
Direct vs. indirect	If the input surface is also the display surface, then the input device is direct. An example of such a device is a touch-screen. Most other input devices are indirect in that the on-screen cursor is not directly controlled by the person, but rather through an intermediary device, such as a mouse, joystick, or stylus.
Footprint	Footprint refers to the amount of space that is required for input. For example, a mouse has a large and variable footprint, whereas a trackball has a smaller but fixed footprint.
Device acquisition time	Device acquisition time refers to the time it takes to grasp the input device before control can be exerted.

Most feedback from an input device is in the form of on-screen movement of a cursor. While the actual shape of the cursor is programmable, an arrow head has become the *de facto* standard. To accommodate smaller screen sizes and visually impaired users, designers of graphical user interface have resorted to increased on-screen cursors. While larger cursor may help with selecting on-screen objects, the shape and form of the cursor may be distracting. For example, empirical evidence collected by Phillips, Triggs, and Meehan (2001, 2003) suggests that the direction in which the arrow head of the cursor is pointing and the size of the cursor shape have a negative impact on reaction time and correct target acquisition.

In some application area, haptic, or force, feedback may be useful. A pointing device that provides haptic feedback can guide the user along a particular path. As the user veers off the correct path, the pointing device makes further movement in that direction more difficult.

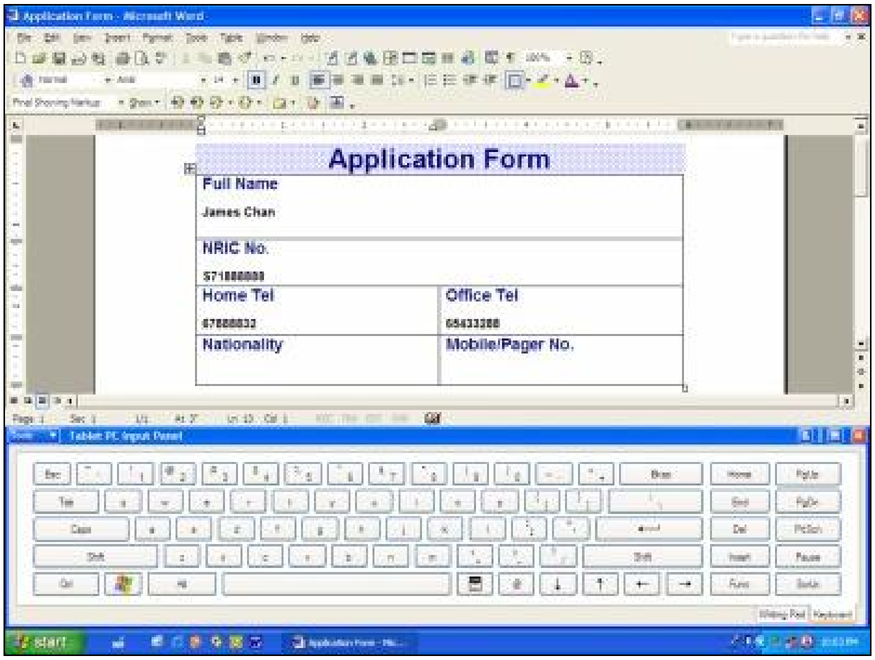
3.2 Taxonomy of Manual Input Devices

3.2.1 Physical and Soft Keyboards

Typewriter-style keyboards represent the most ubiquitous input device. Keyboards are familiar to users and require little learning time. Most keyboards include the full alphanumeric character set coupled with a collection of application programmable function keys for facilitating common input tasks. The trend of keyboard design appears to go in two directions. On the one hand, ergonomic considerations have forced manufacturers to redesign the keyboard to alleviate discomfort during prolonged use (McFarlane, 1996). Such design changes include splitting keyboards into angled arrangements, resizing and respacing keys, adding wrist resting pads, and increasing tactile key-level feedback. On the other hand, keyboards are being miniaturized to accommodate mobile computing devices, such as personal digital assistants (PDA) and mobile telephones.

For systems where a physical keyboard is not practical, a soft, or virtual, keyboard is often constructed using a touch-sensitive screen (see Figure 3). Due to the lack of space, soft keyboards often contain a limited character set and typing is done with fingers or a special stylus (Kölsch & Turk, 2002). The arrangement of the keys differs frequently from the traditional QWERTY layout. More recent models for the layout of soft keyboards, including CHUBON, FITALI, OPTI, and Metropolis have been found to increase the speed and accuracy of text input (Zhai, Hunter, & Smith, 2000). However, while optimized layouts of soft keyboards may improve the text entry speed of expert users, a study by MacKenzie and Zhang (2001b) demonstrated that novice users had significantly lower text entry rates compared to a standard QWERTY layout. This would imply that non-standard keyboard layouts require significant learning time and therefore should be rejected for public access devices or systems that are used sporadically by non-expert users. Nevertheless, using a QWERTY layout means that the user is required to move the stylus more frequently for common English words. After all, the QWERTY layout was invented to slow down the user in an effort to reduce jamming of the mechanical keys when mechanical keyboards were still commonplace. As a result, on a QWERTY layout the text entry rate is diminished (Zhai, Kristensson, & Smith, 2004a). Experiments by Soukoreff and MacKenzie (1995b) fix the theoretical upper bound for text entry on a soft QWERTY keyboard operated with a stylus at 30.1 words per minute.

Although soft keyboards have their limitations they are well-suited for mobile and ubiquitous computing systems where a physical keyboard is not practical. The alternative of using natural hand writing recognition is not realistic. The software algorithms are still to immature which results in recognition errors and slow response time. Consequently, hand writing recognition is not appropriate for mobile system where users are typically distracted by other tasks and cannot focus on the input operation. In addition, if the environment is not stable, drawing with a stylus is difficult.



Application Form

Full Name
James Chan

NRIC No.

Home Tel

Office Tel

Nationality

Mobile/Pager No.

Figure 3. Tablet PC running Microsoft Windows. Touch typing is supported with a virtual keyboard that appears on demand. The keyboard depicted features the standard QWERTY layout.

While soft keyboards have been adopted by designers of ubiquitous computing devices, their use requires significant visual attention due to the absence of tactile feedback. Recent research has reported success with embedding tactile force-feedback mechanisms into touch screens to make it possible to operate soft keyboards in low-visibility situations (Poupyrev & Maruyama, 2003; Nashel & Razzaque, 2003). In the absence of physical tactile feedback, studies report that simulated tactile or auditory feedback is often accepted as natural and that users did not prefer a physical keyboard over a soft keyboard when feedback was present (Oniszczak & MacKenzie, 2004).

Text entry on mobile telephones has been accomplished by overloading each numeric key with a letter (see Figure 4). Entering a character requires that the overloaded numeric key is pressed several times until the desired character appears in the input area. A more recent linguistic approach, called T9, has been added to many mobile phones. T9 searches a dictionary of common English words and attempts to predict which key is needed. Consequently, with T9 only one key stroke is required for most characters. An experimental study by Silferberg, MacKenzie, and Korhonen (2000) pegs the expert rate of text entry at 25 works per minute for standard multi-tap input and at 41 words per minute for T9. Text entry with T9 had an accuracy of approximately 95%.

Figure 4. Mobile phone keypad on which alphabetic characters are added to each numeric key. Text entry is accomplished through repeated pressing of the numeric key. For example, entering the letter 'v' requires that the number '8' is hit three times.

3.2.2 Mouse Devices

The mouse, along with the keyboard, represents the most commonly used manual pointing device. A mouse is a relative and indirect input device that reports movement velocity which is translated into an on-screen cursor movement. See Figure 5 for some examples of modern mouse designs that contain additional input mechanisms, such as one or more push buttons, scroll wheels, sliders, trackballs, and toggles (Buxton, 2005) For proper operation, a mouse requires a stable, flat surface.

Figure 5. Mouse devices from Microsoft, Logitech, and Genovation. Modern mouse input devices contain selection buttons, finger operated wheels, music controls, internet browser controls, keypads, scroll sliders, and application programmable buttons (Logitech; Microsoft; Genovation.)

However, because of the footprint required for proper operation of a mouse, it is not suitable for mobile computing systems. Many of the mouse designs presently manufactured offer wireless connections to the computer, thus at least allowing for remote operation.

3.2.3 Trackball

A trackball is basically an upside down mouse, where the roller mechanism is placed at the top and positioning is accomplished by spinning the ball (see Figure 6). The footprint of a trackball is fixed and much smaller than that of a mouse. Buttons for activating commands are frequently mounted to the side. Manufacturers of trackballs have been able to miniaturize the physical size of the trackball to such a degree that small trackball devices can be mounted on laptops.

Figure 6. Logitech trackball mounted on top of a mouse device Several buttons as well as thumb wheels are mounted on each side to activate selection, scrolling, and panning functions.

3.2.4 Touch Screen

Touch screens are essentially translucent touch pads mounted on top of a display. The use of touch screen technology eliminates the need for additional input devices, such as a keyboard or a pointing device. Pointing to an object on the touch screen is natural and direct and proceeds without an intermediary device that might distort the interaction. Touch technology requires a high sampling rate otherwise the user will encounter selection errors when trying to hit a target that is close to other targets. Since touch screens do not provide push buttons, separate actions are not possible. In addition, dragging, dropping, and scrolling are more cumbersome to achieve. Figures 7, 8, and 9 show several examples of touch screen enabled systems. Depending on the touch technology in use, selection of an on-screen target can be done with either a finger or a stylus. While less convenient, pointing with a stylus is often found to be more accurate.

Figure 7. Finger-operated touch screen device.

Figure 8. Stylus-operated handheld device with a touch screen.

Figure 9. Finger-operated soft (virtual) keyboard on a public access internet kiosk.

3.2.4.1 Touch Screen Technologies

Presently, there are several technologies used in the manufacture of touch screens. Among them are 4-wire resistive, 5-wire resistive, capacitive, surface acoustic wave, near field imaging, and infrared technologies (Mass Multi Media, n.d.). Each technology has certain pros and cons, such as cost, accuracy, reliability, and applicability in dirty or humid environments. 4-Wire and 5-Wire touch technologies represent the low-end of the spectrum. They are reliable, affordable, and due to their pressure sensitive touch mechanism they can be operated with a finger, gloved hand, or stylus. Surface acoustic technology introduces the least image distortion and therefore works well in applications where image clarity is important. However, surface acoustic technology does not work well in dusty environments. Near field imaging touch screens represent the high end of the technology spectrum. They provide excellent image clarity, extreme durability in harsh environments, and are not affected by surface scratches. Operation is possible with finger, gloved hand, or stylus.

3.2.4.2 Visual, Tactile, and Auditory Feedback

Despite the intuitiveness of touch screens, research has shown that the absence of sensory feedback has a significant negative effect on interaction time and accuracy (Akamatsu, MacKenzie, & Hasbrouc, 1995). Users have to spend additional time verifying that their input was correctly received by the computer. Furthermore, the lack of tactile feedback makes touch typing and blind operation impossible. However, recent advances in materials technology has made it possible to add tactile feedback to touch screens (Poupyrev & Maruyama, 2003; Nashel & Razzaque, 2003). In the absence of tactile feedback, Oniszczak and MacKenzie (2004) report that visual or auditory feedback is accepted as natural and those users did not express a preference for a physical keyboard. While tactile feedback produces the most natural feel for a touch screen interface and produces the most effective input method, visual and auditory feedback are almost as good. Auditory feedback works best in situations when the user is distracted and cannot look at the screen for extended periods of time (Buxton, 2005).

3.2.5 Touch Pad

A touchpad is an input device that senses the motion of a finger as it glides over the pad. It is commonly used as a substitute for a computer mouse, particularly in space constrained environments since a touchpad has a fixed footprint (see Figure 10).

A touchpad is a touch-sensitive device that operates by measuring the capacitance that builds up when a person's finger touches the pad. Capacitive electrodes are laid out in a grid fashion inside the touchpad and behind a protective cover. The position of the finger can be derived by sensing which capacitors inside the capacitive layer are charged. In order to function, touchpads require a finger and do not operate with a gloved hand or stylus. Additionally, a change in the electrical properties of a person's finger, *e.g.*, a wet finger or a very humid environment, affects the operation of the touchpad. Touchpads, like mouse devices, are relative motion devices. Most touchpads emulate a button click through tapping.

Figure 10. Synaptics touch pad. It senses a person's finger motion and translates the motion into a relative movement of an on-screen cursor .

3.2.6 Joystick

A joystick is an input device that pivots about its center and the angle of displacement from the center controls an on-screen cursor. Like the touchpad, a joystick has a fixed footprint. The angle of displacement can be measured in one of two ways: an actual deflection from the center (isotonic joystick) or a sensing of the force applied to the joystick (isometric joystick). Isotonic joysticks have a tiny footprint and thus work well in space constrained environments. The IBM Thinkpad introduced the “G” mouse, a tiny pencil eraser like joystick mounted next to the “G” key on the keyboard (see Figure 11). The commercial name for this device is a TrackPoint™.

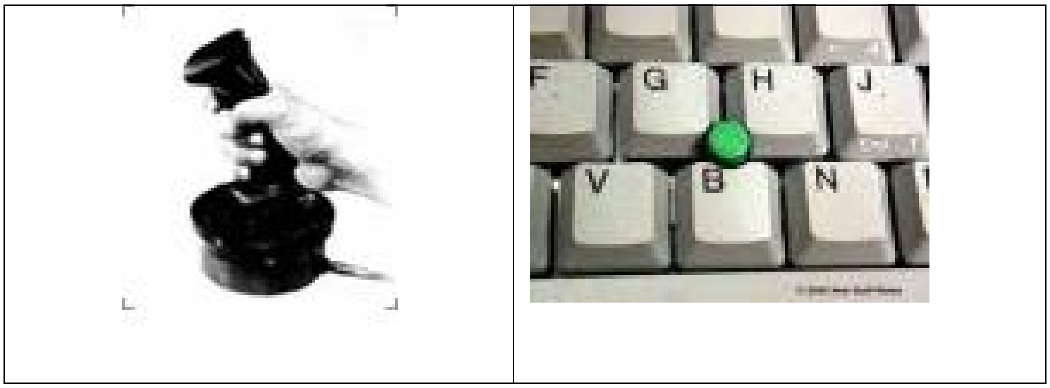


Figure 11. Isotonic (force type) industrial joysticks from Ultra Electronics Measurement Systems, Inc. and IBM. Isotonic joysticks do not move from the center point. Instead the force applied to the joystick is measured.

3.2.7 Comparison of Input Devices

This section presents a comparison of the reviewed input devices based on a set of criteria important for mobile applications. Table 2 summarizes the criteria.

Table 2. Comparison of input devices based on criteria important in mobile computing platforms.

Input Device	**Footprint**	**Positioning**	**Control**	**Feedback**	**Impact of Humidity**	**Impact of Dirt**
Physical Keyboard	Fixed/Large	N/A	N/A	Tactile & Auditory	None	None
Soft Keyboard	Fixed	N/A	N/A	Visual & Auditory	None	None
Mouse	Variable	Relative	Indirect	None	None	None
Trackball	Fixed	Relative	Indirect	None	None	None
Touch Screen	Fixed	Absolute	Direct	Visual	None	Yes
Touchpad	Fixed	Relative	Indirect	None	Yes	Yes
Isometric Joystick	Fixed	Relative	Indirect	None	None	None
Isotonic Joystick	Fixed	Relative	Indirect	None	None	None

4. COGNITIVE AND MOTOR-PERCEPTUAL PREDICTION MODELS

4.1 Univariate and Bivariate Aiming Tasks

Understanding the processes that guide human motor performance is critical in the engineering of usable computer systems. In particular, being able to quantify the production of rapid aiming movements with hands, arms, and fingers has important consequences for human-computer interface (HCI) design. The advancement of engineering models that accurately predict human motor behavior is of great interest to HCI developers. Rapid aiming movements, such as guiding a pointing device to a particular location in a graphical user interface (GUI), are among the most important interaction mechanisms. Movement tasks in GUIs are either spatially or temporally constrained. Spatially constrained movement tasks are those where a target must be hit as accurately as possible while minimizing the average movement times. In contrast, in a temporally constrained movement task, the movement must end at a particular point and must be completed in a certain period of time. Most GUI selection tasks fall into the category of spatially constrained movement tasks. Spatial constraints can be along one dimension (univariate aiming tasks) or two dimensions (bivariate aiming tasks).

One of the earliest and most broadly applied engineering models is Fitts' Law (Fitts, 1954). In his groundbreaking work, Fitts discovered a logarithmic relationship between the spatial accuracy and the duration of rapid limb movements for univariate pointing. The mathematical quantification of speed versus accuracy has established itself as a cornerstone technique for the evaluation of human-computer interfaces. Card, English, and Burr (1978) were among the first to apply Fitts' discoveries to man-machine interfaces when they used Fitts' Law to correctly predict word selection performance in a word processor using either a mouse or a keyboard. While Fitts' original work was directed at rapid aiming movements with a hand-held stylus, numerous studies have demonstrated that Fitts' equations hold for a variety of other human motor processes, such a wrist flexion, saccadic eye movement, foot movement, and finger manipulation (Crossman & Goodeve, 1983; Langolf, Chaffin, & Foulke, 1976; Jagacinski, Repperger, Moran, Ward, & Glass, 1980b).

Since the original publication of the work by Card *et al.*, Fitts' Law has been successfully applied to a variety of HCI domains. Additionally, Fitts' Law has spawned an entire field of research that has resulted in a number of additional engineering models for HCI. An exhaustive review of all of the related research would be a monumental task. At the time of this writing, a Google search for the term "Fitts' Law" resulted in 66,300 matches. An online bibliography maintained by MacKenzie (2002) lists 310 articles. The law has found application beyond HCI and shown itself useful in sports medicine, biomechanical engineering, and animation science (Rosenbaum & Gregory, 2002; Bodenheimer, Shleyfman, and Hodgins, 1999).

The original experiments conducted by Fitts asked subjects to carry out several tapping tasks with a 1 oz. and a 1 lb. stylus. In one experiment, the subjects simply alternated back and forth between two plates (reciprocating task.) A second experiment, shown in Figure 12, measured discrete tasks. This experiment differed in that the subjects did not alternate between tapping two plates, but rather a light above each plate told them which one to tap. The subjects rested the stylus at a homing point equi-distant between the plates when not in use. The results of both experiments were similar and pointed to a correlation between the average duration of the movement and the extent of the target along the axis of movement. Fitts' original goal was to measure the *information capacity* of the human motor system and to mathematically quantify how accurately the motor system can carry out rapid movements to a specific spatial region.

Fitts assumed that the taps were done as quickly as possible without any user induced delay in the motion, *i.e.*, the absence of any decision lag. In addition, there were no variations in the tasks and therefore no learning was involved. The measured motor system responses were based on the presence of the entire perceptual feedback loop taking into account visual and proprioceptive input. In this context proprioceptive refers to the sense of the position of ones own body parts in relation to other body parts. Proprioceptive sense derives from the inputs of neurons located in the inner ear as well as the muscles of joints. There is some evidence that the absence of visual feedback invalidates Fitts' theories (Friedlander, Schlueter, & Mantei, 1998). A change in proprioception likely leads to a change in the validity of Fitts' observations.

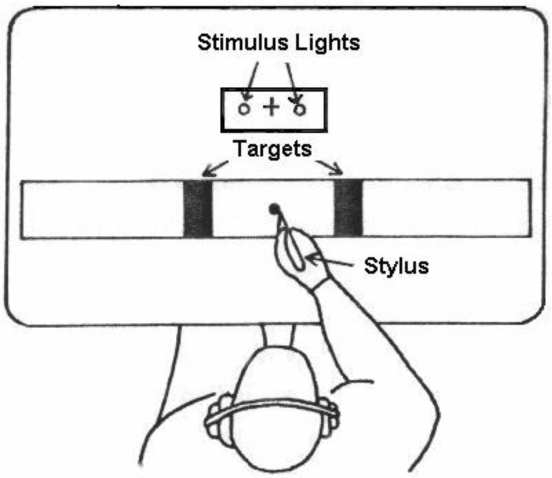


Figure 12. Discrete Tapping Experiment (from MacKenzie, 1991). In this experiment the user taps on the target indicated by the stimulus light. The discrete experiment is one of several tasks that subjects carried out in Fitts' tests.

4.1.1 Classic Representation of Fitts' Law

Essentially, Fitts' Law offers a predictive model for estimating the time it takes to point at a particular element on the screen, based on the size of and distance to the target element. Recent variations discussed later in this chapter provide additional engineering models for estimating the mean time it takes to acquire a target using different pointing techniques. Acquisition of a target can mean clicking on a screen object with an indirect pointing device, such as a mouse or joystick, or directly selecting it on a touch-sensitive screen. The model is well established and has been empirically validated for a variety of pointing tasks and input devices (MacKenzie & Soukareff, 2003; McGuffin, 2002; Hinckley, Jacob, & Ware, 2004).

The original formulation of Fitts' Law as applied to user interface design by Card, Moran, and Newell (1978) expresses the average time T it takes to tap a target with a mouse-controlled cursor from a fixed point as a linear function of the Index of Difficulty (*ID*):

$$T = k \times ID \tag{1}$$

where $k \approx$ 100ms, although many other constants have been reported (MacKenzie, 1995).

The Index of Difficulty (*ID*) is expressed by Fitts (1954) as:

$$ID = \log_2(\frac{2D}{W}) \tag{2}$$

where D is the distance that the user has to move from a home point to the target (also referred to as the amplitude of the movement) and *W* is the width of the target (see Figure 13). In Fitts' experiments, the amplitude or distance of the movement was assumed to be along a direct horizontal path, *i.e.*, along one dimension. The direction of movement from left to right or right to left has been shown by Oel, Schmidt, and Schmitt (2001) to be inconsequential.

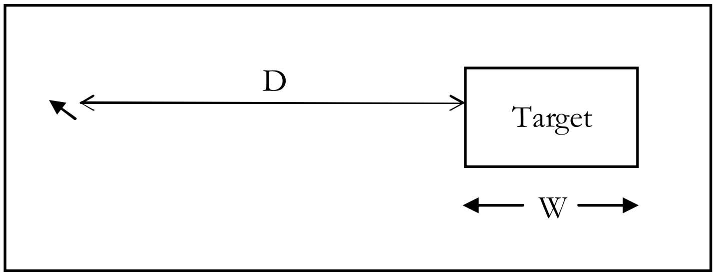


Figure 13. A one dimensional Fitts movement along a direct path of length D from the cursor to the target with width *W*.

Many researchers report an improved fit when using the formulation suggested by Welford (1960) for the Index of Difficulty (*ID*).

$$ID = \log_2(\frac{D}{W} + 0.5) \tag{3}$$

A more general format for the Index of Difficulty (*ID*) can be stated as:

$$ID = \log_2(\frac{D}{W} + \varepsilon) \tag{4}$$

where ε has one of several values depending on the formulation. Table 3 describes the different formulation of *ID* and their associated values for ε.

Table 3. Formulations for ID and associated values for coefficient ε.

Formulation	ε
Fitts	D/W
Welford	0.5
Shannon (MacKenzie)	1

Subsequent research (Card *et al.*, 1978; Welford, 1960; MacKenzie, 1991) suggests that adding a degree of freedom to the original formulation to change the intercept of Equation 1 provides even further improvement to the fit of experimental data. The equation for mean movement time then becomes:

$$T = a + k \times ID \tag{5}$$

where *a* and *k* are constants derived through regression analysis. The values for *a* vary with the input device and the nature of the target acquisition process.

When using a finger a lieu of a stylus, experiments by Hoffmann and Sheikh (1991b) uncover an overestimation of the *ID* and an overestimation of the movement time. They suggest that the *ID* must contain an adjustment for the width of the probe, *i.e.*, the finger or stylus. This has implications to the use of Fitts' Law for estimating movement times on soft keyboards and touch-screen interactions. They suggest that the thickness of the probe be added to the target width.

In practical terms, Fitts' Law suggests that moving buttons closer to the user's home position and making commonly used buttons larger creates a more usable user interface, since that will minimize the mean movement time to an on-screen user interface control. Of course, since Fitts' Law models motor-perceptual performance of a human, we can expect differences between younger and older users and those with motor behavioral disabilities (Worden, Walker, Bharat, & Hudson, 1997). However, while there are observed differences in the constants, the linear correlation between *ID* and *T* remains. Furthermore, the same correlation is observed for adults, older children, and even people with cognitive retardation (Wade, Newell, & Wallace, 1978; Latash, 1996; Kerr, 1975), pointing to the generality of Fitts' analysis and its general validity as a human-computer interface evaluation metric. Although, the movement patterns of pre-school children do not appear to conform to the predictions of Fitts' Law when targeting regions using a mouse (Hourcade, Bederson, Druin, & Guimbretiere, 2003).

The validity of Fitts' Law has also been established for numeric and text input on soft keyboards using a stylus (Soukoreff & MacKenzie, 1995b; MacKenzie & Zhang, 1999; Zhai, Kristensson, & Smith, 2004a). A soft keyboard is one that is simulated on a touch sensitive screen (see Figure 3). When entering text on a soft keyboard, the user taps the stylus on the desired key, rests the stylus on that key, and then moves to the next key. Therefore, movement is characterized by hopping from one key to another, rather than moving from a home position to a key. The mean time to move from key *i* to key *j* on a soft keyboard can be modeled by Fitts' Law:

$$T_{ij} = a + k \log_2 \left(\frac{D_{ij} + W_j}{W_j} + \varepsilon\right) \qquad (6)$$

where W_j is the size of the destination key, D_{ij} is the distance between the keys, and a, k, and ε are empirically determined coefficients. If the mean distance can be kept low, text entry rates can be increased. A minimization of the mean distance between key strokes can be accomplished by changing the layout of the keyboard based on common English language words. A study by MacKenzie and Zhang (1999) shows a significant increase in the input rate when a more optimal keyboard layout is chosen, rather than the standard QWERTY layout. Their paper suggests an optimal layout of keys based on minimizing the average movement for a dictionary of English words. Their improved layout, termed OPTI, provided a 35% increase in typing speed. However, while optimized layouts of soft keyboards may improve the text entry speed of expert users, a different study by MacKenzie and Zhang (2001b) demonstrated that novice users had significantly lower text entry rates compared to a standard QWERTY layout.

Francis (2000) proposes a similar model to describe the time required to navigate a hierarchy of soft menu buttons in a multi-function display (MFD). However, unlike the model of Equation 6, Francis argues that button navigation in an MFD, such as an automated aircraft cockpit or an automated teller machine, does not necessarily require a movement between buttons when repeated selections are made. In addition, the experiments by Francis demonstrate that Fitts' Law does not adequately estimate the movement times for soft menu buttons. In particular, the movement between buttons may go from one side of the screen to the other or it may simply go to an adjacent button. For some tasks, the user may use two hands or two fingers, thus invalidating Fitts' assumptions. As a result, interactions with multi-function displays are more complex than typing on a soft keyboard.

Furthermore, it is important to note that the various formulations of Fitts' Law do not account for the time spent grasping and calibrating the input device and that users move as quickly and as accurately as possible to the target, *i.e.*, rapid aimed movements. In addition, there is little or no time spent in deciding which target to select in the presence of multiple targets. Furthermore, it is assumed that there is no difference in movement time between the 1st and the nth repetition of the target selection, *i.e.*, there is no learning time. If these conditions are not met, then Fitts' Law will not provide useful forecasts (MacKenzie, 1991; Meyer, Abrams, Kornblum, Wright, & Smith, 1988; Meyer, Smith, Kornblum, Abrams, & Wright, 1990).

While at first glance this law might appear obvious, it is among the most commonly ignored user interface design principles (Toggnazzinni, 1999). Often, buttons are made too small and spaced too closely together making them difficult to hit. The toolbar found in many Microsoft Windows applications provides a contrasting example. In most applications, users have the option to display a textual label underneath the tool icon instead of only a small image. Users find clicking the labeled icons easier because they are larger. Fitts' Law states an inverse relationship between size and acquisition time: narrower objects take longer to acquire, whereas wider objects take less time.

Humans appear to have a tendency to recognize "correct" motion if it behaves according to the logarithmic function of Fitts' Law. Bodenheimer, Shleyfman, and Hodgins (1999), programmed that function into the animated behavior of on-screen synthetic characters with the goal of guiding the timing of their movement when reaching for a virtual object. Observers found that the resulting movement is more "live-like" and "smoother".

4.1.2 Approach Angle Adjustment

The width W of the target in Equation 4 is the extent along the axis of movement. Fitts did not consider height of the target as his experiment had the user start out between the two targets and movement was restricted along the horizontal axis (see Figure 12). When the approach to the target is from an angle, an adjustment must be considered for W since the "width" is not simply the horizontal or vertical extent of the target (see Figure 14). In this case, W becomes a function of the approach vector. MacKenzie and Buxton (1992) present a formulation for W that considers the actual extent of the target along an approach vector. The approach vector is placed from the homing point to the center of the target. MacKenzie and Buxton provide empirical data for a number of different measures for the effectual width $W(\varphi)$ as a function of the approach angle φ. They provide the following definitions for $W(\varphi)$:

$$
\begin{aligned}
W^{a}(\varphi) &= W + H \\
W^{b}(\varphi) &= W \times H \\
W^{c}(\varphi) &= \min\left\{\frac{H}{\sin\varphi}, \frac{W}{\cos\varphi}\right\} \\
W^{d}(\varphi) &= \min\{H, W\}
\end{aligned}
\tag{7}
$$

where H is the height of the target, W is the width of the target, and φ is the approach angle to the target. According to MacKenzie and Buxton, the last two formulations (W^c and W^d) provide the best fit with the observed data, although the differences between all of the formulations for $W(\varphi)$ were not very large.

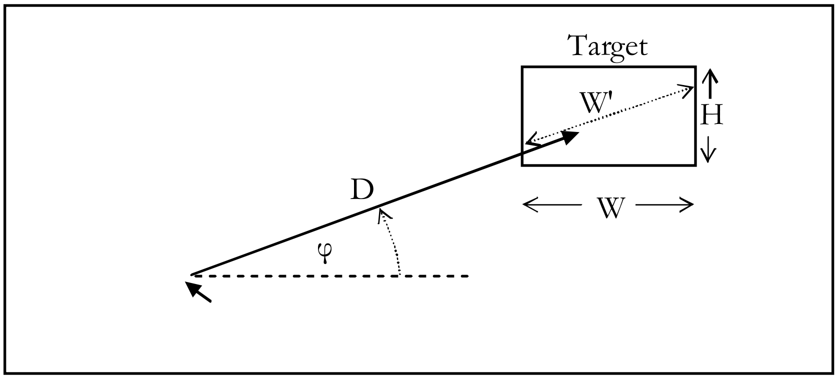


Figure 14. Approach to target from an angle (after Accot and Zhai, 2003).

Murata, Fujii, Arima, and Iwase (1999) extend the calculation of the effective target width to approach vectors that do not cross through the target's center. They apply a joint probability density function to obtain a probable target width based on the homing point and the location of the target in a two-dimensional space. Their approach has greater potential to be extended to non-rectangular targets, such as round or polygonal targets, although further research on this topic is necessary. Although, experiments by Sheikh and Hoffmann (1994) in which subjects were asked to hit triangular, circular, and polygonal targets, find that movement times for non-rectangular shapes are increased.

Whisenand and Emurian (1995) conducted a study in which subjects were asked to hit icon-like targets of varying sizes from different angles using a mouse. They report an increase in movement time when the approach angle was not horizontal. Any approach of a rectangular target from an angle that is not parallel with any of its sides will result in a longer distance. While Whisenand and Emurian did not provide an explanation of the increase in movement time, one can surmise from Equation 4 that an increase in the distance D yields an increased value for T. However, Equation 4 cannot account for the differences in mean movement times reported by Whisenand and Emurian between vertical and horizontal movements of the same distance. Their experiments found that movements along the horizontal axis were faster. In addition, they observed that upward movements were less efficient compared to downward movements.

These results were corroborated by Thompson, Slocum, and Bohan (2004). Their study also found a significant inverse relationship between movement time, gain, target sizes, and angle of approach. They also report that vertical movements took longer than horizontal movements. According to Thompson *et al.*, a decline in up-down movement performance is possibly due to the "horizontal-vertical illusion (HVI)," a well-known optical illusion in which humans tend to perceive vertical lines as longer than horizontal lines. The differences in perception may have an effect on movement planning. They further theorize that biomechanics may be at the root of the performance difference. Vertical movements involve additional limbs compared to horizontal movements. The use of additional limbs and associated muscle groups may explain the increase in movement time along the vertical.

4.1.3 Information Theoretical Foundation of Fitts' Law

Fitts' seminal work extends the theories of information transmission to the human motor system. He argues that the human motor system can be thought of as a transmitter of information, where transmissions are motor behavioral responses. Fitts applies, based on the results of his experiments, the Shannon-Hartley theorem (Shannon and Weaver, 1949; Wikipedia, n.d.) regarding capacity of an analog communication channel that is subject to white (Gaussian) noise. The Shannon-Hartley theorem allows one to calculate the maximum amount of error-free digital data that can be transmitted over a noisy communication link with a specified bandwidth. McGuffin (2002) and MacKenzie (1991) each present succinct derivations of Fitts' Law from the Shannon-Hartley theorem.

4.1.4 Index of Performance

To better describe the performance of a certain input device for particular interaction tasks, throughput is important. Fitts originally refer to *1/k* from Equation 5 as the *Index of Performance* or *bandwidth*. In today's literature, Index of Performance is called *throughput* (*TP*) and is calculated as:

$$TP = \frac{ID}{\tau} \tag{8}$$

where *ID* is the mean Index of Difficulty from Equation 4 and τ is the mean movement time (*T*) from Equation 5 observed in repeated trials. *TP* is measured in bits/second.

The throughput as defined in Equation 8 has been incorporated into ISO9241-9 (after Zhai, 2002) as a mechanism to compare the relative performance and quality of input devices.

The qualitative usefulness of throughput is reduced because the non-zero intercept *a* in Fitts' Law (see Equation 5) can vary dramatically between different populations, gain settings, and input devices. Gain, also known as the Control-Display (C-D) ratio, is the ratio between the movement of the input device and the corresponding movement of the on-screen cursor. Many input devices, such as isometric joysticks, modulate the acceleration of the movement so that the on-screen cursor movement is exponential compared to the movement of the input device. The primary reason for introducing gain is to limit the space required to move the input device if the display area of large. Studies by MacKenzie (1995a) have shown that gain negatively affects performance and that an optimal gain setting is very difficult to find.

Zhai (2002) surmises that the reasons for the existence of a non-zero intercept might be due to regression modeling errors, poor understanding of kinesiology, scaling issues (Crossman and

Goodeve (1983) show that the time it takes to hit small targets over short distances is poorly predicted by Fitts' Law), or fixed overhead time required to initiate the click action, *e.g.*, mouse button click. Zhai recommends that comparative evaluations of the performance qualities of input devices, such as those recommended by ISO9241-9, must be based on a large number of target sizes and must take error rates into account. In addition, he contends that the results are only useful as a relative performance and quality indicator and not as a means for ranking input devices.

4.1.5 Extensions and Refinements to Fitts' Law

Fitts' Law has been shown to work for a variety of task and has found applicability in sports medicine, psychology, and industrial design. Nevertheless, since Card *et al.* (1978) published their seminal work on the application of Fitts' observations to human-computer evaluation, additional experimental evidence has been gathered that has led to a number of refinements and extensions to Fitts' Law. This section takes a look at the most relevant work.

4.1.5.1 Effective Width

The original experiments by Fitts and Card *et al.* either did not record or purposely excluded incorrectly selected targets or taps outside the target area in their data gathering. Consequently, the calculation of *ID* is skewed. According to MacKenzie (1991, 1995) this should be of concern because performance is not solely a factor of movement time, but rather a factor of both movement time and error rate. When users take care to hit a target and slow down their movement time so that they do not make a mistake, Fitts' Law would not apply, since it measures the maximum information capacity in a channel and assumes optimal and direct movement to the target. However, when evaluating input devices, error rate does become important. If error rates are excluded from the calculation of T and therefore the computation of throughput (*TP*), the effective *ID* is reduced, leading to incorrect between-subject comparisons when evaluating input devices.

MacKenzie (1991, 1995) proposes an effective target width W_e that is adjusted for the expected error rate and that new width should be used in Equation 4. The error rate must be measured by recording not only correct, but also incorrect target hits, including under- and overshoots of the target. In the absence of empirical data, MacKenzie proposes an alternative method that requires calculation of the area under the normal distribution curve bounded by a pair of *z* scores that can be obtained from statistical tables. The selection of the *z* scores is based on an estimated error rate. The overall goal of MacKenzie's effective width is to normalize the data collected from different experiments and to allow meaningful comparisons. A normalization technique based on observed error rates calculates an *ID* that reflects what users actually do rather than what they are supposed to do.

The normalization approach advocated by MacKenzie suggests that the error rate for all experimental data be fixed at 4%. If the observed or expected error rate is different from that, an adjustment must be made to the width used in the calculation of *ID*. For example, if the observed error rate is 6%, the effective width must be set larger than the actual width of the target. The effective width must be calculated so that it would produce an error rate of 4% if the effective width were the actual width in the conducted experiment. This is illustrated in Figure 15.

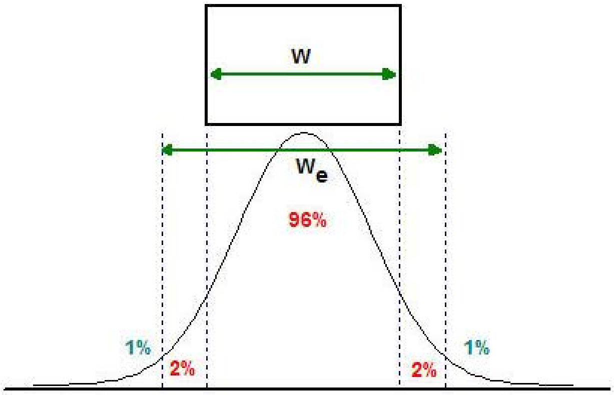


Figure 15. Normalizing of the target width to an error rate of 4%. For instance, if the observed error rate is 6%, an effective width would be calculated that is larger than the actual width so that the effective error rate is brought back to the normalized rate of 4% (from MacKenzie, 1991.)

The adjustment has merit as it more closely models the assumption by the Shannon-Hartley theorem that Gaussian noise is present in a communication channel and that transmissions are subject to statistically predictable errors.

4.1.5.2 Bivariate Pointing

Bivariate pointing looks at the Index of Difficulty under two-dimensional selection where the approach to the target is not along the horizontal as assumed by Fitts' original work. Section 4.1.2 presented a trigonometric adjustment of *W* to allow for bivariate pointing (see Figure 14).

Accot and Zhai (2003) model bivariate pointing tasks as an ℓ_p-norm. Based on certain approximations, they propose the simplified solution:

$$T = a + k\log_2\left(c\frac{D}{\min(W,H)} + 1\right) \tag{9}$$

where *a*, *k*, and *c* are empirically determined constants, *D* is the distance to the target, *W* is the width of a rectangular target, and *H* is the height of a rectangular target.

Accot and Zhai propose an additional solution of the ℓ_p-norm using a Euclidean model which can be written as:

$$T = a + k\log_2\left(\sqrt{\left(\frac{D}{W}\right)^2 + \eta\left(\frac{D}{H}\right)^2} + 1\right) \tag{10}$$

This version of the solution also provides a fit for the data reported by Hoffmann and Sheikh (1994). Experiments by Accot and Zhai fix the values for the constants in the following ranges:

$$-50 \le a \le 200, 100 \le k \le 170, \tfrac{1}{7} \le \eta \le \tfrac{1}{3} \tag{11}$$

This solution is very similar to the one introduced by Meyer *et al.* (1988) in which movement is modeled as a stochastic process. The contributions by Meyer *et al.* are discussed in more detail in Section 4.1.5.8.

4.1.5.3 Acquisition of Small Targets

Several experiments (Schmitt & Oel, 1999; Oel, Schmidt, & Schmitt, 2001; Accot & Zhai, 1999; Cockburn & Firth, 2003) report difficulty in fitting observed movement time to the predicted movement time of Fitts' Law when acquiring small targets or when acquiring targets over a short distance. Small targets are in the neighborhood of 10x10 pixels. This includes GUI controls such as radio buttons, check boxes, scrolling arrows, sliders, and toolbar icons. According to Oel *et al.* (2001), the problems that arise when applying Fitts' Law to situation when the *ID* is low (less than 3) might be due to the movement being primarily ballistic in nature (initial impulse) rather than being controlled in a closed-loop environment with visual feedback. Their results suggest a steeper increase in movement time for low *ID* values than the logarithmic increase predicted by Fitts.

The observations by Oel *et al.* as well as those by Cockburn and Firth (2003), provide strong evidence that Fitts' law is not invariant to scaling the distance to or the size of the target. Instead, they cite evidence that smaller targets require significantly more time to hit. Using a higher-order regression model, Oel *et al.* put forth the following mathematical model for predicting movement time:

$$T = \left(a \times W^{b}\right) \times D^{c + d \times \log_2 W} \tag{12}$$

According to Oel *et al.*, their power formulation for movement time is a higher order power series of the more specific power series proposed by Kvålseth (1980). Fitts' Law can be obtained as a special case Equation 12. Again, W is the width of the target, D is the distance to the target, and a, b, c, and d are empirically derived constants.

Oel *et al.* reanalyzed their results using several other prediction models for movement time, including Fitts, Welford, MacKenzie (Shannon), and Kvålseth, and found that their model exhibited much stronger correlation with the observed data and was more accurate in its predictions.

4.1.5.4 Acquisition of Expanding Targets

The proliferation of increasingly smaller targets is difficult to stop as the size and resolution of displays is getting larger. The MacOS X's Dock (see Figure 16) demonstrates a novel technique for improving the acquisition of small targets: they simply expand as the cursor approaches. However, noteworthy usability problems have surfaced. Since the icons remain anchored in the same spot, they appear to jump when they expand, causing confusion and frustration (McGuffin, 2002; Cockburn & Firth, 2003.) McGuffin (2002) proposed an expansion algorithm in which expansion only occurs after the cursor moves towards the target. In addition, expansion increases gradually as the cursor moves closer. McGuffin experimentally confirms Fitts' Law. However, McGuffin's approach does not take overlapping targets into account and does not appear to be useful in situations when there are many competing or overlapping targets.

Figure 16. Tool dock in MacOS X. Commonly used tools are displayed with a larger icon to make selection time shorter. An additional configuration of the dock allows all icons to be the same size until the cursor passes over the dock. At that point, icons nearest the cursor are expanded.

Another possibility for arranging targets is a *bullseye* or *pie menu* (Friedlander, Schlueter, and Mantei, 1998), where the choices are arranged in a series of sectionally divided concentric circles (see Figure 17.) When the menu is displayed, the cursor is placed at the center of the menu. The nature of the bullseye menu is such that choices closer to the center occupy a smaller display area, whereas items farther away from the center are larger. In essence, the bullseye menu becomes a series of expanding targets. The *ID* for acquiring targets is somewhat uniform as the size increases with distance from the center.

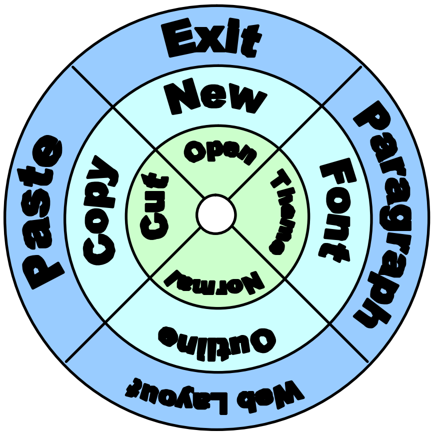


Figure 17. Bullseye (Pie) Menu in which choices are arranged in concentric circles and the cursor is at the center when the menu is displayed.

Friedlander *et al.* have successfully created non-visual bullseye menus that aid in the selection of menu choices for visually-challenged users. When "walking" such menus, the feedback is auditory. As expected, they found that Fitts' Law does not accurately predict the selection time in a non-visual menu. The positive use of auditory feedback to augment the menu selection process has been supported by several studies (Brewster and Crease, 1999).

4.1.5.5 Acquisition of Moving Targets

Intercepting a moving target involves different cognitive processes and therefore Fitts' Law does not apply without modification (Hoffmann, 1991a; Lee, Port, & Georgopoulos, 1997; Mould & Gutwin, 2004). The overall process of acquiring a target that is moving at a constant velocity consists of locating the target, moving towards the target, and finally hitting the target. First, the process of locating the target is more difficult as the reaction time is amplified. Second, the movement towards the target must be continuously adjusted based on visual feedback and the movement speed of the target. Third, the acquisition of the target must happen at the correct time.

Research in the area of moving targets has shown that acquisition times of targets that move at constant speed can be predicted by a variation of Fitts' Law in which the *ID* is a parameterized by the target's linear speed (Jagacinski, Repperger, Ward, & Moran, 1980a.) Taking the work by Jagacinski *et al.* and applying a limit computation establishes a ceiling on the target's speed above which capture becomes nearly impossible. Jacacinski *et al.* propose an experimentally derived formula that provides a good fit (R=0.98) with their data sets. Their estimation for mean capture time (*CT*) is given by:

$$CT = a + bD + c(V+1)(W^{-1} - 1) \tag{13}$$

where *a*, *b*, and *c* are empirically derived coefficients, *D* is the initial distance to the target when the target has not yet started to movie, *i.e.*, *T* is 0, *V* is the target's velocity, and *W* is the target's width. Jagacinski *et al.* reported that subjects had difficulty capturing targets that were small and moving at a high velocity, implying that there's a limit to the capture of moving targets.

Hoffmann (1991a) applies first and second order continuous-control and discrete-movement models to the capture of moving targets and proposes the following equation for mean capture time (*CT*):

$$CT = \frac{1}{K}\log\left(\frac{D - \frac{V}{K}}{\frac{1}{2}W - \frac{V}{K}}\right) \tag{14}$$

where *K* is a constant based on the maximum gain of the motion, and *V* is the velocity of the target.

There is little published research that deals with the acquisition of moving targets when the movement commences after the user has started to move toward the target (McGuffin, 2002). Both Hoffman and Jacacinski *et al.* presume that the target is at rest at the beginning of the acquisition process. Additionally, both assume that the motion is linear and constant. Random and accelerating motion on more than one axis has not received any attention in the literature.

4.1.5.6 Effects of Gain on Movement Time

An indirect input device, such as a mouse or isometric joystick, must have a properly calibrated gain setting. Gain refers to the acceleration or deceleration of the C-D (Control-Display) ratio and the rate of motion, *i.e.*, the on-screen cursor moves a shorter or longer distance for a given physical movement of the input device. Radix, Robinson, and Nurse (1999) found that gain has a negative effect on movement time. To compensate for the influence of gain on *ID*, Radix *et al.* propose an extended model of performance that takes gain into account.

The negative effect of C-D gain on movement time was further corroborated by MacKenzie and Riddersma (1994b) in a study that compared target acquisition using a mouse on an LCD versus a CRT display. Due to the disparity in display technology, there is a difference in the C-D gain between the two display types. Their research found that for a routine target acquisition task using a mouse, movement times were 34% longer and throughput (Index of Performance) was 25% less when an LCD was used as the display device.

4.1.5.7 Influence of Lag

Lag describes the delay between an input stimulus and feedback of the computer system. Feedback is commonly visual, but may also be haptic or auditory. As previously stated, the physiological underpinnings of Fitts' observations presume that actions are carried out in a closed-loop system with visual feedback. Therefore, a degradation of performance must be expected if sufficient lag exists in a human-computer interaction. The most common source of lag is software performance, but hardware may also be a source.

According to MacKenzie and Ware (1993), the presence of delay between the input stimulus and the feedback causes an increase in target acquisition errors, *i.e.*, undershoots and overshoots. The rate of errors increases when gain becomes a factor. They suggest a reformulation of Fitts' Law:

$$T = a + \left(b + cT_{lag}\right)ID \tag{15}$$

where a, b, and c are experimentally fitted parameters, T_{lag} is the system response delay measured in seconds, and *ID* is the Index of Difficulty from Equation 4.

Experimental results reported by MacKenzie and Ware saw performance degradation of 46.5% when lag increased to 225ms, although shorter delays of 8.3ms produced only a very slight degradation in performance (4.3%.) MacKenzie and Ware infer that lag above 75ms has a measurable effect on performance and mean movement time.

4.1.5.8 Wide Probes and Area Cursors

Interactions with touch-screen interfaces are often conducted using a finger rather than a stylus. Hoffmann and Skeikh (1991b) point out that a thicker probe leads to misleading results since the effective target tolerance is much higher. After all, the width of the finger allows for much greater inaccuracy in the pointing compared to a thin probe. Their experiments show that the *ID* must include a correction for probe width:

$$ID = \log_2\left(\frac{D}{W+P} + \varepsilon\right) \tag{16}$$

where ε is the formulation constant from Equation 4, *D* is the distance to the target, *W* is the width of the target, and *P* is the width of the probe. The expression *W+P* is called the *target tolerance*.

However, it is interest to note that an increased width of the probe increased target tolerance and therefore eases the acquisition of small targets. Kabbash and Buxton (1995) apply an area cursor to simplify the selection of small targets. As shown previously, Fitts' Law has been shown to fail when applied to narrow targets (Schmitt & Oel, 1999; Oel, Schmidt, & Schmitt, 2001; Accot & Zhai, 1999; Cockburn & Firth, 2003). However, the experiments by Kabbash and Buxton suggest that when the target size is close to a single point and the size of the cursor is increased beyond the standard size of a single pixel, then Fitts' Law can be used to make movement time predictions only if the width of the area cursor is substituted in Equation 4 for the calculation of *ID* instead of the width of the target.

In fact, this observation by Kabbash and Buxton is a consequence of the findings by Hoffmann and Sheikh. In Equation 16, if W equals 1, then the width of the probe P becomes the important determinant of the ID. Thus, area cursors are in effect a wide probe.

Tasks in which the width of the probe is substantially larger than the width of the area are referred to as *inverted Fitts tasks* (Hoffmann, 1995).

4.1.6 Stochastic Models

The preceding discussion shows that there is a definite quantitative tradeoff between speed and accuracy in rapid aimed movements. As movement speed increases, there is a marked decrease in the spatial accuracy of the movement. Equally, as spatial accuracy increases, movement speed slows. The mathematical representation of the relationship between speed and accuracy is the subject of an on-going scientific debate (Kvålseth, 1980; Meyer *et al.*, 1990; MacKenzie, 1991 & 1995; Burdet & Milner, 1998; Radix *et al.*, 1999; Oel *et al.*, 2001; Zhai, 2002.) Clearly, the resolution hinges on a more complete understanding of the underlying kinesthetic and cognitive processes involved in human motion.

McGuffin (2002) categorizes the different theories of kinesiology as the *iterative corrections model* (ICM), the *impulse variability model* (IVM) (after Meyer *et al.*, 1988 and 1990), and the *optimized initial impulse model* (OIIM).

The ICM views a movement towards a target as a series of discrete submovements. At the end of each submovement, visual and proprioceptive feedback is used to make adjustments in subsequent submovements until the target is reached.

In contrast, the IVM looks at human movement as an initial muscle impulse followed by a gradual movement of the limb towards the target. The movement after the initial impulse is simply a gliding motion without any corrective impulses to the limb muscles. This model appears to be the basis for Fitts' arguments. However, as pointed out by McGuffin, neither the IVM nor the ICM can adequately account for the different observations reported in the literature. For example, neither theory explains the effects of gain (Radix *et al.*, 1999), or the effects of navigating in high-precision environments (Guiard, Beaudouin-Lafon, & Mottet, 1999.)

Instead, McGuffin proposes the hybrid OIIM that combines the ICM and IVM. The suggestion is that Fitts' Law models a motion that consists of an initial impulse movement towards the target. If the target is missed, or will likely be missed based on closed-loop feedback, then shorter, corrective movements are executed. The actual corrective submovements that are applied depend on distance to the target and the size of the target. Smaller targets require additional corrections compared to larger targets.

As discussed in Section 4.1.5.2, McGuffin (2002) suggests that targets should expand as the movement towards them progresses. An expanding target offers a larger target area and thus fewer corrections are necessary. Consequently, the movement time towards the target is optimized. In essence, expanding targets make Fitts' Law work because they increase W as well as W_e (effective width) and therefore small targets that are far away from the origin of the movement can be acquired without additional error.

Meyer *et al.* (1988, 1990) propose a new model for rapid aimed movements that is based on viewing movement as a series of optimized submovements with corrective closed-loop feedback, termed the *impulse variability model*. Meyer *et al.* describe the overall movement as a stochastic process, and they use a stochastic optimized-submovement model which produces Fitts' original ID as a limiting case. Similar arguments for the use of stochasticity in modeling human movement have been made by Crossman and Goodeve (1983), Zhai (2002), and Kvålseth (1980). Research studies in neurophysiology suggest that noise is an integral factor in human motor control and execution and that corrective actions are issued at the neural level (Beers, Haggard, & Wolpert, 2004; Beers, Baraduc, & Wolpert, 2002).

Meyer *et al.* describe the process of acquiring a target as an initial primary submovement. If the submovement succeeds, the process terminates. If the submovement does not result in the acquisition of the target, *e.g.*, an overshoot or undershoot, it is assumed to be caused by noise and a secondary corrective submovement based on visual or proprioceptive feedback is issued. Meyer *et al.* assume that only one corrective submovement is issued.

The most common formulation of Meyer's dual-submovement model for mean movement time is:

$$T = a + k\sqrt{\frac{D}{W}} \tag{17}$$

where T represents the movement time to the target, D is the distance to the target, and W is the width of the target. The coefficients a and k are experimentally derived and depend on the input device. Equation 17 is referred to as *Meyer's Law*. An argument can be made to continue the use of effective width (MacKenzie, 1991) instead of actual width to compensate for selection errors during target acquisition.

Meyer *et al.* (1988) provide a mathematical analysis of a more generalized model that takes multiple submovements into account instead of a single corrective submovement. As the number of submovements (n) grows (*i.e.*, $n \to \infty$), the generalized model becomes:

$$T = a + k\log_e\left(\frac{D}{W}\right) \tag{18}$$

which is in form similar to Fitts' Law with the exception of the logarithm base. A change to base *2* instead of *e* is a simple algebraic manipulation.

An earlier article by Kvålseth (1980) proposed a model for mean movement time that is in form very similar to Meyer's Law, but is expressed as a more general power function:

$$T = a + b\left(\frac{D}{W}\right)^c \tag{19}$$

where *a*, *b*, and *c* are empirically derived parameters. Letting c=½, Equation 19 yields Meyer's Law. The formulation in Equation 19 is referred to as Kvålseth's Law.

4.2 Bivariate Steering Tasks

Accot and Zhai (1997) derive a more general model for two-dimensional trajectory movements rather than movements along a straight line. Their work breaks movement to a target into a series of individual movements along a restricted 2D trajectory. The restriction is the width of the trajectory, producing a kind of navigation *tunnel*. Viewing movements along a 2D tunnel trajectory applies well to a variety of tasks, such as the navigation of a hierarchy of cascading menus (see Figure 21) or drawing. Their derived model predicts the average time required to *steer* a pointing device, such as a mouse or stylus, along a 2D tunnel trajectory. Empirical evidence cited by Accot and Zhai confirms the validity of the general model for movement tasks that are two-dimensional, constrained and non-linear, *i.e.*, the target cannot be acquired through a direct and linear movement.

In its general form, the Accot-Zhai Steering Law reveals the same trade-off that Fitts' Law presents: the more quickly we move, the less accurate the movement will be and vice versa. Accot and Zhai's work extends Fitts' observations from one dimension to two dimensions and from linear (and direct) paths to a 2D constrained trajectory.

4.2.1 Straight Tunnel

The initial derivation of the model restricts movement to a straight trajectory. The movement is viewed as a series of simple goal-crossing movements that can be modeled by Fitts' Law. A goal-crossing task is shown in Figure 18. During such a task, users must move first through the confines of the first goal and then through the second goal. In essence, the goals on both ends of the movement path constrain the motion to a tunnel.

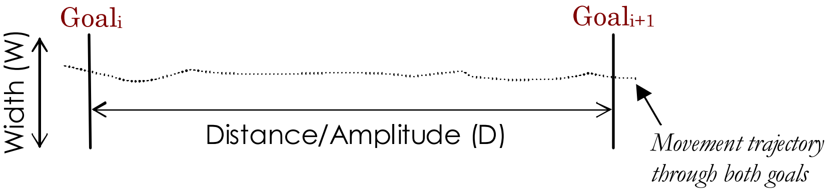


Figure 18. An Accot-Zhai goal-crossing task in which a movement must pass between two goals. The user must "steer" the cursor through a tunnel (after Accot and Zhai, 1997.)

The difficulty of the goal crossing motion can be modeled through Fitts' *ID*. Therefore, Equation 4 using Shannon's formulation applies.

Subdividing the entire movement from the first to the last goal into a series of smaller goal crossing tasks results in an iterative application of Fitts' Law in which the distance of each movement is D/n where n represents the number of steps. Extending the Index of Difficulty (*ID*) of Equation 4 to a series of sequential goal crossing tasks yields the following series:

$$ID_n = n\log_2\left(\frac{D/n}{W}+1\right) \tag{20}$$

where n describes the number of the step in the sequence, D is the overall length of the movement from the first to the last goal, and W is the width of the goal, *i.e.*, the trajectory.

If the movement is divided into an infinite series of goal-crossing steps, then, after applying a Taylor series expansion of the logarithm, Equation 20 becomes:

$$ID_\infty = \lim_{n\to\infty}\left(n\log_2\left(\frac{D/n}{W}+1\right)\right) = \frac{D}{W\log_e(2)} \tag{21}$$

The interpretation of Equation 21 leads to the observation that the difficulty of the movement through a series of goals does not follow the logarithmic correlation observed by Fitts. Instead, after evaluating the logarithm, the Index of Difficulty (*ID*) becomes:

$$ID_{\infty} = \frac{D}{W \log_e(2)} = \frac{1}{\log_e 2} \times \frac{D}{W} = k \times \frac{D}{W} \tag{22}$$

which makes the movement time T for a straight tunnel task:

$$T_{Goals} = a + k \times \frac{D}{W} \tag{23}$$

Thus, movement through a straight tunnel is directly proportional to the ratio of the distance between and the width of the goals.

4.2.2 Narrowing and Curved Tunnels

The model for straight tunnels can be extended to narrowing trajectories, where the first goal has a width that is greater than the second goal's (Figure 19).

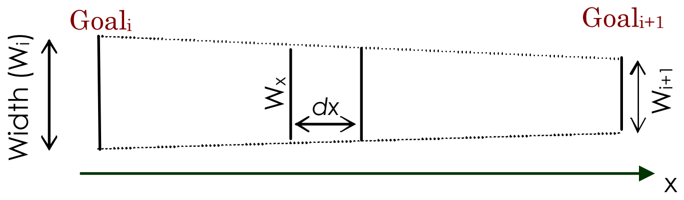


Figure 19. A narrowing tunnel. Each subgoal movement is described as a crossing between two goals of the same size over a very small distance *dx*.

We can treat the crossing between two dissimilarly sized goals as if they were of the same size as long as the distance between them is kept very small. Using differential calculus let the distance between the goals be represented by *dx*, where *x* is the distance from the first goal. Therefore, according to Equation 22, the Index of Difficulty (*ID*) for this goal crossing is:

$$dID(x) = \frac{dx}{W(x)} \tag{24}$$

where *W(x)* is the width of both goals at position *x* along the path. To calculate the *ID* for the entire path, we simply add all of the *IDs* for each of the goal crossings along the path:

$$ID = \int_0^D \frac{dx}{W(x)} = \frac{dx}{W_1 + \frac{x}{D}\left(W_2 - W_1\right)} = \frac{D}{W_2 - W_1} \times \log_e\left(\frac{W_2}{W_1}\right) \tag{25}$$

Again, the overall movement time is logarithmically related to the size of the tunnel, which means that narrow tunnels result in increased movement time compared to wider tunnels.

For circular tunnels (Figure 20), Accot and Zhai restate their equations in polar coordinates and arrive at the following steering law:

$$T = a + b\frac{2\pi R}{W} \tag{26}$$

where *a* and *b* are empirically fitted parameters, *R* is the radius of the circular tunnel and *W* is the width of the tunnel.

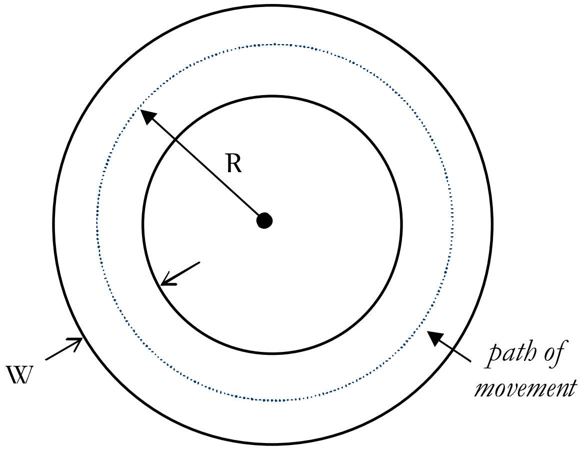


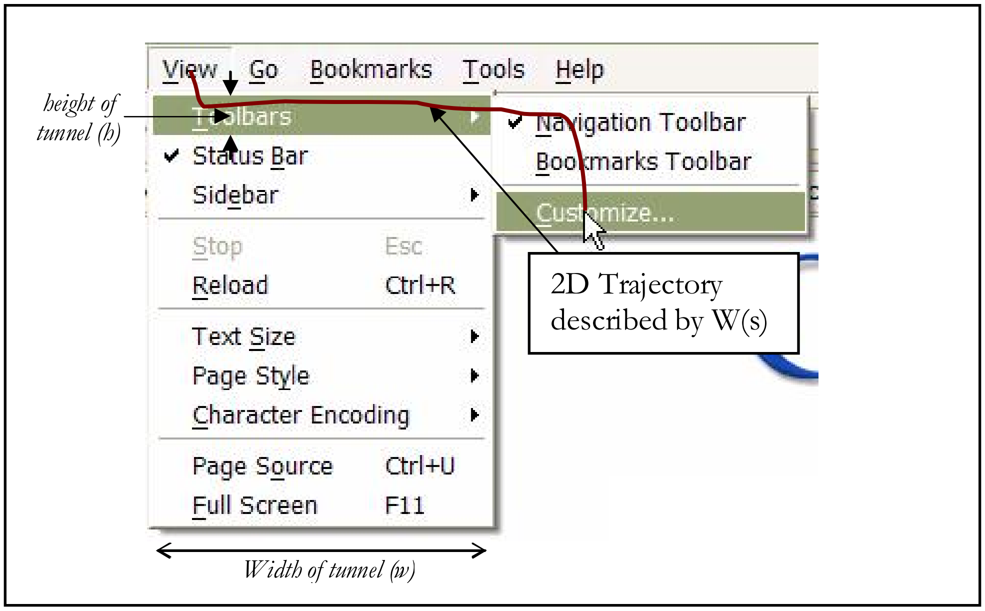
Figure 20. Circular tunnel in an Accot-Zhai steering task. Such steering tasks would occur in drawing and free-hand marking tasks.

In addition to straight and circular tunnel movements, Accot and Zhai consider curved tunnels. Their derivation of the Index of Difficulty (*ID*) for a curved tunnel expressed the abscissa *x* as a curve described by some function ζ. The total movement time along a curved trajectory is therefore:

$$T_{\varsigma} = a + b\int_{\varsigma} \frac{1}{W(s)} ds \tag{27}$$

where *a* and *b* are empirically calibrated constants for a particular user interface design and input device, *s* is the trajectory parameter, and *W(s)* is the thickness, or width, of the trajectory at *s*.

Figure 21 shows a potential path taken during the navigation of a cascading menu. Note that the user must follow along a tunnel. If the user exits the tunnel, *i.e.*, the user moves up or down a menu item in the first menu, the cascading menu disappears.



2D Trajectory described by W(s)

Figure 21. Trajectory for navigating a cascading menu. Notice that the mouse cursor must move along a specific path within a tunnel. If the mouse cursor exits the tunnel, the menu disappears and the task must be aborted. The movement from the start to the "View" menu is a regular Fitts task. Once the menu appears, the "walking" of the menu becomes a steering task.

Given the general structure of a cascading menu, navigation to a particular choice requires that the menu is first displayed, followed by the traversal of a fairly wide vertical tunnel to the cascading menu item. Next, the user must traverse a fairly narrow horizontal tunnel to the cascading menu. Finally, the user must move along a wide vertical tunnel to the correct menu choice. To calculate the mean time it takes to access a particular cascading menu item *n*, such as the "Customize…" in the menu of Figure 21, the following formula can be used:

$$T_n = a + b\left(\frac{n}{x} + x\right) \qquad (28)$$

where *a* and *b* are empirically derived coefficients and *x* is equal to the ratio of the width (*w*) and the height (*h*) of the tunnel ($\frac{w}{h}$), assuming that both menus have similar width and height.

Recent work by Zhai and Woltjer (2003) submits that the steering law not only applies to two-dimensional hand-controlled steering tasks, but also to three-dimensional locomotion tasks, such as biking, running, or swimming. They confirm their findings through driving experiments in three-dimensional virtual reality environments.

4.2.3 Trivariate Pointing

Trivariate pointing describes the acquisition of an object that has extent along three dimensions. Grossman and Balakrishnan (2004) treat trivariate target acquisition as an extension to bivariate pointing. A simple extension to the Accot and Zhai (2003) bivariate pointing model stated in Equation 9 can be defined as:

$$T = a + k \log_2\left(c \frac{A}{\min(W, H, D)} + 1\right) \tag{29}$$

where *a*, *k*, and *c* are empirically derived coefficients, *A* is the distance to the target, and *W*, *H*, and *D* are the dimensions of the target.

Grossman and Balakrishnan conducted their investigation in virtual reality immersion environments using a volumetric rather than a stereoscopic display. A volumetric display is more natural and less likely to induce motion sickness in the user. They tested several models for univariate movement time prediction, including Equation 9, but found that a variant of the Accot and Zhai Euclidian-norm (Equation (10) extended to three spatial dimensions had the best fit with the observed data. They therefore propose the following model to predict target acquisition time for three-dimensional objects:

$$T = a + k \log_2\left(\sqrt{f_W(\theta)\left(\frac{A}{W}\right)^2 + f_H(\theta)\left(\frac{A}{H}\right)^2 + f_D(\theta)\left(\frac{A}{D}\right)^2} + 1\right) \tag{30}$$

where a and k are empirically derived coefficients, A is the distance to the target, W, H, and D are the dimensions of the target, θ is the approach angle to the target, and $f_E(\theta)$ is a coefficient for extent E that is dependent on the approach angle θ.

4.3 Taxonomy of Quantitative Models

The literature is full of proposed improvements to the original model proposed by Fitts. Given the experimental data that has been published, it is reasonable to assume that all of the proposed quantitative models work for at least some situations. The most general models are the ones proposed by Oel *et al.* for direct pointing tasks and Accot and Zhai for steered pointing tasks. Table 4 presents a summary and taxonomy of the various models that have been reviewed. Collectively, these models are referred to as the *Laws of Action* (Kristensson, 2005).

Oel *et al.* (2001) ranked several of the models in Table 4 by comparing their correlation coefficients across their data, as well as data published by others. Table 5 summarizes their findings and rankings. From that analysis, it is clear that the power models proposed by Oel *et al.* and Kvålseth have the best fit with the observations. While acceptable, the original Fitts model has the lowest coefficient of correlation (R^2.)

Table 4. The Laws of Action: Taxonomy of Quantitative Prediction Models for Mean Movement Time along one, two, or three dimension either along a straight line or a trajectory.

Model	**Estimator of Movement Time (*T*)**	**Applicability**
Generalized Fitts' Law	$T = a + k\log_2(\frac{D}{W_e} + \varepsilon)$	1-dimensional direct pointing tasks with effective width
MacKenzie-Buxton Bivariate Pointing	$T = a + k\log_2\left(\frac{D}{\min\left\{\frac{H}{\sin\varphi}, \frac{W}{\cos\varphi}\right\}} + \varepsilon\right)$	2-dimensional direct pointing tasks
Accot-Zhai Bivariate Pointing	$T = a + k\log_2\left(\sqrt{\left(\frac{D}{W}\right)^2 + \eta\left(\frac{D}{H}\right)^2} + 1\right)$	2-dimensional direct pointing tasks

Model	**Estimator of Movement Time (*T*)**	**Applicability**
Oel *et al*. Power Model	$T = \left(a \times W^{b}\right) \times A^{c + d \times \log_2 W}$	small targets or short distances
Meyer's Law	$T = a + k\sqrt{\frac{D}{W}}$	1-dimensional pointing tasks
Kvålseth's Law	$T = a + b\left(\frac{D}{W}\right)^{c}$	1-dimensional pointing tasks
Accot-Zhai Goal Crossing	$T = a + k\frac{D}{W \log_e(2)}$	Movement along a straight tunnel
Accot-Zhai Narrowing Tunnel	$T = a + \frac{D}{W_2 - W_1} \times \log_e\left(\frac{W_2}{W_1}\right)$	Movement along a narrowing tunnel
Accot-Zhai Circular Tunnel	$T = a + b\frac{2\pi R}{W}$	Movement along a circular tunnel trajectory
Accot-Zhai Steering Law	$T_\varsigma = a + b\int_\varsigma \frac{1}{W(s)} ds$	Movement along a curved tunnel trajectory
Grossman-Balakrishnan Trivariate Pointing	$T = a + k\log_2\left(\sqrt{f_W(\theta)\left(\frac{A}{W}\right)^2 + f_H(\theta)\left(\frac{A}{H}\right)^2 + f_D(\theta)\left(\frac{A}{D}\right)^2} + 1\right)$	3-dimensional pointing task (extension to Accot-Zhai bivariate pointing)

Table 5. Ranking of models by Oel *et al.* (2001). The rankings were calculated using data collected by Oel *et al.* R^2 represents the coefficient of correlation in a multiple regression analysis.

Model	**R^2**	**Rank**
Oel *et al.* Power Model	0.9664	1
Kvålseth's Law	0.9154	2
Generalized Fitts' Law (ε = 1, MacKenzie)	0.9011	3
Generalized Fitts' Law (ε = 0.5, Welford)	0.8951	4
Generalized Fitts' Law (ε = D/W, Fitts)	0.8839	5

Note that the equation for the Generalized Fitts' Law is used for input device evaluation in ISO9421-9, which prescribes design parameters for ergonomic computer workstations and work environments.

4.4 Reaction Time

The Hick-Hyman (Hick, 1952; Hyman, 1953) Law is an information theory based model for predicting reaction time when making a decision among several choices. Similar to Fitts, Hick and Hyman attempted to apply information theory to the modeling of human cognitive, perceptual, and motor processes. The Hick-Hyman Law states that the reaction, or decision, time *(RT)* is roughly proportional to the entropy of the decision (*H*).

Specifically, the reaction time to make a choice among *n* equal choices is given by the formula:

$$RT_n = RT_1 + kH \tag{31}$$

where *k* is an empirically derived parameter and RT_1 is the simple reaction time when there is only a single response to a stimulus. An often-used initial value for *k* is 150 msec.

H, the entropy of the decision, is based on the number of possible choices and can be stated as either:

$$H = \log_2(n+1) \tag{32}$$

or

$$H = \sum_{i=1}^{n} p_i \log_2(\frac{1}{p_i}+1) \tag{33}$$

where *n* presents the number of equally probable alternatives and p_i represents the probability of alternative *i* for *n* alternatives of unequal probability. Notice that the number of choices is increased by 1 to account for the *null* choice, *i.e.*, not responding to any choice.

While the Hick-Hyman law is based on the entropy measure, Kvålseth (1996) suggests a more general relationship between the reaction time and the selection of the appropriate response. He proposes the following power function:

$$RT_n = RT_1 + a(n^b - 1) \tag{34}$$

where *a* and *b* are experimentally fitted parameters. According to Kvålseth, the simple reaction time (RT_1 when n=1) is generally reported to be approximately 150-210 msec. for both visual and auditory stimuli. For values of $n \leq 10$, Kvålseth's experiments suggest a simplified form of Equation 34:

$$RT_n = RT_1 n^b \tag{35}$$

Using the observed value of 200 msec. for RT_1 and setting *b* to ½ simplifies the reaction time further:

$$RT_n = 200\sqrt{n} \tag{36}$$

The square-root law for reaction time has been shown by Kvålseth to agree with experimental data published in the literature.

The Hick-Hyman Law and the Kvålseth Square-Root Law can both be used to estimate the decision time in user interfaces, such as the time required to locate the correct item in a menu or toolbar.

4.5 Learning Time

The Power Law of Practice as stated by Card *et al.* (1983) describes the time it takes to perform a task after a series of practice trials. Observations by Card *et al.* indicate that users improve in speed at a decaying rate. In particular, the time it takes to perform a task on the n^th^ try can be stated as:

$$T(n) = T_1 \frac{1}{n^a} \tag{37}$$

where *a* is an empirically derived constant and T_1 is the time it takes to perform the task on the first try. In the absence of empirical data, a commonly-used value for *a* is 0.4. In essence, the practice function *T(n)* describes the *learning curve* for a task.

Evidence cited by Heathcote, Brown, and Mewhort (2000) suggests that the practice function is in fact exponential. They argue that the version of the Law of Practice presented above is based on the average practice time for a universe of users when in fact individual learning times can be significantly different from the average. They suggest the following exponential function as an alternative:

$$T(n) = T_1 e^{-\alpha n} \tag{38}$$

where α is a situation dependent coefficient. The exponential law suggests that subjects master a task much more quickly than the power law would surmise.

The work by Heathcote *et al.* reexamines much of the published experimental data in light of their new model and finds that the power function is a special case of the exponential function. For a small number of trials, the average learning time is reasonably well predicted by the simpler power function.

4.6 Task Completion Time

An interaction with a user interface is typically comprised of several smaller tasks. For example, entering a waypoint into a navigation system requires a menu or command selection, followed by several numeric inputs, and finally a confirmation. Each task has certain movement characteristics that can be modeled with one of the movement prediction models presented in Table 4. Besides the movement time, reaction and learning time are also factors in the overall completion time of the interaction.

According to Jax, Rosenbaum, Vaughan, and Meulenbroek (2003), four issues are at the core of describing motor behavior: (i) task ordering, (ii) learning, (iii) perceptual-motor integration, and (iv) movement. Therefore, an approximation of the total task completion time (*TT*) for an interaction that consists of *n* sub-tasks can be mathematically described as follows:

$$TT = LT + \sum_{i=1}^{n} (RT_i + MT_i) \tag{39}$$

where LT represents the overall learning time for the interaction, RT_i is the reaction time for a single sub-task i, and MT_i is the mean movement time for sub-task i.

The next chapter takes a look at in-vehicle and maritime navigation systems with the goal of understanding the different interactions that frequently occur in those systems.

5. INTERACTIVE SYSTEMS FOR NON-STATIONARY ENVIRONMENTS

5.1 Usability Model

The usability of information systems is affected by a number of factors, including learnability, efficiency, memorability, error prevention, and satisfaction (Nielson, 1992). Current usability and interaction models principally consider stationary environments. When users are interacting with mobile computing systems or information systems deployed into a non-stationary environment, additional usability factors must be taken into account. Hassanein and Head (2003) present an updated usability reference model for ubiquitous information systems. In particular, their model considers user characteristics (expert versus novice), environmental attributes and constraints (noisy versus quiet), and task characteristics (simple versus complex). Figure 22 presents a model that extends the work by Hassanein and Head to include additional characteristics of non-stationary environments.

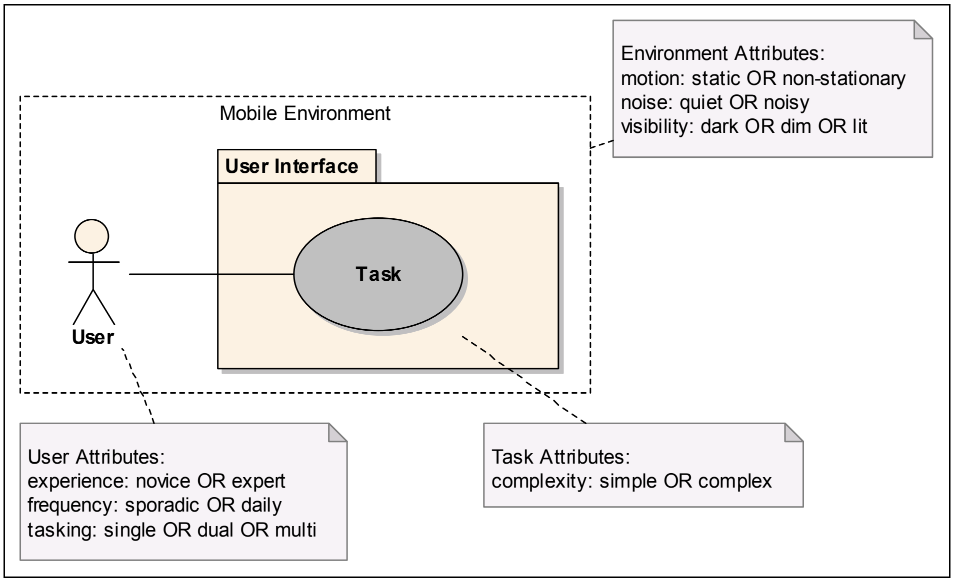


Figure 22. Usability Model.

5.2 In-Vehicle Navigation Systems

There is a significant body of research focused on evaluating the usability of in-vehicle information systems (IVIS) through experiments of actual driving situations as well as simulator-driven experiments. The approaches used to derive the data and the kinds of data that are considered important are of relevance to the proposed research. In addition, the Society of Automotive Engineers (SAE) and the Federal Highway Administration have sponsored several standards for the usability of IVIS (Green, Levison, Paelke, & Serafin, 1994.)

Several studies investigated the impact on driving performance as a function of workload during interactions with in-vehicle navigation systems. In particular, Green *et al.* report that voice input results in faster task completion time compared to using a touch-screen soft keyboard without tactile feedback. Furthermore, as the workload increases, *i.e.*, the vehicle is driven at a faster speed through a more complex series of curves, task completion time increases for touch-screen based input. The subjects of the study rated touch-screen input the least safe as it proved to require more attention and was more error-prone. There was a reported doubling of the task completion time among older subjects compared to younger subjects, suggesting perhaps a difference in mental task scheduling, vision, motor skills or some other factor between the two groups.

In terms of in-vehicle navigation system responses to the driver, a study by Blanco (1999) recommends that driving directions be presented as simple graphical icons instead of paragraphs of text. Output that required high visual demand was found to be distracting and unsafe as it increased overall glance time away from the display to pay attention to the primary task of driving. Glance time, also referred to as visual glance time, is the time a driver spends looking back at the road while interacting with the IVIS. Increased glance times result in longer total task completion times.

5.3 Small-Craft Integrated Navigation Systems

Safe piloting of a small marine craft, such as a pleasure boat, working boat, or yacht, requires the assistance of a multitude of electronic devices, including Radar, GPS, electronic charting, electronic chart plotting, autopilot control, VHF radio, electronic engine controls, and satellite communication for weather information. Many relatively inexpensive devices exist to aid the recreational mariner and professional yacht captain in the operation of his vessel (Chapman, 1999; Aarons, 2002; Husick, n.d.).

Integrated navigation systems (INS), including Electronic Chart Display and Information Systems (ECDIS), such as the SeaRay Navigator (Figure 1, pg. 3) or the Maptech i3 are becoming more prevalent aboard small marine craft, particularly pleasure craft (Ellison, 2005; Husick, 2003), because they have reduced mounting requirements in helm consoles compared to multiple displays for various electronic navigation instruments. In addition, they are cheaper to manufacture and install and as such reduce the cost of the vessel and increase its market potential. However, while they are less susceptible to failure compared to systems with multiple devices, there is a loss of redundancy and partial system operation. Most electronic navigation systems are built on commercial off-the-shelf technology and as such are easier to service and less expensive to develop.

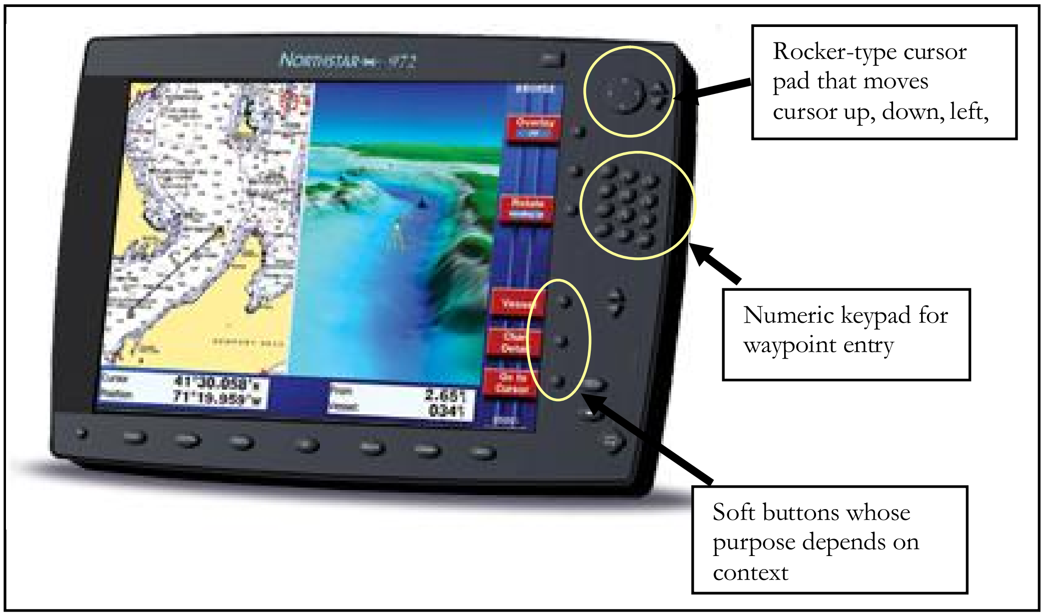
An INS combines several devices into a single device with one display. The display is often multiplexed and shows the output of several sensors, *e.g.*, one window for the Radar, one for the sonar, and one for the ECDIS. Besides INS, marine electronics manufacturers also employ multi-function displays that allow several devices to share a single display. In essence, multi-function displays combine input from several sensors and display the data independently, synthesized, or transformed on a single screen. Besides specialized navigation systems, either in the form of an INS, multi-function display, or dedicated device, personal computers with specialized chart plotting software are also used aboard small craft (Husick, 2003). The most prevalent personal computer aboard small vessels is a Microsoft Windows laptop, but Tablet PCs and small PCs are also in use (Panbo, n.d.)

Small-craft marine electronics manufacturers have embraced modern computing technology and most vendors take advantage of sun-light visible color LCD displays, ruggedized PCs, and modern charting software. Garrison (2004) and Powerboat Reports (2005) provide comparative reviews of recent products, including several of the systems surveyed in Table 6. Based on a survey of manufacturers' web sites (see Table 6), current Small-Craft Integrated Navigation Systems (SCINS), *i.e.*, those installed on and specifically built for vessels less than 65 ft. in length, employ a variety of input devices, including touch screens, numeric key pads, specialized button interfaces, dials, joy sticks, and cursor pads (see Figure 23). None of the navigation instruments surveyed uses a full alphanumeric keyboard or a mouse. Screen sizes range from 7 to 15 inches, although smaller screens with an average size of 10 inches appear to be the most common. Figure 24 shows a sampling of representative products.

Table 6. Survey of input methods used on commonly used marine electronic devices. Information was obtained from manufacturers' web sites (as of February 20, 2005.)

Product Name	**Manufacturer**	**Touch Screen**	**Numeric Keypad**	**Keyboard**	**Soft Buttons**	**Dedicated Buttons**	**Dials**	**Cursor Pad**	**Touch Pad**	**Joystick**	**Mouse**	**Trackball**
NavNet Chart Plotter/Radar	Furuno		X		X	X	X					X
GPS/WAAS Chart Plotter	Furuno		X		X			X				
Northstar 972	Northstar		X		X	X						
Northstart 6000i	Northstar		X		X			X				
Raymarine E-Series	Raymarine				X	X				X		
Sea Ray Navigator	Maptech	X						X				
i3	Maptech	X										
Nobletec Chart Display	Nobletec	X										
Lowrance (all products)	Lowrance					X		X				
ColorMax 11 GPS/Plotter	Si-Tex				X	X				X		
Navigator PC	Navigator	X										
Navman 5600/5500	Navman					X		X				
GPSMAP 30xx Series	Garmin		X		X	X		X				
Radar/Chartplotter 1800CP	JRC				X	X	X			X		
Totals:	14	4	5	0	8	8	2	6	0	3	0	1
		29%	36%	0%	57%	57%	14%	43%	0%	21%	0%	7%

The survey presented in Table 6 includes one entry for each product family that a manufacturer produces rather than one entry for each product. This roll-up of data normalizes the data across manufacturers since all products within a product family feature identical input methods. Where this assumption was not found correct, the survey includes more than one entry. While touch screens are becoming more popular aboard boats, most marine navigation systems employ button interfaces (either dedicated or soft.) Soft buttons are a style of button where the command activated by the button changes and is dependent on the instrument's mode or the display context. About one third of products include a numeric keypad for waypoint entry.



Rocker-type cursor pad that moves cursor up, down, left,

Numeric keypad for waypoint entry

Soft buttons whose purpose depends on context

Figure 23. Keypad, rocker cursor pad, and soft buttons used on Northstar 972 multi-function navigation displays.

Figure 24. Examples of marine navigation systems. From left to right: Navigator Charting PC with Touch-Screen ECDIS, and Navman Tracker 5600 GPS and Chartplotter.

Informal interviews conducted by the author and recent surveys of the boating community (Fedler, 2000; Oregon State Marine Board, 2002) provide insight into the typical boater. Fedler (2000) and a survey by the Oregon State Marine Board (2002) state that the average boater is 56 years old. This suggests that the typical boater is likely to have vision and fine motor control problems. In addition, the Oregon State Marine Board (OSMB) report finds that the average boater makes only 18 voyages per year lasting an average of 1.4 days with a declining trend. The intermittent and sporadic use of boats means that the average operator is unlikely to be well trained in the use of marine electronics and therefore a simple, intuitive, and efficient user interface is required.

Electronic instruments are primarily used during critical and intense situations such as when a collision or grounding is imminent. Interactions are frequently during times of limited visibility, such as fog and night and when the cockpit is dark. In addition, due to the nature of the marine environment, maritime electronics are principally used in confined, noisy, wet, and unstable (rocking) conditions. It is also important to note that most users of marine electronics operate the equipment from a standing position rather than sitting down. It is conjectured that the unpredictable rocking motion aboard a small craft amplifies poorly designed user interface controls.

5.4 Interaction Goals

The interactions goals with an IVIS and a SCINS are more specialized and limited compared to desktop applications. Table 7 summarizes the most common interactions. An understanding of the planned goals is necessary in order to be able to categorize the input mechanisms that user interfaces for such systems must support. The specific input mechanisms will provide a framework for the planned experiments and derivation of completion time models for specific task types.

Table 7. Interaction Goals for IVIS and SCINS.

Task	IVIS		SCINS	
	Approach	**Input Mechanism**	**Approach**	**Input Mechanism**
Destination Entry – Method A	Selection from menu of addresses	Touch menu choice Scroll through menu with up/down cursor pad	Selection from menu of stored waypoints	Touch menu choice Scroll through menu with up/down cursor pad
Destination Entry – Method B	Entering of city and street	Soft keyboard Up/down cursor pad	Entering of numeric waypoint	Soft keypad Physical keypad
Destination Entry – Method C	N/A	N/A	Pointing to destination waypoint on electronic chart	Finger or stylus on touch screen Joystick
Command Selection	Pressing of button	Soft button on touch-screen	Pressing of button	Soft button on touch-screen
Store waypoint			Enter an alphanumeric name for an already entered waypoint coordinate	Soft keyboard
Zoom Map/Chart	Zoom in or out of a graphical map	Press zoom + or – soft button	Zoom in or out of an electronic chart	Press zoom + or – soft button
Pan Map/Chart	Pan left, right, up, or down	Use cursor pad	Pan left, right, up, or down	GUI Scroll bar; activate with finger or stylus Swipe with finger or stylus Cursor pad

From the above analysis, the following elemental interaction tasks become apparent: selection of a menu choice on a touch screen, alphanumeric data entry on a soft keyboard, swiping, and targeting a particular region on the screen. In particular, the acquisition of fixed size targets on a touch screen interface using either a finger or a stylus is a fundamental task. The interactions are carried out while the user is performing additional tasks, such as looking at a chart or map, driving the vehicle or boat, and keeping a lookout for potential collision targets. On a boat, the user must also keep a constant watch on the readings from the depth sounder so as to prevent the vessel from running aground.

Most SCINS support additional features, such as e-mail, weather reports, opening and closing of specific charts, entering routes (a collection of ordered waypoints that the vessel follows), changing to night mode (uses a different set of colors that is less likely to interfere with night vision), recording log entries, making chart annotations, displaying current vessel data (speed, course, heading, position, wind speed and direction, depth under keel), among many others. However, the interaction mechanisms needed to activate those features are no different than the elemental ones already discussed.

6. PROPOSED RESEARCH

6.1 Primary vs. Secondary Tasks

A dual-task situation is one in which two tasks must be carried out concurrently. Therefore, simultaneously operating a small-craft integrated navigation system (SCINS) or an in-vehicle information system (IVIS) while driving constitutes a dual-task situation. In these systems, the tasks are neither of equal importance nor of equal complexity. The interaction with the SCINS or IVIS is less important and cognitively less complex than driving. It is considered the *secondary task*. The completion of the *primary task* is more important and successful completion of the primary task must be done at the expense of the secondary task. Accordingly, a secondary task is one that is not the primary focus of the user and that is carried out simultaneously with at least one other task. The execution of the secondary task is frequently interrupted in order to devote time to the completion of the primary task, *i.e.*, the secondary task is interrupted in favor of scheduling a "time slice" for the primary task.

> ***Research Question***. *Does the amount of attention paid to a secondary task affect cognition enough to cause a difference in performance and therefore result in a significant increase in task completion time? Is the error rate during an interaction with a secondary task greater since the user is not paying as much attention to the task and is focused on the primary task?*

6.2 Total Task Time for Interactions

6.2.1 Glance Time

When interacting with the secondary task, glance time becomes important. Glance time (GT) refers to the time a user spends on the primary task while doing the secondary task. When a user interacts with an SCINS, for example, he needs to occasionally look back at the road ahead to avoid causing an accident. GT has a hypothetical influence on the total time it takes to complete an interaction. Because it distracts the user, it may influence cognition and disrupt the closed-loop feedback system.

Empirical research by Green (1998) and Nowakowski, Utsui, and Green (2000) in the field of driver information systems and in-vehicle navigation systems (IVIS) has shown that the mean glance time during destination entry tasks while driving should not exceed 1.2 to 1.5 seconds and that total glance time should not exceed 10 seconds for drivers to feel safe. When the mean glance time increases above 2.5 seconds, the distractions cause lane changes and unsafe driving performance. The Society of Automotive Engineers (SAE) recommends that destination entry tasks with IVIS are completed within 15 seconds (Green, 1999a; Green 1999b; Green, 1999c). Manufacturers of IVIS devices must provide experimental evidence that input tasks for their devices are compliant with the 15-second rule.

> ***Research Question***. *Is GT distracting to the user in completing a secondary task? Does this influence the ID of Fitts' Law significantly?*

6.2.2 Total Task Completion Time

The total task completion time (TT) is the sum of the completion times for each task from the initiation of the first task and the completion of the last task in a series of interactive tasks. TT must take into account the glance time for the primary task, the reaction and choice decision time, and the movement time to the necessary interaction targets. The glance time is empirically derived and depends on the environment and the attention demand of the primary task as well as the workload of the user. The reaction time is predicted using the Hick-Hyman model. The movement time to an interaction target, such as an icon, soft key, button, or other interface control, can be modeled as a Fitts task. It is conjectured that a new version of Fitts' Law must be derived that takes into account the anticipated negative effects that glance time as well as the motion of the environment has on cognitive and motor performance.

The conjectured *TT* for *n* sub-tasks in an interaction (typically a single use case) can be expressed mathematically as follows:

$$TT = LT + \sum_{i=1}^{n} (RT_i + MT_i + GT_i) \tag{40}$$

where *LT* is the learning time for the task, *GT* is the glance time during a single sub-task within entire interaction, *RT* is the reaction (or recognition) time for each sub-task, and *MT* is the mean movement time to actuate the input.

If we assume that users will be reasonably trained on the use of the interface and the tasks do not require more than five steps, then *LT* becomes small and possibly negligible. Furthermore, if the user interface is fully displayed and the discrimination of which areas to click is intuitive, then *RT* will generally be very small as well. Thus, the model to predict the total task time *TT* can be rewritten with the following approximation:

$$TT \approx \alpha + \sum_{i=1}^{n}(MT_i + GT_i) \tag{41}$$

where α is an empirically derived coefficient and represents the mean learning and reaction times.

Research by Hoffmann and Lim (1997) demonstrates interference between motor and cognitive performance in dual-task situations. Specifically, Hoffman and Lim point out that when manual and cognitive tasks are done sequentially, the combined task completion time is the sum of the individual task completion times. However, when both tasks are done concurrently, the total task completion time increases. In particular, Hoffmann and Lim theorize that corrective submovements are impeded when cognitive tasks such as choosing are made while the movement occurs. Their experiments show that the total time it takes to complete manual and decision tasks concurrently is dependent on the entropy of the decision. Movement time increases as the number of choices gets larger. In addition, the interference is amplified by the difficulty of the task, *i.e.*, as the *ID* component of Fitts' Law increased the effect of choice reaction time on movement time increased. Hoffmann and Lim postulate that cerebral interhemisphere effects are the cause for the interference. The performance degradations observed by Hoffmann and Lim are likely to increase when the effects of variable motion of the environment are added.

Research by Shin and Rosenbaum (2002) finds similar interactions between cognitive and perceptual-motor processes. In particular, their experiments reveal that when cognitive tasks are done in parallel with aiming tasks, the movement time for aiming is longer than if no cognitive work is present. In their experiments, they asked subjects to hit an on-screen target with a mouse while carrying out arithmetic calculations. Their research arrives at the conclusion that cognitive tasks are scheduled to start first before perceptual-motor processes; however, both tasks are interleaved and scheduled to occur concurrently. Interestingly, their evaluation of the empirical data concludes that the overall cognitive task time does not increase when a perceptual-motor task is executed at the same time. This implies that the time to complete the motor task increases.

From these experiments, we conclude that Equation 41 likely must be modified to account for the expected increase in *TT* for dual-task situations. It is hypothesized that *TT* can be approximated with the following revised formula:

$$TT \approx \alpha + \sum_{i=1}^{n} (\beta + MT_i + GT_i) \qquad (42)$$

where α is an empirically derived coefficient and represents the combined mean learning and reaction times and β is a constant that accounts for the interference between movement time, reaction time, and glance time in dual-task situations as demonstrated by Shin and Rosenbaum.

6.3 Hypotheses

The research questions introduced informally in earlier sections are stated below as formal hypotheses and will be investigated experimentally. It is anticipated that one experiment can be used to accept or reject several hypotheses.

In the statement of the hypotheses below, *MT* is movement time, *ID* is Index of Difficulty, *RT* is reaction/recognition time, *GT* is glance time, and *TT* is total task completion time for multiple sub-tasks that comprise a single use-case interaction. Furthermore, H_0 denotes a null hypothesis, whereas H_a (also stated as H_1) denotes the alternative hypothesis.

$H1_0$: For rapid aiming tasks in non-stationary environments, the correlation between *MT* and *ID* is as predicted by the General Fitts formulation of Table 4.

$H2_0$: Posture (sitting versus standing) does not have an effect on *MT* in a rapid aiming task when using either finger or stylus as a direct input probe.

$H3_0$: Performing rapid aiming tasks in a dual-task situation not have an effect on *MT*.

$H4_0$: Acquisition of vibrating targets can be predicted by the General Fitts formulation of Table 4.

$H5_0$: There is no statistically significant difference in *ID* and error rate for indirect target acquisition using a trackball compared to direct target acquisition on a touch-screen using a stylus or a finger in a non-stationary environment compared to a stationary environment.

$H6_a$: *TT* in a non-stationary environment has a positive and linear correlation to *TT* in a stationary environment.

$H7_a$: *TT* for secondary tasks in a non-stationary environment has a positive and linear correlation to *TT* for primary tasks in a non-stationary environment.

$H8_a$: *TT* is proportional to the sum of *MT* and *GT* as described in Equation 42.

7. RESEARCH METHOD

7.1 Proposed Experiments

The hypotheses put forth in the previous chapter will be investigated through a series of experiments. Initially, a set of control experiments will be conducted to establish the validity of the experimental environment. These pilot experiments will focus on standard Fitts tasks, including the selection of multi-shaped on-screen regions using different input methods. The input methods that will be tested are direct touch with finger and stylus, trackball, and isometric joystick. The pilot experiments will consist of variations on Fitts' original discrete tapping experiment with differing sizes, locations, and types of shapes. Participants will be asked to carry out each experiment in a sitting as well as a standing posture to test the effect of posture on movement time. Subsequent experiments will focus on dual-task situations, in which experiment participants are asked to carry out a cognitive task while interacting with the same experiment. The goal is to establish baseline parameters for the conjectured interaction between cognitive and motor-process skills. The next set of experiments will introduce multi-step tasks that are representative of IVIS and SCINS interactions, such as entering a waypoint on a soft numeric keypad. The input to the soft keypad will be done in four modes: isometric joystick, trackball, and direct input with stylus as well as finger. Finally, the same battery of experiments will be performed aboard a boat that is underway to see the effects of an actual non-stationary environment.

If time permits, additional variables may be measured, including but not limited to effects of simulated visual feedback for touch screen selection, auditory feedback, height of subject and angle to display surface, color of targets, color of background, debilitating effects of motion sickness, and ambient light and noise.

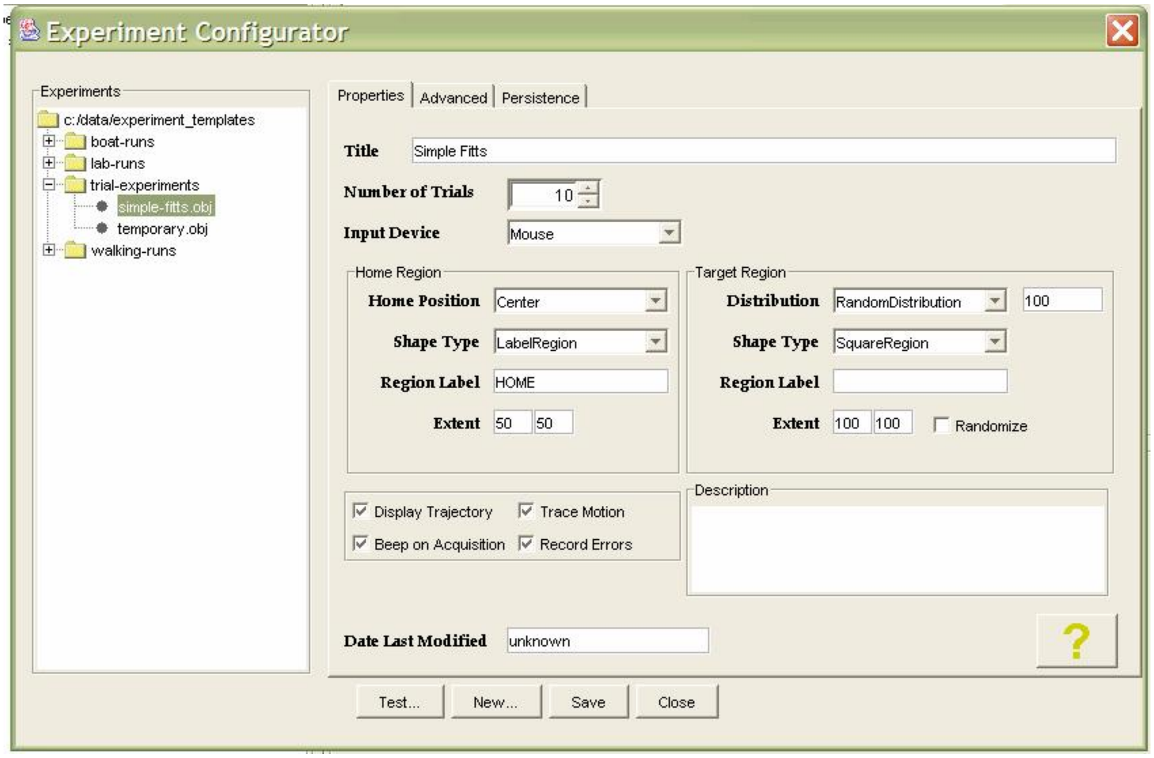
7.2 Proposed Experimental Environment

The proposed experiments involve human participants and therefore require approval by the University's Institutional Review Board (IRB.) The application for an expedited review by the IRB and the Informed Consent form for the participants are provided in the appendix.

7.2.1 Platform

The platform on which the experiments will be carried out consists of a custom software application written by the author in Java (Sun, 2005) and running on Microsoft Windows XP. All of the experiments, both in the lab and in the field, will be done through the same software. The software is configurable for different interaction tasks and allows experiment configurations to be saved so that consistency between the different experiment runs can be assured. It is touch-screen enabled and has the ability to deal with different indirect input devices, including joysticks, keypads, and trackballs. The input devices are supported through the universal mouse driver of Windows XP and are connected via a USB port. Figure 25 shows a screen capture of the experiment configuration screen. It allows an experimenter to control each run of the experiment. The actual conditions under which an experiment is carried out are captured in a different screen, which is shown in Figure 26. Additional screens exist for obtaining information about the subjects that participate in the experiments. Figure 27 shows a screen shot of a target acquisition.

All of the interactions, including all cursor movements, region selections, clicks, cursor traces (trails), and selection errors are recorded using Java object serialization and can be exported into a comma-separated text files (CSV format) so that importing into Excel, the MySQL relational database (MySQL, 2005), and the "R" statistical analysis package (R Development Core Team, 2004) are facilitated. It will be of particular importance to trace the trajectory of the cursor in the trackball and joystick movements and compare the stationary and non-stationary traces.



Title Simple Fitts

Number of Trials 10

Input Device Mouse

Home Region

Home Position Center

Shape Type LabelRegion

Region Label HOME

Extent 50 50

Target Region

Distribution RandomDistribution 100

Shape Type SquareRegion

Region Label

Extent 100 100 ☐ Randomize

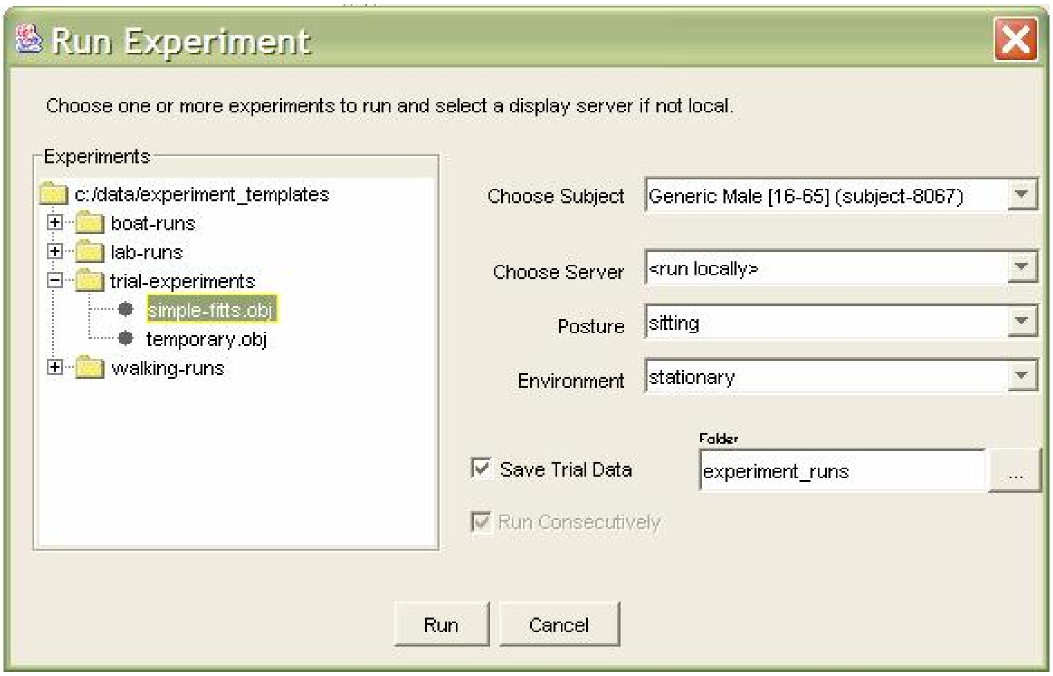
☑ Display Trajectory ☑ Trace Motion

☑ Beep on Acquisition ☑ Record Errors

Description

Date Last Modified unknown

Figure 25. Experiment configuration screen which allows setting of control parameters.



Choose one or more experiments to run and select a display server if not local.

- c:/data/experiment_templates
  - boat-runs
  - lab-runs
  - trial-experiments
    - simple-fitts.obj
    - temporary.obj
  - walking-runs

Choose Subject: Generic Male [16-65] (subject-8067)
Choose Server: <run locally>
Posture: sitting
Environment: stationary
☑ Save Trial Data
Folder: experiment_runs
☑ Run Consecutively

Figure 26. Run screen which captures the specific conditions under which the experiment trial is run.

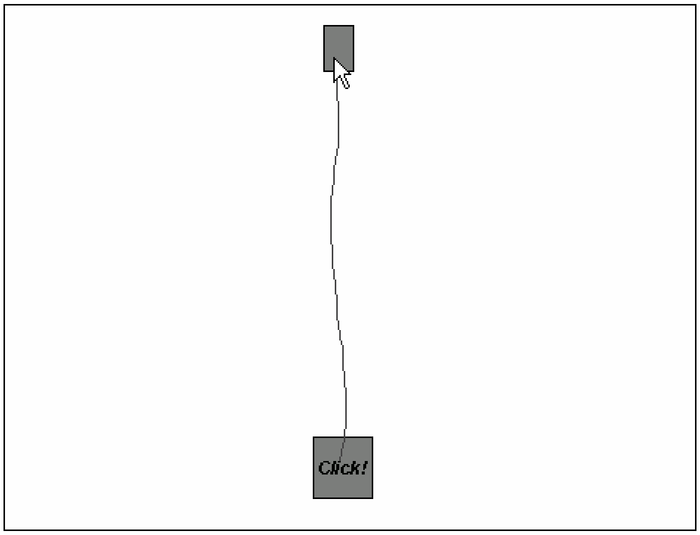


Figure 27. Sample Fitts task in which a square target is being acquired. The screen shows the trajectory of the movement.

The software has a distributed management feature, which allows the experimenter to control the experiment setup from a remote console.

7.2.2 Proposed Laboratory Experiments

The laboratory experiments will be completed in a supervised environment at the Department of Computer Science at the University of Massachusetts Lowell. The experiments will not be video taped. Only the interaction results will be recorded digitally. For each participant, the following information will be recorded: gender, age range, height range, and handedness. No additional private information will be gathered or stored.

7.2.2.1 Experiment I: Control Experiment with General Fitts Tasks

The first battery of laboratory experiments will be geared towards establishing a set of base line results that can be used for comparison with the results of more complex experiments, as well as proving the validity of the experimental platform and associated software. The control experiment measures simple Fitts tasks and therefore is expected to validate Equation 5. In addition, the experiment will be used to contrast the "goodness-of-fit" of the following movement time models: General Fitts (Equation 5) with probe corrections as necessary, Meyer's Law (Equation 17), Kvålseth's Law (Equation 19), and Oel *et al.*'s formulation (Equation 12). The results of the experiment should follow the observations by Oel *et al.* as shown in Table 5 with the exception that the evaluation will also consider Meyer's Law and the effect of posture (standing *vs.* sitting) on touch input.

7.2.2.1.1 Procedure

Participants will be asked to hit randomly appearing square targets. The movement will always start from the center of the screen. The cursor will be automatically returned to the center at the end of each trial and the trial will not start until the user clicks on the "home region" at the center of the screen. Successful target acquisitions will be confirmed by a "beep." Distance to the target (amplitude), target size, and approach angle will be randomized via the software. The same sequence of target sizes and target positions will be repeated for each input method and for each participant.

The tasks will be carried out using an isometric joystick, a trackball, and a direct touch-screen interface utilizing the pointing finger and a stylus as probes.

To reduce the effect of learning time, a series of warm-up trials will be administered before each experiment. The results of the warm-up trials will be recorded as it may aid in the determination of an average coefficient for learning time.

Each of the touch-screen experiments will be performed by each subject in a sitting as well as a standing position. This will help determine if there is natural noise present in motor movement even when the environment is stationary.

7.2.2.1.2 Subjects

The experiments will be carried out by 20-25 randomly selected student volunteers with the following characteristics: mix of male and female participants, right-handed users, normal or corrected-to-normal vision, no physical impairments. The subjects will receive a small amount of compensation, such as free refreshments and gift certificate, for their participation. The amount of compensation will not be tied to the results of the experiment.

7.2.2.1.3 Apparatus

The experiments are planned to execute on a PC running Windows XP, a 15” LCD monitor with 1024x768 or higher resolution, a Logitech Trackball, an isometric joystick (vendor not yet determined), and an LCD touch screen manufactured by Elo using five-wire or surface-acoustic technology. The trackball and joystick will be configured with minimal gain and no perceptible lag.

7.2.2.1.4 Experimental Design

The experiments will vary target distance, target size, and angle of approach as independent within-subject variables. The dependent variables are the Index of Difficulty (*ID*) and the mean Movement Time (*MT*), as well as the error rate (*ER*). The same series of experiments with the exact same target sizes, positions, and approach angles will be repeated with each input device (trackball, joystick, finger-touch, and stylus-touch.) Therefore, input device will be treated as another within-subject variable in the statistical evaluation. Each subject will perform 60 trials with each input device for a total of 240 trials. The touch-screen experiments will be repeated in a standing posture which increases the total number of trials to 480. Each trial should take approximately 5 seconds for a total experiment completion time of 40-45 minutes, not including breaks when changing input device.

Table 8. Design of Control Experiments. For each combination of Device, Posture and Independent Variable, *MT*, *ID*, and *ER* are recorded.

Device		**Independent Variables**		
		Distance to Target	*Size of Target*	*Angle of Approach*
Isometric Joystick		MT,ID,ER	MT,ID,ER	MT,ID,ER
Trackball		MT,ID,ER	MT,ID,ER	MT,ID,ER
Touch with Stylus	Standing	MT,ID,ER	MT,ID,ER	MT,ID,ER
	Sitting	MT,ID,ER	MT,ID,ER	MT,ID,ER
Touch with Finger	Standing	MT,ID,ER	MT,ID,ER	MT,ID,ER
	Sitting	MT,ID,ER	MT,ID,ER	MT,ID,ER

To reduce the effect of fatigue on the subjects, the entire battery of experiments will be designed to take no more than 60 minutes including short breaks.

7.2.2.2 Experiment II: Acquisition of Vibrating Targets

In a non-stationary environment the display will not be in one spot, instead the display will gyrate about its center. This gyrating motion can be simulated in an experiment by offsetting targets from their center while the acquisition occurs. This has the visual effect of a *vibrating target*. Such a vibration is similar to what would happen to a target if the environment is in a rocking motion as would occur on a boat. A gyrating display will only have an effect when a direct input device is used. It will be inconsequential for indirect input devices. Therefore, this experiment will only be carried out using touch interaction. Again, posture (sitting and standing) as well as distance from the touch screen will be introduced as an independent variables.

It is expected that the acquisition process will generally follow the models for acquiring moving targets, presented in Section 4.1.5.5.

7.2.2.2.1 Procedure

Participants will be asked to hit randomly appearing square targets that are vibrating randomly about their center. Successful target acquisitions will be confirmed by a "beep." Distance to the target and approach angle will be randomized via the software. All targets will have the same extent.

The tasks will be carried out using a direct touch-screen interface utilizing the pointing finger as a probe as well as a stylus.

To reduce the effect of learning time, a series of warm-up trials will be administered before each experiment. The results of the warm-up trials will be recorded as it may aid in the determination of an average coefficient for learning time.

Each of the touch-screen experiments will be performed by each subject in a sitting as well as a standing position. This will help determine if there is natural noise present in motor movement even when the environment is stationary.

7.2.2.2.2 Subjects

The experiments will be carried out by the same 20-25 randomly selected student volunteers from the first experiment.

7.2.2.2.3 Apparatus

The experiments are planned to execute on a PC running Windows XP, a 15" touch-sensitive LCD monitor with 1024x768 or higher resolution using finger and stylus input

7.2.2.2.4 Experimental Design

The experiments will vary target distance, frequency and amplitude of vibration and angle of approach as independent within-subject variables. The dependent variables are the Index of Difficulty (*ID*) and the mean Movement Time (*MT*), as well as the error rate (*ER*). The same series of experiments with the exact same target sizes, positions, and approach angles will be repeated with finger and stylus control. In addition, several different frequencies and amplitudes of vibration will be tested. Therefore, frequency and amplitude of vibration will be treated as another within-subject variable in the statistical evaluation. Each subject will be presented with 60 different targets at each of the three vibration settings. The subjects will perform these 180 trials with both stylus and finger in a standing as well as sitting position for a total of 720 trials. Each trial should take approximately 5 seconds for a total experiment completion time of 60 minutes, not including breaks when changing position and mode of input.

Table 9. Design of Experiment with Vibrating Targets. For each combination of Device, Posture and Independent Variable, *MT*, *ID*, and *ER* are recorded.

Device		**Independent Variables**		
		Distance to Target	*Vibration Setting*	*Angle of Approach*
Touch with Stylus	Standing	MT,ID,ER	MT,ID,ER	MT,ID,ER
	Sitting	MT,ID,ER	MT,ID,ER	MT,ID,ER
Touch with Finger	Standing	MT,ID,ER	MT,ID,ER	MT,ID,ER
	Sitting	MT,ID,ER	MT,ID,ER	MT,ID,ER

To reduce the effect of fatigue on the subjects, the entire battery of experiments will be designed to take no more than 60 minutes including short breaks.

7.2.2.3 Experiment III: Dual-Task Situations and Glance Time

This experiment will measure the effect of glance time. Subjects will be asked to pay attention to a second screen that displays a number indicating "water depth." The depth will change and subjects must monitor this value to make sure it does move below a certain value, which would be akin to vessel grounding. The trials of this experiment are identical to those of the fist experiment, which will provide an opportunity to measure the effect of glance time on movement time in dual-task situations.

7.2.2.3.1 Procedure

The setup for the experiment will be identical to that of experiment I. In addition, an LCD projector will display several numbers, including a numeric depth sounder reading that subjects must monitor. The subjects will be asked to state orally if the number moves below the limit. The experiments will be carried out in a standing position only, again with a variety of target distances, and approach angles. The size of the target will remain constant for all trials.

7.2.2.3.2 Subjects

The subjects will be the same as those in experiments I and II.

7.2.2.3.3 Apparatus

The apparatus will be the same as the one of experiments I and II.

7.2.2.3.4 Experimental Design

The experiments will vary target distance, and angle of approach as independent within-subject variables. The dependent variables are *ID* and *MT*, as well as the error rate (*ER*). The same series of experiments with the exact same target sizes, positions, and approach angles will be repeated with trackball and touch screen input using finger and stylus as probes. If time permits, the trials will be repeated using a joystick as an input device.

7.2.2.4 Experiment IV: Fitts Tasks While Walking

In this experiment, subjects will be walking while carrying out standard Fitts tasks. This will determine if movement of the body impacts *ID*. In addition, the speed of walking will help determine what the influence of dual-tasks situations is on *MT*. Based on observations by Shin and Rosenbaum (2002) *MT* should increase as the speed of walking increases. An increase in the speed of walking amounts to an increase in the complexity of the primary task.

7.2.2.4.1 Procedure

Participants will be asked to hit randomly appearing square targets while walking at various speeds on an indoor track or a treadmill. Successful target acquisitions will be confirmed by a "beep." Distance to the target (amplitude), target size, and approach angle will be randomized via the software.

The tasks will be carried out using a direct touch-screen interface utilizing the pointing finger and a stylus as a probe.

To reduce the effect of learning time, a series of warm-up trials will be administered before each experiment. The results of the warm-up trials will be recorded as it may aid in the determination of an average coefficient for learning time.

7.2.2.4.2 Subjects

The experiments will be carried out by the same subjects as those of the first three laboratory experiments.

7.2.2.4.3 Apparatus

The experiments are planned to execute on a Pocket PC (iPAQ, Dell Axim) running Windows Mobile 2003 with a touch-sensitive color LCD display with 480x640 or higher resolution.

7.2.2.4.4 Experimental Design

The experiments will vary target distance, target size, angle of approach as independent within-subject variables. The dependent variables are the Index of Difficulty (*ID*) and the mean Movement Time (*MT*), as well as the error rate (*ER*). The same series of experiments with the exact same target sizes, positions, and approach angles will be repeated with finger and stylus control. Each subject will be presented with 30 targets for each probe type at each walking speed for a total of 120 trials assuming two different walking speeds.

Table 10. Design of Walking Experiments. For each combination of walking speed, touch input probe and Independent Variable, MT, ID, and ER are recorded.

Device		**Independent Variables**		
		Distance to Target	*Size of Target*	*Angle of Approach*
Touch with Stylus	Slow	`MT,ID,ER`	`MT,ID,ER`	`MT,ID,ER`
	Fast	`MT,ID,ER`	`MT,ID,ER`	`MT,ID,ER`
Touch with Finger	Slow	`MT,ID,ER`	`MT,ID,ER`	`MT,ID,ER`
	Fast	`MT,ID,ER`	`MT,ID,ER`	`MT,ID,ER`

7.2.3 Proposed Field Experiments

7.2.3.1 Experiment V: Fitts Tasks In a Non-Stationary Environment

This series of experiments will be done aboard an actual vessel. Initially, participants in the study will perform a series of control experiments similar to experiment I while the vessel is at rest on the dock. Next, the same experiments will be done while the vessel is underway in various sea conditions.

7.2.3.1.1 Procedure

Participants will first be asked to hit a series of randomly appearing square targets of varying sizes similar to the tasks of experiment I. Next, participants are asked to enter a numeric waypoint on a soft keypad. After that, the waypoint entry experiment will be repeated in a dual-task setting, where participants are once again asked to monitor a "depth indicator" while entering the waypoint. The battery of Fitts tasks and waypoint entries will be done first while at dock and then while underway.

The tasks will be carried out using trackball, isometric joystick, and direct touch with finger and stylus probes. Only a standing posture will be considered.

To reduce the effect of learning time, a series of warm-up trials will be administered before each experiment. The results of the warm-up trials will be recorded as it may aid in the determination of an average coefficient for learning time.

7.2.3.1.2 Subjects

The experiments will be carried out by 10-15 randomly selected volunteers with the following characteristics: mix of male and female participants, right-handed users, normal or corrected-to-normal vision, no physical impairments. The subjects will be compensated for their participation. The amount of compensation will not be tied to the results of the experiment.

7.2.3.1.3 Apparatus

The software apparatus and experiment batteries will be the same as with the other experiments. In addition, a Vernier Accelerometer (3-Axis Accelerometer with LabPro connected via USB and using Vernier's LoggerPro software) will be used to measure the motion pattern and acceleration forces along all three axes of motion (pitch, roll, and yaw) in the environment. To obtain an understanding of the amplitude of the motion in various sea conditions, the vessel will be fitted with a pendulum suspended from the bridge ceiling. The swing of the pendulum will indicative of the amplitude of the motion.

7.2.3.1.4 Experimental Design

The Fitts task part of the experiment will vary target size, target distance, and angle of approach as independent within-subject variables. During the waypoint entry, only the target sizes (size of virtual numeric keys) will be varied. The dependent variables are the Index of Difficult (*ID*) and the mean Movement Time (*MT*), as well as the error rate (*ER*). The same series of experiments with the exact same target sizes, position, and approach angles will be repeated with each input device under consideration (trackball, isometric joystick, finger-touch, and stylus-touch.) Therefore, input device will be treated as another within-subject independent variable in the statistical evaluation. Each subject will perform 40 trials (30 Fitts tasks, 10 waypoint entries) with each input device for a total of 160 trials. The waypoint trials will be repeated as a secondary task. The entire battery of tests of all tasks will be repeated while underway.

7.2.4 Evaluation Methods

For each of the experiments, a thorough and appropriate statistical analysis will be carried out, including linear regression analysis and ANOVA. The statistical calculations will be done using Microsoft Excel for Windows XP and the R programming language. In addition, the data will be stored in a relational database and custom Java programs will be used to provide additional analysis and data displays.

8. RESEARCH GOALS

In the course of this research, we hope to make the following contributions:

1. A review and organization of recent literature on Fitts' Law and other perceptual-motor prediction models with a focus on the application of Fitts' Law to input devices commonly used to interact with applications in non-stationary environments, such as boats and automobiles.
2. A study of the research results for in-vehicle and driver information systems and their broader applicability to systems for other non-stationary environments, such as maritime small-craft integrated navigation systems.
3. An empirical investigation of the applicability of the MacKenzie, Meyer, Welford, Oel, Kvålseth, and Accot-Zhai formulations of Fitts' Law for secondary tasks in non-stationary environments.
4. An empirically derived predictive model for mean Task Completion Time (TT) of secondary numerical data input tasks. Such a model will provide specific heuristics to designers when creating user interfaces to assure that interaction tasks can be completed in the proper amount of time.
5. An experimental framework for testing Fitts' Law and other cognitive and motor behavior models.

9. SCHEDULE

9.1 Phases

The proposed research will be carried out in six main phases:

1. **Investigation Phase**: During the investigation phase a complete literature search on cognitive and motor-perceptual prediction models and their applicability to human-computer interface design will be carried out. In addition, experiments that have been used by others to derive empirical data supporting or rejecting various prediction models will be examined, including experimental setups for testing Fitts' Law and its derivatives, such as Myer's Law, the Accot-Zhai Steering Law, Kvålseth's Law, the Hick-Hyman Law, the Law of Practice, as well as other more specialized and applicable engineering models. Furthermore, current small-craft interactive navigation systems as well as in-vehicle information systems will be surveyed so that interactions patterns with such systems can be categorized and likely stimuli for user input can be determined.
2. **Experiment Design Phase**: During this phase a set of PC-based experiments will be devised that will allow for the gathering of data in a laboratory setting as well as aboard an actual vessel. After obtaining approval from the University's Institutional Review Board (IRB) for experiments with human subjects, a series of pilot experiments will be executed.
3. **Data Collection Phase**: During the data collection phase experiments will be carried out in a variety of stationary and non-stationary environments. When applicable, the experiments will be video taped for later analysis. All interactions with the experiments will be recorded.
4. **Data Evaluation Phase**: During the data evaluation phase a series of statistical analysis computations will be carried out on the collected data in order to make a determination if the stated hypothesis are supported by the data or must be rejected. In addition, an attempt will be made to derive an engineering model that describes task completion time when interacting with the experimental setup.

5. **Assessment Phase**: During the assessment phase the general applicability of our findings will be investigated and general recommendations for the design of controls for graphical user interfaces of touch-screen based SCINS will be stated.
6. **Documentation Phase**: During the documentation phase the results of the previous stages will be collected and organized into a final dissertation.

9.2 Schedule

		2005												2006				
	%	J	F	M	A	M	J	J	A	S	O	N	D	J	F	M	A	M
Literature Review	95%	▨	▨	▨	▨													
Experiment Design	80%				▨	▨												
Experiment Software	30%			▨	▨	▨	▨											
Testing (Lab)	10%					▨	▨	▨	▨	▨								
Testing (Field)								▨	▨									
Data Evaluation							▨	▨	▨	▨	▨							
Statistical Analysis & Modeling											▨	▨	▨	▨				
Write Dissertation														▨	▨	▨	▨	▨

10. GLOSSARY OF TERMS & ACRONYMS

IVIS	In-Vehicle Information System, such as an automotive GPS-based navigation system that provides drivers with location information and destination directions.
SCINS	Small-Craft Integrated Navigation System, such as Maptech's i3. A SCINS provides operators of small marine craft, such as boats or launches, with up-to-date GPS-based position information. Most SCINS include electronic charting, vessel operation data, status of machinery, and integration with satellite-based weather services.
HCI	Human-Computer Interface.
MMI	Man-Machine Interface.
MFD	Multi-Function Display.
HVI	Horizontal-Vertical Illusion
ID	Index of Difficulty. The component of Fitts' Law that describes how difficult a target is to hit.
IP	Index of Performance. See also *throughput*.
ICM	Iterative Corrections Model.
IVM	Impulse Variability Model.
OIIM	Optimized Initial Impulse Model.

11. REFERENCES

Aarons, R. (2002). *Small-Boat Seamanship Manual*. Camden, ME: International Marine/McGraw Hill.

Accot, J, Zhai, S. (1997). Beyond Fitts' Law: Models for trajectory-based HCI tasks. *Proceedings of the ACM CHI '97 Conference on Human Factors in Computing Systems*, Atlanta, GA: ACM, 295-302.

Accot, J, Zhai, S. (2001). Scale effects in steering law tasks. *Proceedings of the ACM CHI 2001 Conference on Human Factors in Computing Systems*, Seattle, WA: ACM, 1-8.

Accot, J, Zhai, S. (2003). Refining Fitts' law models for bivariate pointing. *Proceedings of the ACM CHI 2003 Conference on Human Factors in Computing Systems*, April 2003, Ft.Lauderdale, FL: ACM, 193-200.

Akamatsu, M., MacKenzie, I. S., Hasbrouq, T. (1995). A comparison of tactile, auditory, and visual feedback in a pointing task using a mouse-type device. *Ergonomics*, 38, 816-827.

Akamatsu, M., & MacKenzie, I. S. (1996). Movement characteristics using a mouse with tactile and force feedback. *International Journal of Human-Computer Studies*,45, 483-493.

Alexander, L., Ryan, J., Casey, M. (2004). Integrated Navigation System: Not a sum of its parts. *Proceedings of the Canadian Hydrographic Conference*, Ottawa, Canada, May 2004.

Anderson, P. (1999). Elastic Interfaces: Maritime instrumentation as an example. *Proceedings of the CSAPC '99*, Valenciennes, France: University of Valenciennes, 35-41.

Balakrishnan, R., & MacKenzie, I. S. (1997). Performance differences in the fingers, wrist, and forearm in computer input control. *Proceedings of the ACM Conference on Human Factors in Computing Systems – CHI '97*, pp. 303-310. New York: ACM.

Beck, E., Christiansen, M., Kjeldskov, J. Kolbe, N. and Stage, J. (2003). Experimental evaluation of techniques for usability testing of mobile systems in a laboratory setting. In *Proceedings of OzCHI 2003*, Brisbane, Australia, CHISIG, 106-115.

Beers, R. van, Baraduc, P., Wolpert, D. (2002). *Role of uncertainty in sensorimotor control. [Electronic Version]* Philosophical Transactions: Biological Sciences London: The Royal Society. Available from http://www.journals.royalsoc.ac.uk.

Beers, R. van, Haggard, P., Wolpert, D. (2004). The role of execution noise in movement variability. *Journal of Neurophysiology*, 91, 1050-63.

Blanco, M. (1999). *Effects of in-vehicle information systems (IVIS) tasks on the information processing demands of a commercial vehicle operations (CVO) driver.* Unpublished Master's Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA.

Bodenheimer, B., Shleyfman, A., Hodgins, J. (1999). The effects of noise on the perception of animated human running. *Computer Animation and Simulation '99, Eurographics Animation Workshop*, September 1999, 53-63.

Bohan, M., Phipps, C., Chaparro, Halcomb, C. (1999). A psychophysical comparison of two stylus-driven soft keyboards. *Proceedings of the 1999 Conference on Graphics Interface '99*, Kingston, Ontario, Canada, San Francisco, CA: Morgan Kaufmann Publishers Inc., 92 – 97.

Brewster, S., Crease, M. (1999) Correcting menu usability problems with sound. *Behaviour and Information Technology*, 18(3), 165-177.

Buhr, R. (1998). Use case maps as architectural entities for complex systems. *IEEE Transactions on Software Engineering*, 24 (12), pp. 1131-1155.

Burdet, E., Milner, T. (1998). Quantization of human motions and learning of accurate movements. *Biological Cybernetics*, 78, 307-318.

Burnett, G. (2000). Usable vehicle navigation systems: Are we there yet? *Proceedings of Vehicle Electronic Systems 2000*, ERA Technology Ltd., June 2000, 3.1.1-3.1.11.

Buxton, W. (1990). A Three-State Model of Graphical Input. In D. Diaper et al. (Eds), *Human-Computer Interaction - INTERACT '90*. Amsterdam: Elsevier Science Publishers B.V. (North-Holland), 449-456.

Buxton, W. (2004). *A directory of sources for input technologies*. Retrieved from web site at http://www.billbuxton.com/InputSources.html.

Buxton, W. (2005). *Human Input to Computer Systems: Theories, Techniques and Technology [Electronic Version]*. Unfinished Book Manuscript. Retrieved February 19, 2005 from Web site http://www.billbuxton.com/inputManuscript.html.

Card, S., English, W., & Burr, B. (1978). Evaluation of mouse, rate-controlled isometric joystick, step keys, and text keys for text selection on a CRT. *Ergonomics*, 21, 601-613.

Card, S., Moran, T., Newell, A. (1983). *The Psychology of Human-Computer Interaction*. Hillsdale, NJ: Erlbaum.

Carroll, J. (Ed.) (2003). *HCI model, theories, and frameworks: Toward a multidisciplinary science*. San Francisco, CA: Morgan Kaufmann Publishers.

Chapman (1999). *Seamanship and Small Boat Handling*. New York, NY: Hearst Marine Books, William Morrow & Company, Inc.

Chiang, D., Brooks, A., Weir, D. (2000). An experimental study of destination entry with an example automobile navigation system. (SAE Paper 2001-01-0810), Warrendale, PA: Society of Automotive Engineers.

Cockburn, A., Firth, A. (2003). Improving the acquisition of small targets. *Proceedings of the ACM CHI 2003 Conference on Human Factors in Computing Systems*, April 2003, Ft. Lauderdale, FL: ACM.

Constantine, L., Lockwood, L. (1999). Use cases in task modeling and user interface design. *Proceedings of the ACM CHI '99 Conference on Human Factors in Computing Systems*, Pittsburgh, PA: ACM, May 1999, 352-352.

Crossman, E., Goodeve, P. (1983). Feedback control of hand-movement and Fitts' law. *Quarterly Journal of Experimental Psychology*, 35A, 251-278. (First appeared in 1963).

Crow, E., Davis, F., Maxfield, M. (1960). *Statistics manual.* Mineola, NY: Dover Publications, Inc.

Cunningham, H. A. (1989). Aiming error under transformed spatial mappings suggests a structure for visual-motor maps. *Journal of Experimental Psychology: Human Perception and Performance*, 15(3), 493-506.

Dalgaard, P. (2002). *Introductory statistics with* R. New York, NY: Springer Verlag.

Douglas, S., Kirkpatrick, A., MacKenzie, S. (1999). Testing pointing device performance and user assessment with the ISO 9241, Part 9 Standard. *Proceedings of the ACM CHI '99 Conference on Human Factors in Computing Systems*, Pittsburgh, PA: ACM, May 1999, 215-220.

Draper, S. (1993) The notion of task in HCI. In (eds.) Ashlund, S., Mullet, K., Henderson, A., Hollnagel, E., White, T. (Eds) *Interchi'93 Adjunct Proceedings*, 207-208, New York, NY: ACM.

Ellison, B. (2005). In touch with the future. *Offshore Magazine*, February 2005, 118-123.

Enns, N. R. N., & MacKenzie, I. S. (1998). Touchpad-based remote control devices. *Companion Proceedings of the ACM Conference on Human Factors in Computing Systems – CHI '98*, pp. 229-230, New York: ACM.

Fedler, A. (2000). *Participation in recreational boating and fishing: a literature review.* Report prepared for the Recreational Boating and Fishing Foundation, Alexandria, Virginia.

Fitts, P. M. (1954). The information capacity of the human motor system in controlling the amplitude of movement. *Journal of Experimental Psychology*, 47, 381-391.

Francis, G. (2000). Designing multi-function display: An optimization approach. *International Journal of Cognitive Ergonomics*, 4(2), 107-124.

Friedlander, N., Schlueter, K. , Mantei, M. (1998). Bullseye! When Fitts' law doesn't fit. *Proceedings of the ACM CHI '98 Conference on Human Factors in Computing Systems*, Los Angeles, CA: ACM, 257-264.

Garrison, G. (2004). *Without re-course: These nine new navigation electronics will help you stay on the map and on time to your destination.* Retrieved February 8, 2005 from Boatingworldonline.com web site: http://www.boatingworldonline.com/News.htm?CD=1020&ID=3903.

Grabowski, M., Sanbord, S. (2003). Human performance and embedded intelligent technology in safety-critical systems. *International Journal of Human-Computer Studies*, 58, 637-670.

Green, P., Levison, W., Paelke, G., Serafin, C. (1994). *Suggested human factors design guidelines for driver information systems.* Technical Report UMTRI-93-21, University of Michigan, Transportation Research Institute, Ann Arbor, MI. Retrieved January 15, 2005 from Web site http://www.umich.edu/~driving/publications/UMTRI-93-21.pdf.

Green, P. (1999a). Estimating compliance with the 15-second rule for driver-interface usability and safety. *Proceedings of Human Factors and Ergonomics Society 43rd Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Green, P. (1999b). *Navigation system data entry: Estimation of task times*. Technical Report UMTRI-99-17, Ann Arbor, MI: The University of Michigan Transportation Research Institute.

Green, P. (1999c). The 15-second rule for driver information systems. *ITS America Ninth Annual Meeting Conference Proceedings*, Washington, D.C.: ITS America.

Green, P. (1998). *Visual and task demands of driver information systems*. Technical Report UMTRI-98-16, Ann Arbor, MI: The University of Michigan Transportation Research Institute.

Grossman, T., Balakrishnan, R. (2004). Pointing at trivariate targets in 3D environments. *Proceedings of the ACM Conference on Human-Computer Interaction – CHI 2004*, April 2004, Vienna, Austria, 6(1), 447-454, New York, NY: ACM.

Guiard, Y., Beaudouin-Lafon, M., & Mottet, D. (1999). Navigation as multiscale pointing: Extending Fitts' model to very high precision tasks. *Proceedings of ACM Conference on Human Factors in Computing Systems - CHI '99*, 450-457, New York: ACM.

Hassanein, K., Head, M. (2003). Ubiquitous usability: Exploring mobile interfaces within the context of a theoretical model. In Johann Eder, Roland Mittermeir, Barbara Pernici (Eds.): *The 15th Conference on Advanced Information Systems Engineering (CAiSE '03)*, Klagenfurt/Velden, Austria, 16-20 June, 2003, pp. 180-194.

Heathcote, A., Brown, S., Mewhort, D. (2000). The power law repealed: The case for an expotential law of practice. *Psychonomic Bulleting & Review*, 7, 185-207.

Hick, W. (1952). On the rate of gain of information. *Quarterly Journal of Experimental Psychology*, 4, 11-26.

Hinckley, K., Cutrell, E., Bathiche, S., Muss, T. (2002). Quantitative analysis of scrolling techniques. *Proceedings of the ACM CHI '02 Conference on Human Factors in Computing Systems*, Minneapolis, MN: ACM.

Hinckley, K. (2003). Input technologies and techniques. In Jacko, J., Sear, A. (Eds.). *The Human-Computer Interaction Handbook*. Mahwah, NJ: Lawrence Erlbaum Associates, 151-168.

Hinckley, K., Jacob, R., & Ware, C. (2004). Input/output devices and interaction techniques. In *Tucker, A. (Ed.) (2004). Computer Science Handbook, 2nd Edition*, Boca Raton, FL: Chaoman & Hall/CRC Press.

Hoffmann, E. R. (1991a). Capture of moving targets: a modification of Fitts' Law. *Ergonomics*, 34(2), 211-220.

Hoffmann, E. R., Sheikh, I. (1991b). Finger width corrections in Fitts' Law: Implications for speed-accuracy research. *Journal of Motor Behavior*, 23(4), pp. 259-262.

Hoffman, E. R. (1992). Fitts' law with transmission delay. *Ergonomics*, 35(1), 37-48

Hoffman, E. R. (1995). Effective target tolerance in an inverted Fitts task. *Ergonomics*, 38(4), 828-836.

Hoffmann, E., Sheikh, I. (1994) Effect of varying target height in a Fitts' movement task. *Ergonomics*, 36(7), 1071-1088.

Hoffmann, E., Lim, J. (1997). Concurrent manual-decision tasks. *Ergonomics*, 40(3), 293-318.

Holbrook, C. (2003). *Input methods for notification systems: A design analysis technique with a focus on input for dual-task situations*. Unpublished Master of Science Thesis, Virginia Polytechnic Institute, Department of Computer Science, Blackburg, VA.

Hornof, A. (1999). *Computational models of the perceptual, cognitive, and motor processes involved in the visual search of pull-down menus and computer screens*. Ph.D. Dissertation, Department of Computer Science, University of Michigan.

Hourcade, J., Bederson, B., Druin, A., Guimbretiere, F. (2003) *Accuracy, target reentry and Fitts' law performance of preschool children using mice [Electronic Version]*. Technical Report CS-TR-4472, Department of Computer Science, University of Maryland. Retrieved on March 12, 2005 from Web Site: http://www.cs.umd.edu/Library/TRs/CS-TR-4472/CS-TR-4472.pdf.

Husick, C. (2003). Navigation and plotters [Electronic Version]. *BoatUS Magazine*, September 2003, Retrieved from http://www.boatus.com/husick/techno09_03.asp.

Husick, C. (n.d.). *Electronic Navigation Charts*. Retrieved February 20, 2005 from BoatUS Web site: http://www.boatus.com/husick/n_electronchart.asp.

Hyman, R. (1953). Stimulus information as a determinant of reaction time. *Journal of Experimental Psychology*, 45, pp. 188-196.

International Maritime Organization (1996). *Recommendation on performance standards for electronic chart display and information systems (ECDIS)*. IMO Resolution MSC.64(67), Annex 4, December 8, 1998, London.

Jacko, J., Sear, A. (Eds.) (2003). *The Human-Computer Interaction Handbook*. Mahwah, NJ: Lawrence Erlbaum Associates.

Jagacinski, R. J., Repperger, D. W., Ward, S. L., & Moran, M. S. (1980a). A test of Fitts' law with moving targets. *Human Factors*, 22, 225-233.

Jagacinski, R. J., Repperger, D. W., Moran, M. S., Ward, S. L., & Glass, B. (1980b). Fitts' law and the microstructure of rapid discrete movements. *Journal of Experimental Psychology: Human Perception and Performance*, 6, 309-320.

Jax, S., Rosenbaum, D., Vaughan, J., Meulenbroek, R. (2003). Computational motor control and human factors: Modeling movements in real and possible environments. *Human Factors*, 45(1), 5-27, Human Factors and Ergonomics Society.

Kabbash, P., MacKenzie, I. S. & Buxton, W. (1993). Human performance using computer input devices in the preferred and non-preferred hands. *Proceedings of the ACM Conference on Human Factors in Computing Systems - CHI '93*, 474-481. New York: ACM.

Kabbash, P., Buxton, B. (1995). The "Prince" technique: Fitts' law and selection using area cursors. *Proceedings of the ACM Conference on Human Factors in Computing Systems - CHI '95*, 273-279. New York: ACM.

Kerr, R. (1975). Movement control and maturation in elementary-grade children. *Perceptual and Motor Skills*. 41(1), 151-154.

Kjeldskov, J., Graham, C. (2003a). A review of mobile HCI research methods. In *Proceedings of the 5th International Mobile HCI 2003 Conference*, Udine, Italy. Lecture Notes in Computer Science, Berlin, Springer-Verlag, 317-335.

Kjeldskov, J. and Skov, M. (2003b) Creating a realistic laboratory setting: A comparative study of three think-aloud usability evaluations of a mobile system. In *Proceedings of the 9th IFIP TC13 International Conference on Human Computer Interaction, Interact 2003*. Zürich, Switzerland: IOS Press, 663-670.

Kjeldskov, J., Skov, M., Als, B., & Høegh, R. (2004a). Is it worth the hassle? Exploring the added value of evaluating the usability of context-aware mobile systems in the field . In *Proceedings of the 6th International Mobile HCI 2004 Conference*, Glasgow, Scotland. Lecture Notes in Computer Science, Berlin, Springer-Verlag, 61-73.

Kjeldskov, J., Stage, J. (2004b). New techniques for usability evaluation of mobile systems. *International Journal of Human Computer Studies (IJHCS)*, Elsevier, 60(2004), 599-620.

Ko, H. (2000). *Open systems advanced workstation transition report*. Technical Report 1822, July 2000, United States Navy, SPAWAR Systems Center, San Diego, CA.

Kölsch, M., Turk, M. (2002). *Keyboards without keyboards: A survey of virtual keyboards*. Technical Report 2002-21, July 12, 2002, Department of Computer Science, University of California at Santa Barbara, Santa Barbara, CA.

Kristensson, P. (2005). Breaking the laws of action in the user interface. *Proceedings of the ACM Conference on Human Factors in Computing Systems - CHI '05, Doctoral Symposium*, Portland, OR: ACM.

Kvålseth, T. (1980). An alternative to Fitts' law. *Bulletin of the Psychonomic Society*, 16(5), 371-3.

Kvålseth, T. (1993). The paternity of the power law for motor control. *Perceptual and Motor Skills*, 76(1), 277.

Kvålseth, T. (1996). Square-root formula for choice reaction time. *Perceptual and Motor Skills*, 83(2), 475-8.

Langolf, G. D., Chaffin, D. B., & Foulke, J. A. (1976). An investigation of Fitts' law using a wide range of movement amplitudes. *Journal of Motor Behavior*, 8, 113-128.

Larkin, F. (1999). *Basic Coastal Navigation: An Introduction to Piloting*. Dobbs Ferry, NY: Sheridan House, Inc.

Latash, M.L., Anson, J.G. (1996). What are "normal movements" in atypical populations? *Behavioral and Brain Sciences*. 19 (1), 55-106.

Lee, D., Port, N., Georgopoulos, A. (1997). Manual interception of moving targets. *Experimental Brain Research*, 116, 421-433.

Leiden, K., Laughery, K., Keller, J., French, J., Warwick, W. (2001). *A review of human performance models of the prediction of human error.* NASA Report, Retrieved February 9, 2005, from NASA Web site: http://human-factors.arc.nasa.gov/ihi/hcsl/HPM_pubs/HumanErrorModels.pdf.

Lowry, R. (2005). *Concepts and applications of inferential statistics [Electronic Version]*. Web Site: http://faculty.vassar.edu/lowry/webtext.html.

Mathes, S., Herberg, J. , Berking, B., Behnke, J., and Jonas, M. (2001). *Functional scope and model of integrated navigation systems.* Bundesamt für Schiffahrt und Hydrographie (BSH) Report No. 28/2001 (ISSN 0946-6010), Hamburg, Germany: BSH.

MacKenzie, S. (1991). *Fitts' law as a performance model in human-computer interaction.* Unpublished Doctoral Dissertation, University of Toronto, Department of Computer Science, Toronto, Canada.

MacKenzie, S., & Buxton, W. (1992). Extending Fitts' law to two-dimensional tasks. *Proceedings of the ACM Conference on Human Factors in Computing Systems - CHI '92*, 219-226. New York: ACM.

MacKenzie, S., & Ware, C. (1993). Lag as a determinant of human performance in interactive systems. *Proceedings of the ACM Conference on Human Factors in Computing Systems - INTERCHI '93*, 488-493. New York: ACM.

MacKenzie, I. S., & Buxton, W. (1994a). The prediction of pointing and dragging times in graphical user interfaces. *Interacting with Computers*, 6, 213-227.

MacKenzie, I. S., & Riddersma, S. (1994b). Effects of output display and control-display gain on human performance in interactive systems. *Behaviour & Information Technology*, 13, 328-337.

MacKenzie, I. S., Nonnecke, B., Riddersma, S., McQueen, C., & Meltz, M. (1994c). Alphanumeric entry on pen-based computers. *International Journal of Human-Computer Studies*, 41, 775-792.

MacKenzie, S. (1995a). Movement time predictions in human-computer interfaces. In *Readings in Human-Computer Interaction*, 2nd Edition, 483-493, Los Altos, CA: Morgan Kaufman.

MacKenzie, I. S. (1995b). Input devices and interaction techniques for advanced computing. In W. Barfield, & T. A. Furness III (Eds.), *Virtual environments and advanced interface design*, 437-470. Oxford, UK: Oxford University Press.

MacKenzie, I. S., Zhang, S. X. (1999). The design and evaluation of a high-performance soft keyboard. *Proceedings of the ACM Conference on Human Factors in Computing Systems - CHI '99*, 25-31. New York: ACM.

MacKenzie, I. S., Kauppinen, T., & Silfverberg, M. (2001). Accuracy measures for evaluating computer pointing devices. *Proceedings of the ACM Conference on Human Factors in Computing Systems - CHI 2001*, 9-16. New York: ACM.

MacKenzie, I. S., Zhang, S. (2001b). An empirical investigation of the novice experience with soft keyboards. *Behaviour & Information Technology*, 20, 411-8.

MacKenzie, S. (2002). Web site http://www.yorku.ca/mack/RN-Fitts_bib.htm.

MacKenzie, S. (2003). Motor behaviour models for human-computer interaction. In J. M. Carroll (Ed.) *Toward a multidisciplinary science of human-computer interaction*, 27-54, San Francisco: Morgan Kaufmann.

MacKenzie, S., Soukoreff, R. W. (2003). Card, English, and Burr (1978) – 25 years later. *Extended Abstracts of the ACM Conference on Human Factors in Computing Systems – CHI 2003*, 760-761. New York: ACM.

Manes, D., Green, P. (1997). *Evaluation of a driver interface: Effects of control type (knob versus buttons) and menu structure (depth versus breadth) [Electronic Version]*. Technical Report UMTRI-97-42, University of Michigan, Transportation Research Institute, Ann Arbor, MI. Retrieved January 21, 2005 from Web site http://www.umich.edu/~driving/publications/UMTRI-97-42.pdf.

Mass Multi Media, Inc. (n.d.) *How touchscreens work*. Retrieved February 20, 2005 from Web site: http://www.touchscreens.com.

McFarlane, D. (1996). *An ergonomic assessment of a segmented keyboard [Electronic Version]*. Unpublished M.Sc. Thesis, University of New South Whales, Sydney, Australia. Retrieved from http://www.goldtouchtechnologies.co.uk/about_rsi/ergonassesofkbd.pdf.

McGuffin, M. (2002). *Fitts' law and expanding targets: An experimental study and applications to user interface design [Electronic Version]*. Unpublished M.Sc. Thesis, Department of Computer Science, University of Toronto, Toronto, Canada. Retrieved February 3, 2005 from Web site http://www.dgp.toronto.edu/~mjmcguff/research/msc-thesis/msc-thesis.pdf.

McGuffin, M., & Balakrishnan, R. (2002). Acquisition of expanding targets. *Proceedings of the ACM CHI 2002 Conference on Human Factors in Computing Systems*, April 2002, Minneapolis, MN: ACM.

McQueen, C., MacKenzie, I. S., & Zhang, S. X. (1995). An extended study of numeric entry on pen-based computers. *Proceedings of Graphics Interface '95*, 215-222. Toronto: Canadian Information Processing Society.

Mendenhall, W., Scheaffer, R., Wackerly, D. (1986). *Mathematical Statistics with Applications*. Boston, MA: PWS Publishers.

Meyer, D., Abrams, R., Kornblum, S., Wright, C., & Smith, J. (1988). Optimality in human motor performance: Ideal control of rapid aimed movements. *Psychological Review*, 95:3, 340-370.

Meyer, D. E., Smith, J. E. K., Kornblum, S., Abrams, R. A., & Wright, C. E. (1990). Speed-accuracy tradeoffs in aimed movements: Toward a theory of rapid voluntary action. In M. Jeannerod (Ed.), *Attention and performance XIII*. Hillsdale, NJ: Lawrence Erlbaum, 173-226.

Mould, D., Gutwin, C. (2004). The Effects of Feedback on Targeting with Multiple Moving Targets [Electronic Version]. *Proceedings of the 2004 Conference on Graphics Interface*, London, Ontario, Canada. Retrieved February 19, 2005 from Web site: http://hci.usask.ca/ publications/2004/targets-gi04/targets-gi04.pdf.

Murata, A., Fujii, M., Arima, Y., Iwase, H. (1999). Extending Effective Target Width in Fitts' Law to a Two-Dimensional Pointing Task. *International Journal of Human-Computer Interaction*. 11(2), 137-152.

MySQL (2005). *The MySQL™ database server, Windows XP desktop edition, Version 4.1.10*, Web Site: http://dev.mysql.com/downloads/mysql/4.1.html.

Nashel, A., Razzaque, S. (2003). *Tactile virtual buttons for mobile devices. Proceedings of the ACM CHI 2003 Conference on Human Factors in Computing Systems*, April 2003, Ft. Lauderdale, FL: ACM, 854-5.

Newman D., Bussolari S. (1990). Dual-task performance on an interactive human/computer space shuttle flight experiment. *Journal of Biomedical Sciences*, 26, 213-25.

Nielsen, J. (1992) Finding usability problems through heuristic evaluation. *Proceedings of the ACM CHI '92 Conference on Human Factors in Computing Systems*, Monterey, CA.: ACM, 373-380.

Nowakowski, C., Utsui, Y., and Green, P. (2000). *Navigation system evaluation: The effects of driver workload and input devices on destination entry time and driving performance and their implications to the SAE recommended practice*. Technical Report UMTRI-2000-20. Ann Arbor, MI: The University of Michigan Transportation Research Institute.

Nowakowski, C., Green, P., Tsimhoni, O. (2003). Common automotive navigation system usability problems and a standard test protocol to identify them. *Proceedings of the 13th Annual ITS America Meeting*, Washington, D.C.: Intelligent Transportation Society of America.

Oel, P, Schmidt, P., A. Schmitt (2001). Time prediction of mouse-based cursor movements. In *Proceedings of Joint AFIHM-BCS Conference on Human-Computer Interaction IHM-HCI 2001*. September 2001, Lille, France, Volume II, 37-40.

Oniszczak, A., & MacKenzie, I. S. (2004). A comparison of two input methods for keypads on mobile devices. *Proceedings of NordiCHI 2004*, New York: ACM, 101-104.

Oregon State Marine Board (2002). *Triannual Boating Survey [Electronic Version]*. Retrieved February 20, 2005 from http://www.marinebd.osmb.state.or.us/Library/TriSurvey01.

Panbo (n.d.). *Marine Electronics & Communications Blog*. http://www.panbo.com/.

Pascoe, J., Ryan, N., Morse, D. (2000). Using while moving: HCI issues in fieldwork environments. *ACM Transactions on Computer-Human Interaction*, 7(3), 417-437.

Poupyrev, I., Maruyama, S. (2003). *Tactile interfaces for small touch screens. Proceedings of ACM Symposium on User Interface Software and Technology (UIST 2003)*, Vancouver, BC, Canada, 217-220.

Phillips, J., Triggs, T., & Meehan, J. (2001). Arrowhead cursors have irrelevant features that influence cursor velocity and overshooting [Electronic Version]. *Proceedings of OZCHI 2001*, Retrieved February 18, 2005 from Web site http://www.unimelb.edu.au/development/web/docs/ozchi01/arrow.pdf

Phillips, J., Triggs, T., & Meehan, J. (2003). Conflicting directional and locational cues afforded by arrowhead cursors in graphical user interfaces. *Journal of Experimental Psychology Applications*, 9(2):75-87.

Plamondon, R., Alimi, A. (1997). Speed/accuracy tradeoffs in target-directed movements. *Behavioral and Brain Sciences*, 20(2), 279-349.

Powerboat Reports (2005). Chartplotters. 18(3), pp. 11-15. Norwalk, CT: Belvoir Publications.

R Development Core Team (2004). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing. ISBN 3-900051-07-0, Web Site: http://www.R-project.org.

Radix, C., Robinson, P., Nurse, P. (1999). Extension of Fitts' Law to modeling motion performance in man-machine interfaces. *IEEE Transactions on Systems, Man and Cybernetics, Part A: Systems and Humans*, 29(2), 205-209.

Recreational Boating & Fishing Alliance (2000). *Participation in boating and fishing: A literature review [Electronic Version]*. Retrieved February 20, 2005 from Web site: http://www.rbff.org/research/Lit-Review-Final.pdf.

Rosenbaum D, Gregory R. (2002). Development of a method for measuring movement-related effort: biomechanical considerations and implications for Fitts' law. *Journal of Experimental Brain Research*; 142(3), 365-73.

Rosenberg, D., Scott, K. (1999). *Use Case Driven Object Modeling with UML*, Reading, MA: Addison-Wesley.

Ross, T. (2001). Evaluating the human-machine interface to vehicle navigation systems as an example of ubiquitous computing. *Journal of Human-Computer Studies*, 55, 661-674.

Schedlbauer, M. (1999). *Effective Use Case Modeling*. Maynard, MA: Technology Resource Group, Inc.

Schmitt, A., Oel, P. (1999). Calculation of Totally Optimized Button Configurations Using Fitts' Law." *Proceedings of HCI International (the 8th International Conference on Human-Computer*

Interaction) on Human-Computer Interaction: Ergonomics and User Interfaces, 1, 392-396, Mahwah, NJ: Lawrence Erlbaum Associates, Inc.

Schneider, G., Winters, J. (1997). *Applying Use Cases: A Practical Guide*, Reading, MA: Addison-Wesley.

Silferberg, M., MacKenzie, S., Korhonen, P. (2000) Predicting text entry speed for mobile phones. *Proceedings of the ACM Conference on Human-Computer Interaction – CHI 2000*, Amsterdam, 9-16.

Silfverberg, M., MacKenzie, I. S., & Kauppinen, T. (2001). An isometric joystick as a pointing device for hand-held information terminals. *Proceedings of Graphics Interface 2001*, pp. 119-126 Toronto, Canada: Canadian Information Processing Society.

Shannon, C., Weaver, W. (1949). *The mathematical theory of communication.* Urbana, IL: The University of Illinois Press.

Sheikh, I., Hoffmann, E. (1994). Effect of target shape on movement time in a Fitts task. *Ergonomics*, 37(9), 1533-1547.

Shin, J., Rosenbaum, D. (2002). Reaching while calculating: Scheduling of cognitive and perceptual-motor processes. *Journal of Experimental Psychology*, 131(2), p. 206-219.

Shneiderman, B., & Plaisant, C. *Designing the user interface: Strategies for effective human-computer interaction.* Fourth Edition, Boston, MA: Pearson Education/Addison-Wesley.

Smits-Engelsman B., Van Galen G., Duysens J. (2002). The breakdown of Fitts' law in rapid, reciprocal aiming movements. *Experimental Brain Research*, 145(2), 222-230.

Soukoreff, W., & MacKenzie, I. S. (1995a). Generalized Fitts' law model builder. *Proceedings of the ACM Conference on Human Factors in Computing Systems – CHI '95*, Denver, CO, 113-114. New York: ACM.

Soukoreff, W., & MacKenzie, I. S. (1995b). Theoretical upper and lower bounds on typing speed using a stylus and soft keyboard. *Behaviour and Information Technology*, 14, 370-9.

Stevens, A., Quimby, A., Board, A., Kersloot, T., Burns, P. (2002). *Design Guidelines for Safety of In-Vehicle Information Systems*. [Electronic Version], Project Report PA3721/01, Transport Research Laboratory Ltd, United Kingdom. Retrieved January 30, 2005 from http://www.trl.co.uk/pdf/IVISGuidelines_finalversion.pdf.

Sun Microsystems (2005). *The Java™ 2 Platform, Standard Edition, Version 1.4.2*. Web Site: http://java.sun.com/j2se/1.4.2/download.html.

Tognazzinni, B. (1999). *A quiz designed to give you Fitts*. AskTOG Column, February 1999, Retrieved February 9, 2005 from Nielsen Norman Group Web site: http://www.asktog.com.

Thompson, S., Slocum, J., Bohan, M. (2004). Gain and angle of approach effects on cursor-positioning time with a mouse in consideration of Fitts' law. *Proceedings of the Human Factors and Ergonomics Society 48th Annual Meeting*, 823-7.

Tsimhoni, O., Green, P. (2001a). Visual demand of driving and the execution of display-intensive, in-vehicle tasks. *Proceedings of the Human Factors and Ergonomics Society 45th Annual Meeting*. Santa Monica, CA: Human Factors and Ergonomics Society.

Tsimhoni, O., D. Smith, P. Green (2001b). *Destination entry while driving: Speech recognition versus a touch-screen keyboard [Electronic Version]*. Technical Report UMTRI-2001-24, Ann Arbor, MI: University of Michigan, Transportation Research Institute, Retrieved January 7, 2005 from http://www-personal.engin.umich.edu/~omert/WWW/Documents/UMTRI%202001-24.pdf.

Tsimhoni, O., Smith, D., Green, P., (2004). Address entry while driving: Speech recognition versus a touch-screen keyboard, *Human Factors*, 46(6), 600-610.

Tucker, A. (Ed.) (2004). Computer Science Handbook, 2nd Edition, Boca Raton, FL: Chaoman & Hall/CRC Press.

Venables, W., Smith, D. (2004). *An introduction to R.* (Revised Edition). Briston, United Kingdom: Network Theory, Ltd.

Wade, M., Newell, K., Wallace, S. (1978). Decision time and movement time as a function of response complexity in retarded persons. *American Journal of Mental Deficiency*, 83(2):135-44.

Welford, A. (1960). The measurement of sensory-motor performance: Survey and reappraisal of twelve years' progress. *Ergonomics*, 3, 189-230.

Welie, M. van, Trætteberg, H. (2000). Interaction patterns in user interfaces. *Proceedings of Pattern Languages in Program Design – PloP '00*, August 2000, Monticello, IL.

Whiseand, T., Emurian, H. (1995). Some effects of angle of approach on icon selection. *Proceedings of the ACM Conference on Human Factors in Computing Systems – CHI '95*, Denver, CO, 298-299. New York: ACM.

Wikipedia (n.d.). Shannon's Theorem. Retrieved February 13, 2005 from Web site http://en.wikipedia.org/wiki/Shannon's_theorem.

Worden, A., Walker, N., Bharat, K., Hudson, S. (1997) Making computers easier for older adults to use: area cursors and sticky icons. In *Proceedings of the SIGCHI conference on Human Factors in Computing Systems*, Atlanta, GA: ACM, March 1997, 266-271.

Zhai, S., & MacKenzie, I. S. (1998). Teaching old mice new tricks: Innovations in computer mouse design. *Proceedings of the First World Congress on Ergonomics for Global Quality and Productivity*, 80-83. Hong Kong University of Science and Technology: Clear Water Bay, Hong Kong.

Zhai, S., Hunter, M., & Smith, B. (2000). The Metropolis keyboard – An exploration of quantitative techniques for virtual keyboard design. *Proceedings of ACM Symposium on User Interface Software and Technology (UIST 2000)*, November 2000, San Diego, CA, 119-128.

Zhai, S. (2002). *On the validity of throughput as a characteristic of computer input [Electronic Version]*. IBM Research Report, RJ 10253 (A0208-026), August 21, 2002. Retrieved February 14, 2005 from http://www.almaden.ibm.com/cs/people/zhai/papers/ZhaiIBMReporRJ10253.pdf.

Zhai, S., Woltjer, R. (2003). Human movement performance in relation to path constraint – The law of steering in locomotion. *Proceedings of the IEEE Virtual Reality 2003*, pp. 149-156.

Zhai, S., Kristensson, P., Smith, B. (2004a). In search of effective text input interfaces for off the desktop computing. *Interacting with Computers*, 16(2004).

Zhai, S. (2004b). Characterizing computer input with Fitts' law parameters – the information and non-information aspects of pointing. *International Journal of Human-Computer Studies*, 61(6), pp. 791-809.

Zhai, S., Kong, J., Ren, X. (2004c). Speed-accuracy trade-off in Fitts' law tasks – on the equivalency of actual and nominal pointing precision. *International Journal of Human-Computer Studies*, 61(6), pp. 823-856.

12. INDEX