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PERFORMANCE AND MOVEMENT KINEMATICS OF MOUSE POINTING TASK: PERSPECTIVES FROM AGE, PSYCHOMOTOR ABILITY, AND VISUAL ABILITY

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A DISSERTATION APPROVED FOR THE
SCHOOL OF INDUSTRIAL ENGINEERING

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TABLE OF CONTENTS

Page

LIST OF TABLES

Page

LIST OF FIGURES

Page

ABSTRACT

This dissertation research consists of three related studies evolving around the movement kinematics of mouse-mediated pointing task. Movement time and error rates are the common performance measures used in similar studies. However, the performance-oriented approach is not capable of providing information about what happens "during" the movement. It is believed that much can be learned from studying the movement process. Investigation of movement process is often done by studying its kinematics, by which can be characterized using various measures. However, despite the common belief, it is suspected that certain kinematic measures do not have any relationship with movement performance. Therefore, the first study was conducted to determine the kinematics-performance relationship of a mouse pointing task.

Of greater interest are the effects of age and functional abilities on the kinematics of aiming movement. The age effect is often identified as the cause of reduced performance. However, some argue the direct cause of such a reduction is actually due to age-related changes in functional abilities such as psychomotor ability. Based on that notion, it is hypothesized that the age effect on mouse use will become negligible if the effect of psychomotor ability is considered in parallel. Thus, the second study investigated the effects of age on mouse use, including after the psychomotor ability is included. Since good eye-hand coordination is required for mouse use, the research will be incomplete without considering how varying degree of visual ability can affect movement kinematics. Following along that line, the third study determined kinematic differences between people with low vision and those with normal vision.

Results from the first study confirmed the suspicion that not all kinematic measures reported in the literature were related to performance. For instance, although peak velocity is the most reported measure in the literature, it does not have any effect on performance. Kinematic measures correlate with performance are mainly temporal in nature, such as time to peak velocity, time to peak acceleration, and time from peak velocity until the end of movement. In the second study, as expected, age effects were detected in various kinematic measures. However, further investigation revealed the differences could in fact be attributed to psychomotor ability, but not the age effect per se. In general, the results confirm the notion of age being a surrogate variable, and that the causal relationship is in fact more directly related to age-related changes in psychomotor ability. In the third study, kinematics of the initial submovement for the low vision and the normal vision groups are stereotypical. However, the homing phase was significantly different between the two groups.

CHAPTER 1

INTRODUCTION

Despite the advances of computing technology, the mouse remains a primary, if not the most important device for interacting with computers. It has proven to be a useful tool in various computing tasks, whether it is browsing the Web or editing text documents. The direct manipulation paradigm offered by the mouse is so intuitive that even the relatively new touchpad had to be redesigned to match that of a mouse (MacKenzie, 2003).

Successful use of a mouse requires well-coordinated motor movements, as well as good visual condition. From a human control system point of view, mouse use is a closed-loop system characterized by high-level interaction between motor control (output) and visual function (input). In other words, the cursor on the screen provides visual feedback to the user who may subsequently control the mouse to produce desired results. Nevertheless, this description is rather simplistic because researchers have shown that the movement is more complex than it seems.

An obvious approach to study motor control and visual function concurrently is by observing the eye-hand coordination of the user. Eye-hand coordination is a generic term used to describe the spatial and temporal coupling of a user's hand and eye movements when performing tasks such as using a computer mouse. Studies of eye-hand coordination are not uncommon in human-computer interaction (HCI) research. Smith, Ho, Ark, & Zhai (2000) superimposed cursor positions on eye gaze positions in order to gain insights about the eye-hand coordination of mouse users. Although mixed results were obtained, the study by Smith and colleagues nevertheless represents a rudimentary but yet a logical extension of basic research in eye-hand coordination to the HCI domain.

In the context of the computer mouse, there are various user attributes affecting performance. A variable of significant interest is the age effect. However, Birren & Renner (1977) and Salthouse & Maurer (1996) suggested that, in most cases, the age effect is only a surrogate variable. It is variables such as knowledge, skills, and abilities that have direct causality relationship with performance differences. Such conjecture has been confirmed by other researchers. For instance, Czaja & Sharit (1998) and Smith, Sharit, & Czaja (1999) found that the age effect alone did not account for differences in performance of computing tasks, but it was the age-related changes in functional abilities that caused such differences.

Perhaps a more valid approach is to investigate factors that directly affect performance (e.g., psychomotor ability and visual functions). Degraded visual conditions due to pathologies such as macular degeneration have been known to affect visual ability. Therefore, being an intertwined component of most visuomotor tasks, visual condition is expected to contribute to performance differences in mouse use. Similar arguments can also be made in regard to the effects of psychomotor ability, whereby conditions such as cerebral palsy would certainly be detrimental to mouse use performance.

The effects of psychomotor ability have been considered in many studies involving a mouse (e.g., Czaja & Sharit, 1998, Hwang, 2001; and Jacko, Vitense, & Scott, 2003). The effects of visual ability on mouse use have also been studied (e.g., Jacko, Dixon, Rosa, Scott, & Pappas, 1999; Jacko et al., 2003; Jacko, Barreto, et al., 2000; and Jacko, Rosa, Scott, Pappas, & Dixon, 2000). Traditionally, endpoint performance measures such as movement time and error rate are analyzed in order to make empirical comparisons. However, such a performance-oriented approach is quite limited because it does not offer information as to why a particular observation is obtained. This approach is incapable of providing sufficient information regarding the movement process (Chua, Weeks, & Goodman, 2003; Douglas & Mithal, 1997; MacKenzie, Kauppinen, & Silfverberg, 2001; and Smith, Ho, Ark, & Zhai, 2000), and consequently additional insights may be overlooked.

An alternative to the performance-oriented approach is the process-level approach, where the process itself is investigated. Jagacinski, Repperger, Moran, Ward, & Glass (1980) conducted one of the first studies of cursor movement by performing a micro-analysis on Fitts' law using cursor movements controlled by a joystick. More recent work has led to the process approach for studying pointing devices. MacKenzie, Kauppinen, & Silfverberg (2001), Mithal & Douglas (1996), and Phillips & Triggs (2001) all have demonstrated that there is more information to be gained using such an approach. The process-level approach also has been recently reported in studies that are more applied in nature, including those with interest in special populations such as the elderly and people with disabilities (e.g., Hwang, Keates, Langdon, & Clarkson, 2004; and Ketcham, Seidler, Van Gemmert, & Stelmach, 2002).

A related area of research is the modeling of aiming movement. Mouse tasks are mainly goal-directed involving aimed movements. First proposed in a doctoral dissertation in the late 19th century, a two-component model of aimed movements posits that the movement consists of two phases: the ballistic or open-looped phase in the beginning, followed by the homing phase that is characterized by visually-controlled, overt discontinuities in the movement (Elliott, Helsen, & Chua, 2001). The two-component model is currently accepted by many researchers as the most adequate model that describes aiming movement. However, data used in similar studies were usually not stratified according to individual differences (e.g., age, psychomotor ability, and visual function). Therefore, little is known as to how the two-component model differs for individuals with varying degree of abilities.

In summary, while many factors affecting mouse use performance were uncovered from past research, perspectives from "during" the movement were rarely offered. Therefore, it was determined that the process-level approach could provide additional insights on mouse use based on understanding the effects of age, psychomotor ability, and visual ability. While the process-level approach is not unprecedented, the novelty of the current study lies in the fact that individual differences are taken into consideration for investigating mouse cursor movement. Also, it is believed that by identifying the differences in the process of aiming movement in respect to age, psychomotor ability, and visual ability can facilitate a greater understanding of mouse use from a more diverse population.

CHAPTER 2

RESEARCH KNOWLEDGE BASE

Mouse use is a process that is influenced by various user abilities, albeit to varying extents. Among these abilities is motor control. This has to do with effective movement of the body through utilization of skeletal muscles, the nervous system, and joints. Electromyography (EMG), a technique for detecting muscular electrical potentials, is often used for measuring motor activities. Studies of motor control often overlap with cognitive function, as evidenced in Willingham's (2004, p. 287) definition of motor control as the ". . . ability to plan and execute movements." Another important aspect of mouse use is visual ability. Vision is the sensory ability that allows detection of light sources, and subsequently perception of visual information. The Snellen visual acuity test and visual field test are some common psychophysical techniques for measuring visual ability. Psychomotor ability also is also believed to play a vital role in mouse use performance; Jacko & Vitense (2001) suggested psychomotor ability to be a hybrid of cognitive, perceptual, and physical abilities.

The Venn diagram in Figure 1 illustrates an idealistic representation of the relationships between various human abilities in the context of mouse use performance. It should be noted that the diagram scale does not suggest the magnitude of the relationships. The diagram posits that variability of mouse use performance may be explained by three aspects of human ability, namely: motor control, vision, and cognitive ability. These abilities do not act independently but they can complement each other. Rather, various functional abilities are integrated with one another to various extents, as depicted in Figure 1. For instance, the intersection of motor control and cognitive ability can be seen as efferent motor control where the motor movements are activated as a result of cognitive processing. While it is unlikely that coordination between vision and motor control does not involve cognition, the two-way intersection between the two functional abilities can be seen as a representation of visuomotor function. Generally, visual perception requires some level of cognitive processing; thus it is represented in the intersection between vision and cognitive ability. Finally, psychomotor ability, which has been suggested as a hybrid of all three functional abilities (Jacko & Vitense, 2001), is represented in the three-way intersection.

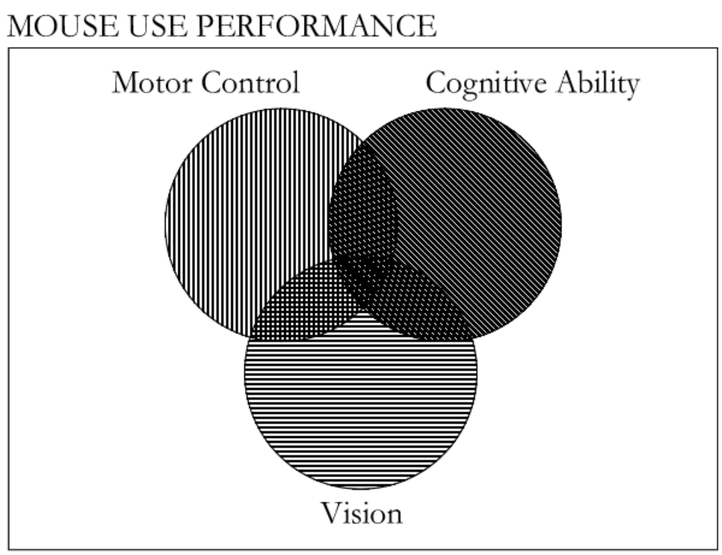

Figure 1. Functional Abilities Influencing Performance of Mouse Use.

2.1. Psychomotor Ability

Psychomotor generally describes actions that require coordination of various parts of the body. Executive control is needed to facilitate such coordination of multiple body parts. This view was reinforced by Jacko & Vitense (2001) who posited that cognitive function is a component of psychomotor ability, and that psychomotor ability is in fact composed of a combination of cognitive, perceptual, and physical abilities. Furthermore, Fleishman (1972) differentiated psychomotor skill from psychomotor ability. Ability is referred to as a general personal trait that is developed during childhood and adolescence. It is relatively enduring under normal circumstances. On the other hand, skills pertain to the levels of proficiency specific to the task criterion itself.

There are infinite tasks where good psychomotor ability is necessary. In the context of HCI, psychomotor tasks can be as simple as reaching out to push the power button, or as complex as typing on a keyboard. However, with adequate training, one can type on the keyboard with only modest effort. Fleishman (1975) differentiated psychomotor ability from psychomotor skill. Ability is referred to as a general personal trait that is developed during childhood and adolescence. It is relatively enduring under normal circumstances. On the other hand, skills pertain to the levels of proficiency specific to the task. To illustrate the difference, finger dexterity is a type of psychomotor ability that has been linked to the psychomotor skill of keyboard typing (Knight & Salvendy, 1992).

2.1.1. Fleishman's Taxonomy of Elemental Psychomotor Ability

Similarly to the cognitive domain, some researchers believe that psychomotor ability can be classified into several elemental components. There have been many attempts to identify and to classify these components. Of these, Fleishman's taxonomy is the most extensive attempt (Merrill, 1972). Originally developed for use in Air Force personnel training and selection, the works by Fleishman and colleagues are based on the assumption that certain abilities are required for specific tasks. Therefore, they believed performance could be improved if the task was matched with the required abilities.

Fleishman's, taxonomy was developed using factor analytic methods (Fleishman, 1975). Its development process spanned many years, and several hundred laboratory tasks were investigated. The development process began from a large dataset collected from laboratory tasks. The data were then treated as the variables for the subsequent factor analysis. After a fair amount of computation, common variables were delineated from the dataset. The common variables were considered to account for the most variance in task performance, and to represent most, if not all, aspects of psychomotor domain. Multiple factors were identified based on the loading of the variables, and subsequently the factors were defined and labeled semantically to reflect the communality among the variables. These factors were then considered as the elemental components of psychomotor ability. Collectively, the labels and pertinent definitions form Fleishman's taxonomy.

Depending on the version consulted, Fleishman's taxonomy contains ten or eleven independent psychomotor abilities. Fleishman & Reily (1992) listed ten abilities: (1) control precision, (2) multilimb coordination, (3) response orientation, (4) rate control, (5) reaction time, (6) arm-hand steadiness, (7) manual dexterity, (8) finger dexterity, (9) wrist-finger speed, and (10) speed-of-limb movement. These abilities can be assessed using an array of simple laboratory tests. For instance, control precision can be assessed using the rotary pursuit test; multilimb coordination can be measured using a two-arm coordination test. Table 1 describes the elemental psychomotor abilities as outlined in the taxonomy, as well as the appropriate test equipment.

Table 1. Description and Test of Elemental Psychomotor Ability (Fleishman & Reily, 1992).

Psychomotor Ability	Description	Test Equipment
Control precision	• Ability to make highly controlled and precise adjustments that are quick or continuous.	Rotary pursuit test
Multilimb coordination	• Ability to coordinate movements of two or more limbs in a rather static position. • Does not involve movements when body is in motion.	Two arm coordination test
Response orientation	• Ability to respond quickly to two or more signals, by choosing between two or more movements. • Also known as choice reaction time.	Multi-choice reaction time apparatus
Rate control	• Ability to adjust equipment control in response to change of speed or direction of a target. • Only applies to target that is unpredictable.	Bassin anticipation timer
Reaction time	• Ability to respond to a single signal. • Also known as simple reaction time.	Multi-choice reaction time apparatus
Arm-hand steadiness	• Ability to keep arm and hand steady, either while moving the arm or while both arm and hand are in static position.	Steadiness tester (groove or hole type)
Manual dexterity	• Ability to handle fairly large objects with one or both hands. • May also include arm-hand movements.	Minnesota manual dexterity test
Finger dexterity	• Ability to make skillful, coordinated finger movements. • Usually involves handling of small, pin-sized objects.	Purdue pegboard test
Wrist-finger speed	• Ability to make fast and repeated movements of the fingers, hands, and wrists. • May involves some degree of eye-hand coordination.	Tapping board
Speed-of-limb movement	• Ability to make quick, gross movements of the arms or legs.	Toggle switch device

Researchers have found the taxonomy useful in several ways. Knight & Salvendy (1992) were among the first authors to suggest the linkage between manual computer tasks and elemental psychomotor ability. Even though Fleishman's taxonomy was originally developed for personnel selection, it was argued that the taxonomy also was useful for identifying the skills required for performing computer tasks. For instance, it was suggested that finger dexterity and wrist-finger speed were required for keyboard typing, whereas mouse use was linked to control precision and arm-hand steadiness. Unlike highly-controlled settings such as the in the military, it is not feasible to select users to match the psychomotor requirements of the task in computing environments. Thus, a more appropriate approach is to provide alternative interaction techniques to accommodate users with varying degrees of psychomotor ability.

Fleishman's taxonomy also can be used to characterize individual differences. There has been some interest among researchers in creating a new framework for developing user interfaces that are adaptable to user needs. This effort is of particular interest in the area of designing for special populations. Jacko & Vitense (2001) suggested that user profiles, in addition to storing information such as user skills, requirements, and preference, should also include a database of user abilities. It was further argued that pathological information, such as the type of impairment, is unable to capture real user needs. Rather, the knowledge of impairments should be used to construct a database of functional abilities. Existing classification of psychomotor ability and other functional abilities (i.e., cognitive, perceptual, and physical) would allow researchers to model users more systematically. It was further argued that by including information on user abilities a more comprehensive user profile can be constructed, which in turn, facilitates the implementation of a more effective adaptive user interface.

Fleishman's taxonomy also may be used as a reference tool for reporting study participants' psychomotor ability as part of their demographic data. Phenomena observed in behavioral studies may be tied to the population from which study participants are drawn.

Therefore, it is important to include demographic and relevant information when reporting a study. This practice allows readers to scrutinizing the generalizability of the study outcomes. Some of the most common demographic information reported include age and gender. Reporting information about participant characteristics also provides a basis for critical comparison of one study to another. Similar goals also can be achieved by reporting participants' functional abilities, such as psychomotor ability.

2.1.2. Limitations of Fleishman's Taxonomy

Despite its potential, there are some limitations associated with Fleishman's taxonomy. Other than critiques pointed at the factor analytic methods of which the taxonomy was developed, other researchers questioned the applicability and practicality of the taxonomy. In fact, the proponents themselves (Fleishman & Quaintance, 1984) cautioned that since the abilities were semantically defined, and despite their best effort to be precise, subjectivity is inevitable. Therefore, interpretation issues may arise when the taxonomy is used by researchers other than the original authors. In addition, Cheong, Pham, Phan, & Shehab (2005) argued that there may be some mismatch between the characteristics of the standardized test used to characterize psychomotor ability and that of the actual task itself. Characteristics unique to the task context may not match those of the standardized test, thus rendering the proposed relationship artificial. Therefore, the predictive validity of psychomotor abilities is an overarching concern. It is a question of whether the abilities specified in Fleishman's taxonomy are indeed correlated with actual performance in broad practical settings.

Disagreement against Fleishman's works emerged as soon as the taxonomy was published (see Adams, 1987; Alvares & Hulin, 1972; and Bechtoldt, 1962). There were two primary concerns: statistical and methodological. The first is related to the factor analytic methods used for developing the taxonomy. Unlike other statistical methods, factor analysis treats all variables alike. It is a method for computing the communalities of variables to the hypothesized factors. The method cannot be used for assessing how a set of variables (e.g., independent variables) regress to another variable (e.g., dependent variable) because it does not make the distinction of independent-dependent variable. However, Fleishman's taxonomy was developed by identifying common variance in regard to a criterion (i.e., dependent) variable, a method not warranted under factor analysis. The second concern has to do with the experimental procedure, specifically the uncorrelated factors (i.e., independent factors in the language of the taxonomy) produced. Even though orthogonal rotation was used, Bechtoldt (1962) contended that it was insufficient because the experimental procedure did not warrant independence. This is due to the fact that data were obtained from repeated trials, thus disqualifying them from being independent. There were also additional concerns: (1) ambiguous objective of the tests whereby data is collected, (2) possible non-unique solution if the data is subjected to factor analysis at a different point of time, and (3) misuse of exploratory factor analysis methods.

2.1.3. Aging, Psychomotor Ability, and Computing Tasks

Operating under the task requirements approach, psychomotor ability has been investigated by researchers for use as performance indicator of computer tasks. An example of such work is Hwang (2001), whose goal was to identify a methodology for evaluating the type of pointing devices for patients with upper-limb motor impairments (e.g., cerebral palsy, spina bifida, muscular dystrophy, and quadriplegia). Participant manual dexterity was measured using the Minnesota manual dexterity test. Completion times of the test were later analyzed to determine the correlation with performance using various pointing devices. The significant correlation found between the two measures prompted the conclusion that manual dexterity tests could be utilized to select the appropriate pointing devices for people with upper-limb motor impairments.

Czaja & Sharit (1998) investigated performance of a computer data entry task for participants aged 20 to 75 years old. Even though age was significant, it was found that the age-related changes in functional abilities, not age per se, caused the performance differences. Psychomotor ability, and to a lesser extent, cognitive ability, were found to contribute to the variability of task performance. In a separate study, Smith, Sharit, & Czaja (1999) tested participants on a series of computer mouse tasks (i.e., pointing, clicking, double-clicking, and dragging). Participant psychomotor ability was measured using various standardized tests (i.e., trail making test, block design test, and grooved pegboard test). As expected, performance differences were detected in regards to age. However, further investigation showed it was age-related changes in psychomotor abilities that accounted for such differences. Said differently, when controlling for differences in psychomotor ability, the age effect was no longer a significant factor in driving performance differences.

There is a large body of research providing alternative explations of the age effect on psychomotor ability. Salthouse & Somberg (1982) attempted to localize the stage that is responsible for reduced psychomotor ability. Stages such as encoding, response selection, and execution were found to contribute to the decline. Other researchers took a more biological approach and investigated the role of sensorimotor systems, specifically the central nervous system (CNS), muscle composition and activation, and proprioception (for a review, see Ketcham & Stelmach, 2001). In short, there is no doubt that declines in psychomotor ability are associated with aging, which it may in turn contribute to reduced performance in computer tasks such as mouse use. There is some evidence indicating that after controlling for basic functional abilities, the age effect on task performance diminishes. This evidence is consistent with the view that the age effect is only a surrogate variable, and that underlying abilities are the true causal variables for performance differences (see Birren & Renner, 1977; and Salthouse & Maurer, 1996).

2.2. Visual Condition

From a human control system point of view, visual information is vital for determining subsequent output actions. Likewise, mouse use also relies heavily on visual feedback. There are many studies that investigate the contribution of vision in non-mechanized, direct hand movements (e.g., Elliott, Carson, Goodman, & Chua, 1991; Helsen, Elliott, Starkes, & Ricker, 1998; and Ricker et al., 1999), and to a lesser extent, computer-mediated movements such as the use of a mouse (e.g., Chua & Elliott, 1993). However, studies involving participants with limited visual function are relatively scarce. Jacko and colleagues (e.g., Jacko, et al., 1999; Jacko et al., 2003; Jacko, Barreto, et al., 2000; and Jacko, Rosa, et al., 2000) are among the few who have investigated computer users with vision impairment. The general objective of their studies was to investigate the impacts of low vision on mouse use. This line of research belongs to the domain of universal access.

2.2.1. Classifications of Visual Condition

A framework is needed to allow characterization of visual conditions across a wide spectrum, i.e., from normal vision to partial-sighted vision. An effective scheme is especially vital for describing partially sighted vision. For instance, both cataracts and diabetic retinopathy have been linked to diabetes. It is therefore possible that a person may suffer from multiple eye diseases, and that an individual's vision may be compromised by compound vision loss. In order to describe consequences of a disease more cohesively, the International Classification of Impairments, Disabilities and Handicaps (ICIDH) and the International Classification of Functioning, Disability and Health (ICF), have been developed by the World Health Organization (WHO). These frameworks, particularly ICIDH, have been shown useful for describing partially sighted vision from multiple perspectives.

Although often used interchangeably, the terms "disorder", "impairment", "disability", and "handicap" are used in ICIDH for differentiating among various aspects of medical condition. As summarized by Colenbrander (2000), "disorder" refers to anatonomical or physiological changes due to the pathology; "impairment" refers to functional changes to the organ; "disability" focuses on the functional abilities of the individual; " handicap" refers to the socioeconomic consequences caused by the condition. In the context of the visual system, disorder refers to the anatomical and physiological changes associated with an eye disease. For example, age-related macular degeneration (AMD) is known to be associated with changes in the macula, the fovea, and the retina. On the other hand, impairment refers to the functional abnormality of the eye. For instance, AMD causes blurred vision, increased sensitivity to glare, and central blind spots. Outside of the biological aspects of the patient, disability refers to the limited ability of the patient to perform tasks. For example, AMD patients were found to spend more time searching for information on the computer screen (Jacko et al., 2002). More broadly, handicap refers to the socioeconomic consequences of a disability. It was reported by Scott et al. (1994) that there was a high risk for decreased functional status and quality of life among ophthalmic patients. Table 2 shows the aspects of vision loss captured by ICIDH, as illustrated in Colendrander (2000).

Table 2. Aspects of Vision Condition (Colenbrander, 2000).

The Organ		The Person	
Visual Disorder	Visual Impairment	Visual Disability	Visual Handicap
Anatomic changes	Functional changes	Skills and abilities	Social and economic consequences
Examples: Inflammation, astrophy, scar	Examples: Visual acuity, contrast sensitivity	Examples: Reading, writing, daily living, mobility	Examples: Extra effort, loss of independence

In applied settings, visual condition is often measured along a functional vision dimension. Eligibility for assistance and intervention programs (e.g., educational assistance, tax benefits, and social security assistance) are often based on measures of functional vision. Functional vision refers to a person's ability to use his vision in order to perform daily tasks effectively (Flom, 2004). Common measures of functional vision include visual acuity, visual field, color sensitivity, and contrast sensitivity. Some of the less common measures include light sensitivity, oculomotor control, and accommodation. Among these, visual acuity, visual field, and contrast sensitivity are the greatest determinants of the ability to accomplish daily tasks (Flom, 2004). Visual acuity is the ability to see fine details. It is expressed using the Snellen ratio where the numerator represents the distance between the person and the object at which the person can recognize the object and the denominator is the distance at which a person with normal eyesight can correctly recognize the object. To illustrate, a person with 20/40 vision can resolve objects at 20 ft., but the same objects can be resolved by a person with normal vision at 40 ft. Visual field is a three-dimensional sensitivity to differential light at various positions, often measured in degree-radius or degree-diameter (Colenbrander, 2000). Color sensitivity is the ability to differentiate colors; it often involves the ability to discern two different colors such as green and red, or the ability to discriminate a normal range of colors. Finally, contrast sensitivity is the ability to discern the differences in luminance (brightness) between an object and its background. Contrast sensitivity is typically measured using a number of charts such as the Pelli-Robson chart.

In the United States, the most common classification scheme for visual condition is ICD-9-CM (U.S. Department of Health and Human Services [DHHS], 1980), which involves ordinal grouping of visual acuity scores. It is in fact the American adaptation of the International Classification of Diseases Ninth Revision (ICD-9) developed by the WHO (1977). A person is considered as being visually impaired when his visual acuity cannot be corrected to a level of 20/80. There are two broad ranges of visual impairments as defined in ICD-9-CM, namely low vision and blindness. Low vision characterizes acuity scores from 20/80 to 20/1000, whereas a person is considered as being near-blindsighted if he is 20/1250 or above. At the end of the continuum is total blindness; that is, no light perception is possible in the eyes (see Table 3). Another classification scheme is the one based on visual field. A person is considered as being visually impaired when his visual field is less than 30º; and the severity increases as the degree-radius becomes narrower (Colenbrander, 2000). Similar to that of the visual acuity scheme, the extreme is total vision loss (see Table 4).

Table 3. Visual Condition as Classified according to Visual Acuity (DHHS, 1980).

Visual Condition	Ranges of Visual Acuity (in Snellen Ratio)
Normal vision	20/12 – 20/25
Near-normal vision	20/30 – 20/60
Moderate low vision	20/80 – 20/160
Severe low vision	20/200 – 20/400
Profound low vision	20/500 – 20/1000
Near blindness	20/1250 – 20/2500
Total blindness	No light perception

Table 4. Visual Condition as Classified according to Visual Field (Colenbrander, 2000).

Visual Condition	Ranges of Visual Field (in Degree Radius)
Normal vision	51° – 70°
Near-normal vision	31° – 50°
Moderate vision loss	11° – 30°
Severe vision loss	6° – 10°
Profound vision loss	3° – 5°
Near total vision loss	Less
Total blindness	No light perception

Corn & Koenig (1996) commented that laboratory-based measures of visual functions (i.e., visual acuity and visual field) may not represent the requirements of real-world tasks. Despite the skepticisms, such practice seems to be well-received at large (e.g., Colenbrander, 2000; Flom, 2004). In some respects, the concerns are somewhat ameliorated by recent studies that have successfully demonstrated the significance of visual functions in computing tasks. A team of researchers (i.e., Scott, Feuer, & Jacko, 2002; Jacko, Barreto, et al., 2000; Jacko et al., 1999; and Jacko, Rosa, et al., 2000) have shown visual acuity, contrast sensitivity, visual field, and color deficiencies are indeed predictive of the performance of mouse use.

2.2.2. Aging, Low Vision, and Computing Tasks

One of the most common conditions of reduced visual function is low vision. As shown in Tables 3 and 4, low vision describes a wide range of visual conditions between normal vision and blindness. Some authors refer to low vision as a condition whereby despite the use of corrective devices, visual limitations are still profound. It should be made clear that low vision does not necessarily translate to blindness; it is an umbrella term that encompasses a large number of visual impairments. Only 10% of those who suffer from vision loss are functionally blind (Nelson & Dimitrova, as cited in Kraut & McCabe, 2000). Functional blindness refers to conditions whereby individuals no longer have useful vision and they have to rely on other sensory systems to perform daily activities. On the other hand, people with low vision still retain some useful vision (Lighthouse International, 2001). Also referred to as partially sighted, these individuals often rely on corrective techniques and devices to perform their daily activities.

Statistics show that low vision is more prevalent in the older population. The Eye Diseases Prevalence Research Group (2004) reported a steady increase of low vision conditions among adults aged 40- to 80-years-old. A similar trend of visual impairments in the older population was also reported by Desai, Pratt, Lentzner, & Robinson (2001, March), who reported that 19% of individuals 70 years of age and older were visually impaired. It has even been suggested that vision loss is only second to arthritis as the leading cause of disability among older adults (Pegels, as cited in Kraut & McCabe, 2000).

There are many causes for low vision. Despite the statistics, aging itself does not necessarily lead to vision loss. Although there are physiological changes in the eyes as one ages (Kline & Scialfa, 1996), it is believed that these changes are not the major cause for low vision. For instance, certain aged ocular structures, such as the cornea, present negligible effects on visual functions (Klien & Scialfa, 1996). The main cause for low vision among older adults seems to be disease-related. Among these diseases, AMD, cataracts, glaucoma, and diabetic retinopathy are known to be the main causes of low vision (Kraut, 2000). AMD is a condition caused by deterioration of the macula, the central part of the retina responsible for visual acuity in the central visual field. Due to the loss of acuity in the central visual field, AMD patients usually have to rely on their peripheral vision (Jacko et al., 2002). Cataracts are associated with clouding of the lens. Common effects of cataracts include blurred and hazy vision, particularly in places with high illumination. Glaucoma is caused by pressure build-up inside the eyeball that damages the optic nerve, which in turn causes loss of peripheral vision. Diabetic retinopathy is caused by the leaking of retinal blood vessels in diabetic patients. Visual impairments due to diabetic retinopathy include blurred vision and increased sensitivity to glare. Descriptions of these diseases are available in Table 5.

Although less common, low vision may be also caused by age-related neurophysiological changes. Changes in the cornea, aqueous humor, iris and pupil, lens, vitreous humor, and the retina have been associated with aging (Kline & Scialfa, 1996); they have been linked to various degrees of vision loss, ranging from negligible effects to major impairments. For instance, the aged cornea is found to have little effect on visual function. In contrast, the increase in intraocular pressure due to aged aqueous humor has been associated with glaucoma.

Table 5. Characteristics of Common Eye Diseases.

Disease	Description	Anatomical Structure Involved
AMD	What is affected • Central scotoma (blind spots) • Blurred vision • Sensitivity to glare What is not affected • Peripheral vision	• Fovea • Macula • Retina • Lens (if cataracts is present)
Cataracts	What is affected • Reduced acuity • Reduced contrast sensitivity • Hazy vision • Increased sensitivity to light and glare What is not affected • Field of vision • Scotoma (blind spots)	• Cornea • Pupil • Lens • Vitreous humor
Glaucoma	What is affected • Periphery vision • Night blindness	• Retina • Optic nerves
Diabetic Retinopathy	What is affected • Central scotoma (blind spots) • Blurred vision • Sensitivity of glare What is not affected • Peripheral vision	• Fovea • Macula • Retina • Lens (if cataracts is present)

Jacko et al. (1999) investigated performance differences along various graphical user interface (GUI) attributes for participants with eye diseases such as retinitis pigmentosa, albinism, optic neuritis, and myopia. Participants' visual conditions were characterized using visual function measures, i.e., visual acuity, contrast sensitivity, visual field, and color discrimination. The results indicated that these measures were significant predictors of task performance, particularly in regard to icon size and background color. In another study involving AMD patients, Jacko, Barreto, et al. (2000) found that characteristics of cursor movement (i.e., movement time and velocity) change as visual acuity changes. Differences in movement time and velocity were detected between fully sighted and partially sighted participants; it was also found movement time increases as visual acuity worsens.

2.3. Aiming Movement

Aiming movement is often referred to as goal-directed movement in spatially constrained tasks, and is subject to the speed-accuracy tradeoff. Studies of aiming movement have been an ongoing effort since the seminal work by Woodworth (1899) who reported a series of experiments to investigate the spatial and temporal behavior of the hand in goal-directed aiming movements. Woodworth's experiments consisted of an aiming task where participants were required to make reciprocal horizontal movements with a pencil on a paper rotating at a constant speed (see Elliott, Helsen, & Chua, 2001). Studies of direct aiming movement have been performed involving different human limbs (e.g., arm, fingers, the eyes, and the head) and in various conditions, such as underwater and at high altitude (for a review, see Plamondon & Alimi, 1997). The same technique has been used very successfully in studies related to performance of computer input devices. Aiming movements with input devices are often referred to as indirect movements because rather than pointing directly with the hands, such movements are usually performed with a device that mediates between the hand and the computer.

2.3.1. Fitts' Pointing Paradigms

Most studies of aiming movement, particular those involving computer pointing devices are influenced by Fitts' paradigm (MacKenzie, 1992; Soukoreff & MacKenzie, 2004). Traditionally, there are two variants: reciprocal and discrete pointing tasks. The reciprocal task involves making back and forth movements between two targets (see Figure 2); it was first used in the original Fitts experiment (Fitts, 1954/1992). A decade later, the discrete tapping task was reported in Fitts & Peterson (1964). In contrast to the reciprocal task, the discrete task requires subjects to make only one movement from the starting point to the desired target (see Figure 3). It is not known whether these two tasks differ significantly in terms of their influence on the model's parameter (i.e., the intercept and the slope). Perhaps the differences are subtle, if any, because a search in the literature failed to return any relevant studies.

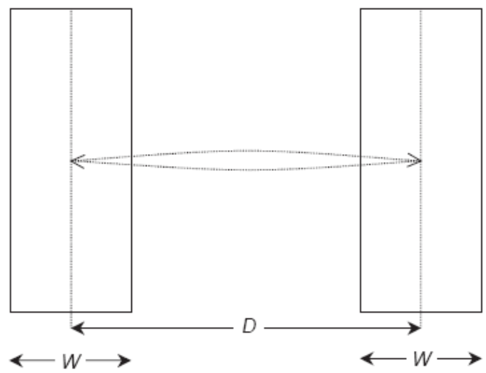

Figure 2. Fitts' Reciprocal Pointing Task (Soukoreff & MacKenzie, 2004).

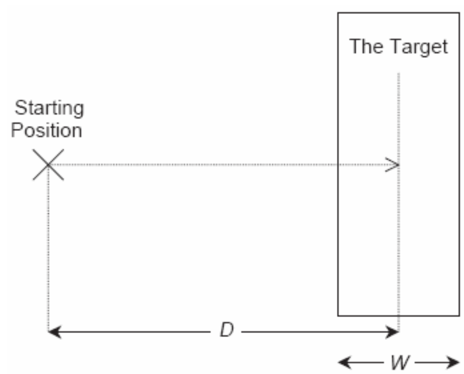

Figure 3. Fitts' Discrete Pointing Task (Soukoreff & MacKenzie, 2004).

A recently discovered problem with the classic Fitts' paradigms is the likelihood of movement angle confound (Phillips & Triggs, 2001). To avoid such bias, a multidirectional paradigm was proposed in ISO 9241-9 (International Organization for Standards [ISO], 2000). In the paradigm, subjects are required to sequentially click the targets spaced around the circumference of a circle. The targets are arranged in a way that the movement distance from one target to another is approximately the diameter of the circle. In a clockwise direction, the participants is required to first click the topmost target followed by the bottommost target and then return to the target adjacent to the first. Therefore, the multidirectional task is similar to a reciprocal task except it is two-dimensional (see Figure 4).

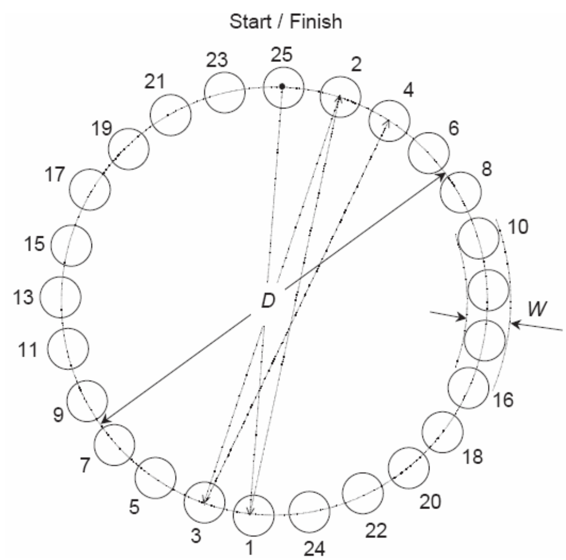

Figure 4. Multidirectional Pointing Task (Soukoreff & MacKenzie, 2004).

Recent developments indicate that the two-dimensional, multidirectional task is preferred over the one-dimensional task (e.g., Douglas, Kirkpatrick, & MacKenzie, 1999; and Soukoreff & MacKenzie, 2004). The main rationale for the switch is to avoid directional bias towards performance data such as movement time (MT) and throughput (TP). It should be noted that proponents of the multidirectional task are usually interested in aiming movements at the performance level. Studies have been scarce in addressing the question of whether different paradigms can affect the process of the movement itself. There is at least one study (i.e., Keele & Posner, 1968) that found the reciprocal pointing task yields higher MT due to the additional time needed to reverse the movement.

2.3.2. Models of Aiming Movement

2.3.2.1. Fitts' Law

Fitts' Law is one of the most studied models of aiming movement. It is a psychomotor behavior model that describes the relationship between movement time, distance amplitude, and target size. Movement time (MT) is simply the travel time from one point to another. Distance amplitude (D) is the total displacement traveled, whereas target size (W) is usually described as the width of the target. Simply, the model states that movement time has an inverse relationship with distance amplitude but at the same time it is directly related to target size (see Equation 1).

$$MT = a + b\log_2\left(\frac{2D}{W}\right) \tag{1}$$

Fitts' law was born from the notion of human information processing that became widely accepted during World War II. Its development is credited to information theory, particularly Shannon's Theorem 17 (Shannon, 1948) on electronic signal-to-noise ratio. According to MacKenzie (1992), Fitts' law is unique in two ways. First, it views the difficulty of a task in terms of the amount of information the task carries, which is measurable in bits. Second, Fitts' Law considers that a human's ability to accomplish a task is limited by interlocking cognitive and neuromuscular capacities. Therefore, human information capacity was viewed by Fitts as analogous to the channel capacity of an electronic system. When Shannon's formulation is rewritten in the context of human as an information processor, it is represented as Equation 2:

$$TP = ID / MT \tag{2}$$

where index of difficulty (ID) is the logarithmic portion of Equation 1, and is analogous to the ratio of signal strength to background noise of an electronic system. As the result, throughput (TP), sometimes referred to as index of performance (IP), represents the capacity of human as an information processor; and is measured in bits per second. TP is a composite measure that incorporates the two most important measures of Fitts' Law: speed and accuracy. The speed-accuracy trade-off is an inherent characteristic in a typical aiming movement, because generally it is not possible to be quick and at the same time accurate. TP also can be used as a standardized measure for comparing device performance from different studies. Because researchers often use different sets of target parameters (i.e., D and W) in their individual studies, MT, which itself is derived from the parameters, cannot be used as a standard measure for comparing outcomes from different studies. TP, on the other hand, is free from such contextual dependency; thus it can be used as a standardized measure for cross study comparisons. TP has also been computed as the reciprocal of the slope coefficient (1/b) in Equation 1 (e.g., Hwang, 2001).

After its publication, Fitts' formulation was immediately appraised by researchers from all fields. Most of the time, an alternative formulation was proposed and subsequently was claimed to be a better fit. To date, there are no less than 14 variations of Fitts' law (see Plamondon & Alimi, 1997). It is believed that most variations are highly localized and may be overly contextual. Furthermore, some researchers (Desmurget, Pralanc, & Rossetti, 1997; and Heuer, 1997) believe that certain efforts in retrofitting the original formula have resorted to number crunching rather than relying on theoretical foundations.

In spite of that, there are several alternative formulations that worth mentioning. One of the most popular variations is the one proposed by Welford (1960), as shown in Equation 3.

$$MT = a + b\log_2\left(\frac{D}{W} + 0.5\right) \tag{3}$$

Another common variation involves replacing the logarithmic portion of Equation 1 with Shannon's formulation of ID (see Equation 4). This ID has direct analogy with the electronic signal-to-noise ratio as originally suggested by Fitts (1954/1992), where D as analogous to signal strength and W represents the noise. Proponents of Shannon's formulation include MacKenzie (1989), MacKenzie (1992), and Soukoreff & MacKenzie (2004).

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

The ISO 9241-9 standard (ISO, 2000) recommends Equation 4 for calculating degree of difficulty associated with selection, pointing, and dragging task, whereas $ID = D / W$ was recommended for a tracking task.

It was later realized that Fitts' Law, being a performance-level model, is unable to capture what happens "during" the movement. Thus, alternative models were proposed to overcome that limitation. Despite being a century-old, Woodworth's study laid the groundwork in the quest for understanding the process of aiming movement. Based on his experiments, Woodworth suggested that aiming movement can be decomposed into two phases: the initial impulse phase and the current control phase (Elliott et al., 2001). The initial impulse phase is generally ballistic and is programmed to arrive at the vicinity of the target, whereas the current control phase is the homing phase and is characterized by frequent use of visual information to make adjustments. A number of contemporary models had been proposed since, a notable model was the deterministic iterative corrections model proposed by Crossman & Goodeve (1963/1983), which later refined by Keele (1968). Due to the overly restrictive assumption, the deterministic model was later deemed inappropriate and it had been largely discarded in favor of the stochastic optimized submovement (SOS) model (Meyer, Abrams, Kornblum, Wright, & Smith, 1988; Meyer, Smith, Kornblum, Abrams, & Wright, 1990).

2.3.2.2. The Deterministic Iterative Corrections Model

Unlike Fitts' information theoretic approach, Crossman & Goodeve (1963/1983) interpreted aiming movements using feedback-control theory. They suggested that aiming movements are deterministic because the model assumes no spatial variability for movement endpoints. The model offers three postulations. First, it posits that aiming movements consist of several discrete ballistic phases, called submovements in Crossman & Goodeve's terminology. Each of these submovements covers a certain distance between the starting point and the end point, and each submovement travels at a constant proportion of the distance. Referring to Figure 5, there are three submovements in the velocity profile of a hypothetical aiming movement. Notice that distance traveled reduces in each successive submovement. In fact, using D to denote the entire distance between starting point and end point, the distance covered by the first submovement can be expressed as pD; the second submovement would travel $p(D - pD) = p(1 - D)$; then followed by the third submovement that travels $p(1 - D)^2$, and so forth. The movement terminates when it arrives to the inside of the target area. The second postulation states that each submovement takes an equal amount of time to complete. The third postulation states that the control of submovements is based on intermittent visual and kinesthetic feedbacks; such a feedback-control postulation was later elaborated by Keele (1968).

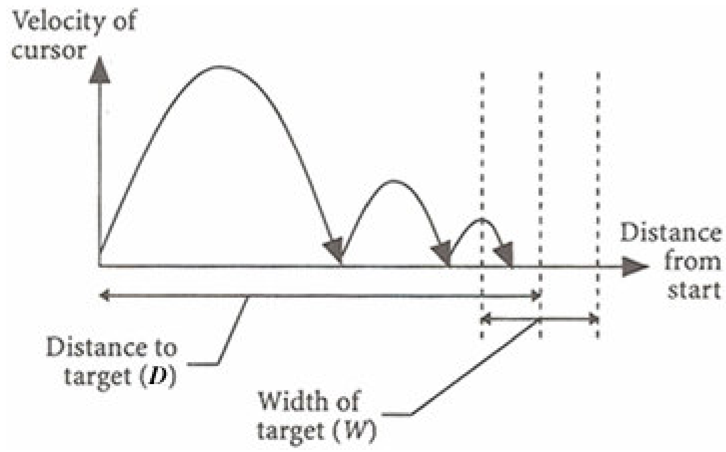

Figure 5. Deterministic Iterative Corrections Model (Douglas & Mithal, 1997).

Subscribing to Crossman & Goodeve's (1963/1983) feedback-control postulation, Keele (1968) suggested that given ample time for visual processing, or about 190 ms to 260 ms (Keele & Posner, 1968), movement corrections (i.e., submovements) can be made based on visual feedback. Aside from visual feedback, kinesthesis was also considered as a feedback mechanism. Kinesthetic feedback is part of the afferent system that includes muscles, joints, and touch that provide spatial orientation to movement control. Even though kinesthetic feedback was found to contribute to movement control, most studies were inconclusive in determining kinesthetic processing time. Furthermore, recent studies showed kinesthetic feedback alone is not as effective as visual feedback for movement control (Meyer et al., 1988). In addition to visual and kinethestic feedback, preprogrammed motor movement was also suggested to contribute to movement control. However, the degree to which motor programs contribute to movement control it is not known, "[while] motor programs may be used in reproducing active movements . . . other cues might also be important" (Keele, 1968, p. 399).

Many inconsistencies in the deterministic model were uncovered in later studies (see Meyer et al., 1988; and Meyer et al., 1990). Contrary to the notion of constant proportion, several studies found the duration of the initial submovement is indeed dependent upon target width (W) and distance amplitude (D). Perhaps the most obvious limitation of the model is its assumption that submovement endpoints are deterministic (i.e., no variability). There is a large amount of evidence proving otherwise. Furthermore, the model fails to account for movement errors (i.e., target misses), which are frequently observed in other studies. Finally, it has been observed that only one or two submovements are needed to arrive at the target; this phenomenon cannot be accounted for by the model, because it states that the systematic variation in the number of submovements is a function of D/W. As a result, the deterministic iterative corrections model was abandoned in favor of alternative models (Elliott et al., 2001).

2.3.2.3. The Stochastic Optimized Submovement (SOS) Model

After the rejection of the deterministic iterative corrections model, several other models were proposed, e.g., the single correction model, the second-order under-damped function, and the impulse variability model (for a review, see Douglas & Mithal, 1997; and Elliott et al., 2001). Current consensus indicates that the stochastic optimized submovement (SOS) model developed by Meyer and colleagues (Meyer et al., 1988; and Meyer et al., 1990) is the most appropriate model for describing the process of aiming movement. Like its predecessor, the SOS model operates under the assumption that optimization of aiming movement requires a compromise between time and accuracy (i.e., speed-accuracy tradeoff). The SOS model builds upon previous models (i.e., the deterministic iterative corrections model and the impulse variability model), by synthesizing the best feature from each of them. It inherits the feedback-control hypothesis from the deterministic model, as well as the endpoint variability hypothesis of the impulse variability model (Elliott et al., 2001).

The most recognizable attribute of the SOS model is the notion of neuromotor noise. Due to noise, submovement endpoints may be normally distributed around the center of the target. Feedback systems (i.e., visual sensory, and kinesthetic sensory to a lesser extent) may detect movement discrepancies (i.e., overshooting or undershooting) and that causes corrective submovements. To illustrate, Meyer et al. (1988) suggested that a typical aiming movement may consist of one or two submovements. Primary submovement is the initial submovement programmed to end within the target. If the primary submovement ends as intended, no secondary submovements are needed. However, neuromotor noise may prevent the initial submovement to arrive at the target as intended and in that case, corrective secondary movements are needed. It was further suggested that a typical aiming movement needs only one or two submovements. Third-order and higher submovements are possible; but these are usually absorbed within the secondary submovement. In general, higher-order submovements are quite unlikely and are often observed in special situations such as when extremely difficult targets are involved, or when errorless performance is required. The velocity profile of a typical movement is illustrated in Figure 6; the solid lines indicate possible primary submovements, whereas the dotted lines indicate the subsequent secondary submovements required if the initial movement misses the target area.

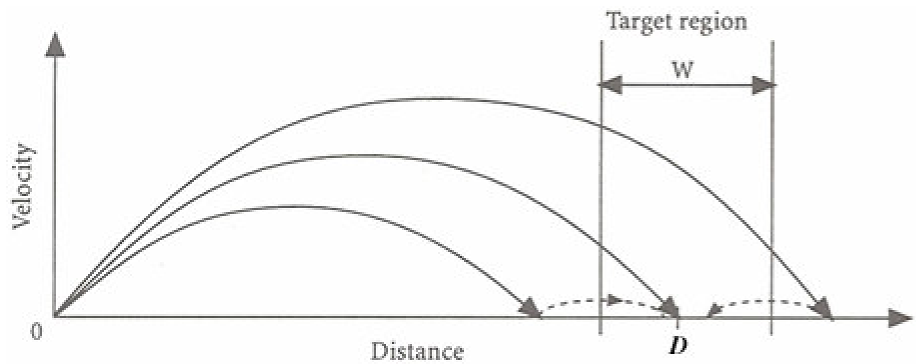

Figure 6. Stochastic Optimized Submovement Model (Douglas & Mithal, 1997).

Other than explaining the process of aiming movement, the SOS model also offers a number of quantitative predictions. The first has to do with the overall movement time (MT), as shown in Equation 5:

$$MT = A + B\sqrt{\frac{D}{W}} \tag{5}$$

where A and B are non-negative constants. The second prediction concerns the duration of the primary submovement; it is expressed similarly to Equation 5 with the conditions that $A_1 < A$ and $B_1 < B$ (see Equation 6):

$$MT_1 = A_1 + B_1\sqrt{\frac{D}{W}} \tag{6}$$

Thus, Equation 6 specifies that primary submovement's MT is proportional to the ratio of target width and distance amplitude. Meyer et al. (1990) also stated that MT typically increases as D increases and W decreases. The SOS model also states that the proportion of secondary submovements (i.e., the proportion of trials in which secondary submovements are needed) increases as the ratio D/W increases. Similarly, error rate also increases as D/W increases.

There is a general agreement that the SOS model is the best theory for explaining aiming movement at the process level. The model was found to hold for isotonic movements; however, there are some differences in opinion on how the model works with isometric movements, even among its original proponents (Douglas & Mithal, 1997).

2.3.3. Kinematic Measures of Aiming Movement

Kinematics is the study of motion without considering the forces that may cause the motion. Primary kinematic properties are displacement, velocity, and acceleration. Based on these properties, movement kinematics (also known as movement microstructure) can be studied in detail and the process of aiming movement can be characterized and understood. Furthermore, the correlation between certain kinematic and performance measures allows explanation of certain performance differences. More interestingly, some kinematic measures can explain the nature of aiming movement at an entirely different dimension. This sentiment was elaborated in MacKenzie et al. (2001). Citing the use of a trackball to control cursor movement, they stated that the trackball has to be flicked quickly to move the cursor over a long distance. On the other hand, the trackball has to be slid gently several times when precise cursor movement is needed. In this case, performance measure such as MT is insufficient to reveal what happens during the movement; kinematic measures such as displacement and velocity of cursor movement would be more informative. Furthermore, it is also plausible that while there are no differences in performance measures, there can be differences in kinematic measures. For example, older mouse users may take a similar amount of time as younger users to complete an aiming movement; however, age-related individual differences (e.g., visual condition, motor control ability) may produce large differences in movement kinematics.

The literature shows that kinematic analysis is more prevalent in basic research involving limb aiming movement (e.g., Carlton, 1979; Carlton, 1994; Chua & Elliott, 1993; Elliott et al., 1991; Helsen et al., 1998; and Ricker et al., 1999). Recently this approach has been adopted in studies involving computer input devices (MacKenzie et al., 2001; Phillips, Triggs, & Meehan, 2005; Slocum, Chaparro, McConnell, & Bohan, 2005; and Slocum, Thompson, & Chapparo, 2005). Derived from displacement, velocity, and acceleration profiles, there are multiple kinematic measures reported in the literature. In general, these measures are computed from parameters such as distance traveled, peak velocity, peak acceleration, and zero crossings. Tables 6 and 7 summarize some spatial and temporal kinematic measures. It is unclear how these measures relate to eventual performance, nonetheless they have been used for describing the process of aiming movement.

Table 6. Spatial Kinematic Measures of Aiming Movement.

Movement Landmark / Parameter	Kinematic Measure	Description
Distance traveled	Proportion of distance traveled at PV	• Reported in Chua & Elliott (1993), Helsen et al. (1998), Ketcham et al. (2002), and Slocum, Chaparro, et al. (2005) • Defined as the ratio of distance traveled at PV (primary movement) and total movement distance • Used as positive indicator for movement efficiency
Peak velocity (PV)	PV amplitude	• Reported in Chua & Elliott (1993), Elliott et al. (1991), Helsen et al. (1998), Ketcham et al. (2002), Phillips et al. (2005), Ricker et al. (1999), and Slocum, Thompson, et al. (2005) • Used as positive indicator for movement speed
Peak acceleration (PA)	PA amplitude	• Reported in Carlton (1994), and Helsen et al. (1998) • Exact indication unknown
Zero crossing (ZC)	Number of ZC in acceleration profile	• Reported in Phillips et al. (2005) • Used for counting number of submovements
	Number of ZC following PV in acceleration profile	• Reported in Chua & Elliott (1993), Elliott et al. (1991), and Ketcham et al. (2002) • Used for counting number of secondary submovements

Table 7. Temporal Kinematic Measures of Aiming Movement.

Movement Landmark / Parameter	Kinematic Measure	Description
Movement time	Gross MT	• Reported in Phillips et al. (2005), and Slocum, Thompson, et al. (2005) • Defined as MT between beginning of movement to first zero crossing in velocity profile
	Fine MT	• Reported in Slocum, Thompson, et al. (2005) • Defined as MT from the end of gross MT to end of movement
Peak velocity (PV)	Time to PV	• Reported in Carlton (1994), Elliott et al. (1991), Helsen et al. (1998), Phillips et al. (2005), and Ricker et al. (1999) • Direct indicator for movement efficiency
	Time from PV until the end of movement	• Reported in Elliott et al. (1991) • Indicates time spent in homing phase
	Proportion of time to PV	• Reported in Chua & Elliott (1993), Helsen et al. (1998), Ketcham et al. (2002), and Ricker et al. (1999) • Defined as the ratio of time to PV and the overall time
Peak acceleration (PA)	Time to PA	• Reported in Carlton (1994), and Helsen et al. (1998) • Exact indication unknown
	Proportion of time to PA	• Reported in Helsen et al. (1998) • Defined as the ratio of time to PA and the overall time

2.3.4. Vision and Aiming Movement

Visual feedback is generally regarded as more critical than kinesthetic feedback (Keele, 1968). There is a host of studies that investigate the role of visual feedback in aiming movement. Perhaps the most widely cited study is Keele & Posner (1968), who suggested 190 to 260 ms is needed for corrective action in aiming movement. About ten years later, that figure was revised to 100 ms by Carlton (1981). Clarification was added by Chua & Elliott (1993) who found more time was spent in the deceleration phase (i.e., time from peak velocity to end of movement) when visual feedback was available. They speculated that the additional time was needed to allow visual detection and subsequently error reduction in the movement. It was further suggested that visual feedback occurs primarily after peak velocity, and that it is more critical in the latter half of the movement, i.e., when the movement is near its target. Some would argue that the availability of visual feedback in the deceleration phase would result in an increased number of corrective submovements (i.e., zero crossings in the acceleration profile). On the contrary, Elliott et al. (2001) pointed out while the initial phase (i.e., ballistic phase) of aiming movement is somewhat stereotypical; however, the second half (i.e., deceleration phase) is less conforming in terms of its kinematic characteristics. In other words, the presence of visual feedback does not necessarily translates to higher number of corrective submovements during the deceleration phase.

Using eye tracking techniques, researchers were able to investigate the nature of eye-hand coordination in aiming movements, particularly those involving the hand. In general, many studies found that the eyes usually move towards the target before the limb, and arrive at the target first. Abrams (1992) and Abrams et al. (1990) argued the eye-lead-hand behavior in aiming movement is highly dependent on the experimental paradigm used. In a common paradigm, movement targets are not visible on the screen initially but only appear during the course of the trial. The sudden appearance of the target may cause the eyes to move towards the target before the hand does. Yet in a different paradigm, the targets are presented ahead of time. Since the target is known in advance, the eyes would move towards the target before the hand (Elliott et al., 2001). Obviously no matter which paradigm is used, irrespective of whether the target is known in advance, the eyes always lead the hand. However, there is very limited, if any, empirical data available to support both arguments. More research is definitely needed.

2.4. Mouse Tasks and Mouse Device Parameters

Task primitive is a description of interaction techniques involving input devices at their most elemental level (Foley, Wallace, & Chan, as cited in Hinckley, 2001). While this research has addressed two task primitives essential in mouse tasks (pointing and selecting), there are three additional relevant primitives: (1) dragging, (2) drawing or tracing, and (3) free-hand input. Pointing is an action where users move the cursor from one point to another. Selecting is often accomplished by clicking the mouse button. Dragging can be thought as a combination of pointing and selecting; this action often involves holding down the mouse button while moving the cursor from one point to another. Tracing is similar to pointing and dragging except the path along which the cursor moves is instrumental for task accomplishment (Douglas & Mithal, 1997). The fifth primitive, free-hand input, is quite similar to tracing and can be thought as sequence of tracing actions. An example of free-hand input is the action of entering text using a mouse or a stylus. When evaluating an input device researchers usually collect data from more than one task primitive to ensure generalizability. Examples of experimental tasks include tapping task (one dimensional or multidimensional), dragging task, steering task, pursuit tracking, freehand drawing, and many others (see Hinckley, 2001). Data from tapping and dragging tasks can be analyzed using Fitts' law. However, a different formulation may be required for other tasks. For instance, Accot & Zhai (1997) suggested that steering task data should be analyzed using the Steering law. An overview of the appropriate formulation for specific task primitives is available in ISO 9241-9 standard (ISO, 2000).

Some researchers believe certain characteristics of pointing devices are the concomitant factors that affect actual performance. Among them, control order and gain receive the most attention. Control order refers to the time-based output control by the input device. A zero-order control device is also called a position-control device because there is a direct relationship between the device movement and its output; there is a one-to-one mapping between the input and the output. A first-order control device is a rate-control device, in which controlling the device translates to controlling the speed of the output. Higher-order control devices are possible but most computer pointing devices are either zero-order or first-order control devices (Douglas & Mithal, 1997).

Choice of control-order device is an important consideration in the design of a computer input device. Knowledge about the behavior of the device allows an operator to plan for successive submovements in order to achieve the ultimate goal (Kantowitz & Sorkin, 1983). To elaborate, during the movement trajectory of a pointing task, the operator has to decide whether he needs to move faster to avoid undershooting, or slow down to avoid overrshooting the target.

Gain setting is also known as control-display (C/D) ratio, or C/D gain. It describes the control movement needed to produce the desired output movement (Kantowitz & Sorkin, 1983). The idea of C/D ratio is best described by the sensitivity of the device itself. For a device that has low sensitivity (or low gain), a given control movement will result in limited gain; it is regarded as a device with a high C/D ratio. On the other hand, for a device with high sensitivity (or high gain), the same control movement will produce a much larger response; this device has a low C/D ratio. For most computer input devices, the C/D ratio is not constant and it changes according to the order of control for that device. A rate-control mouse would move the cursor a greater length if its displacements are sped up; such a mouse is commonly employed in computers running on Microsoft Windows environment. Many researchers (Accot & Zhai, 2001; Douglas & Mithal, 1997; Hinckley, 2001; and MacKenzie, 1995) believe empirical investigation of gain is obsolete because empirical studies (i.e., Jellinek & Card, 1990; Kantowitz & Elvers, 1988; and Lin, Radwin, & Vanderheiden, 1992) have found no evidence of gain setting effecting performance while using input devices. It appears that the advantage of gain setting is the impact on the real estate required for the input device.

To summarize further, it is a well-known fact that users often encounter difficulties with higher order pointing devices (Birmingham & Taylor, as cited in Kantowitz & Sorkin, 1983). Therefore, it is not surprising to say that users typically perform better using a zero-order control device, such as the mouse. In addition, C/D gain can be dismissed as a critical control parameter in mouse tasks largely because previous studies have found negligible influence on the performance of pointing device.

CHAPTER 3

RESEARCH QUESTIONS

3.1. Background

Eye-hand coordination is a loose term that describes actions involving finely controlled limb movements. It can be defined as the spatio-temporal coupling between the eyes and the hand. From switching on a light bulb to driving a car, most daily tasks are visuomotor in nature. Therefore, it is not an exaggeration to say that eye-hand coordination is fundamental for effective mouse use. Furthermore, eye-hand coordination is a function of visual ability and motor control. Because executive control is needed to facilitate the coordination of visual input and motor output, cognitive ability may also play a part in eye-hand coordination (see Figure 1). Age is also known to impact eye-hand coordination. Functional abilities have been known to be influenced by the age effect; the age effect is subsequently reflected in the performance and characteristics of the task. The notion of age having an indirect effect is not a new idea. It has been suggested by researchers (Birren & Renner, 1977; and Salthouse & Maurer, 1996) that performance differences are not caused by age per se, but they are more directly influenced by age-related changes in functional abilities. The intertwined relationships of various factors and their causal relationships (i.e., direct or indirect) on mouse use are illustrated in Figure 7.

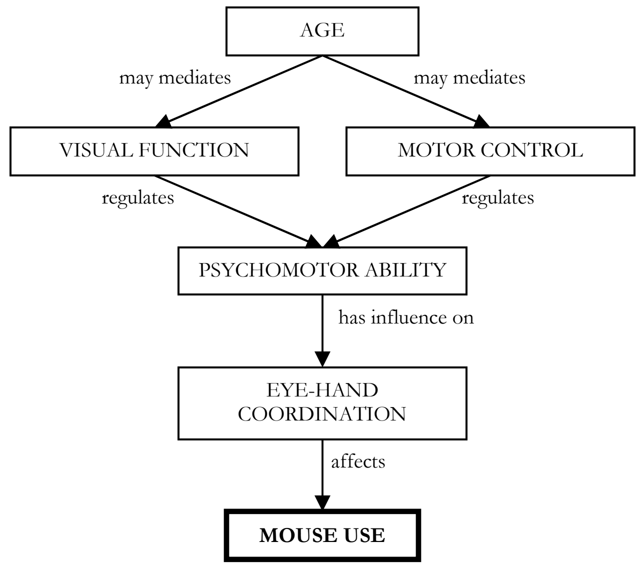

Figure 7. Inter-relationship of Various Factors and the Influence on Mouse Use.

A performance-oriented approach is commonly employed in research involving mouse use. Such an approach is often dominated by endpoint measures such as movement time and error rate. However, this approach is incapable of providing sufficient information regarding the movement process (Chua, Weeks, & Goodman, 2003; Douglas & Mithal, 1997; MacKenzie, Kauppinen, & Silfverberg, 2001; and Smith, Ho, Ark, & Zhai, 2000), and consequently additional insights may be overlooked. It is believed that much can be learned from studying the process of the movement. The same approach has been used extensively in other domains, particularly in direct aiming movement of a limb (e.g., hand). However, very little research has been done in indirect aiming movement involving the use of a mechanized device such as the mouse. Consequently, this research intends fill the gap, that is, to understand the effects of visual function and motor control on mouse use, at a process level. However, exact motor control data is difficult to obtain without specialized equipment such as electromygraphy and electrogoniometer. As a result, motor control was observed indirectly by measuring psychomotor ability. A drawback of such an approach is the inability to partial out the cognitive and visual aspects of psychomotor ability. Nevertheless it is believed that the purpose of this research remains intact: to understand how pertinent functional abilities affect the process of mouse use.

3.2. Specific Questions

The process of mouse use is the focus of this research. A common approach in characterizing the process is by observing movement kinematics. There are multiple kinematic measures reported in the literature. However, the kinematics-performance relationshis are still unclear. To elaborate further, the question is: do all kinematic measures affect eventual performance? If not, which specific measures impact performance? Determination of various kinematics-performance relationships is addressed in Chapter 4.

Fundamental psychomotor abilities such as control precision and arm-hand steadiness were mentioned by Knight & Salvendy (1992) as important for mouse use. In addition, Hwang (2001) found manual dexterity to correlate with mouse performance. Finger dexterity and wrist-finger speed may also be relevant. Recall that finger dexterity is defined as the ability to make skillful and coordinated finger movements (Fleishman & Reily, 1992). It is believed that such an ability maybe vital for the operation of a mouse, particularly in pressing its buttons. Wrist-finger speed is thought to be relevant because it entails the ability to make fast and repeated movements of the hands and wrist (Fleishman & Reily, 1992), in which such movements are common in mouse usage. This research will examine whether certain psychomotor abilities are indeed predictive of mouse use performance and most importantly, the underlying process of the movement.

Age is often identified as the cause of reduced performance. However, the direct cause of such a reduction has been attributed to age-related changes in functional abilities such as psychomotor ability. Based on that notion, it is hypothesized that the age effect on mouse use will become negligible after the effect of psychomotor ability is taken into consideration. This question will be addressed in Chapter 5.

Largely inspired by a series of studies by Jacko and colleagues (e.g., Jacko, et al., 1999; Jacko et al., 2003; Jacko, Barreto, et al., 2000; and Jacko, Rosa, et al., 2000) who have shown the impact of low vision on the performance of mouse use, this research will extend their findings by investigating the impacts of reduced visual function on the underlying process of mouse use. While reduced performance is certainly associated with low vision, it is still unclear how low vision affects the underlying process. Hence, the specific question is how does mouse use behavior for low vision users differ from those with normal vision? A comparative study of mouse use between low vision and normal vision users is presented in Chapter 6.

CHAPTER 4

FITTS' POINTING TASK USING A MOUSE: THE RELATIONSHIP BETWEEN MOVEMENT KINEMATICS AND MOVEMENT TIME

4.1. Introduction

Despite advances in computing technology, the mouse remains a primary, if not the most important device for interacting with computers. The mouse has proven to be useful in various computing tasks, whether it is browsing the Web or editing text documents. There are many studies investigating the performance of the mouse, and they generally focus on endpoint measures such as movement time and target misses. Only recently have researchers started taking advantage of the additional information that can be gained from studying the process of mouse use.

Among the early studies of cursor movement kinematics is Jagacinski, Repperger, Moran, Ward, & Glass (1980); they conducted a micro-analysis of Fitts' law using data collected from cursor movements controlled by a joystick. Recent studies involving movement kinematics by MacKenzie, Kauppinen, & Silfverberg (2001), Mithal & Douglas (1996), and Phillips & Triggs (2001) each demonstrated that there is more information to be gained using such an approach. The process-level approach also has been reported in studies that are more applied in nature, including those focused toward special populations such as the elderly and people with disabilities (e.g., Hwang, Keates, Langdon, & Clarkson, 2004; Ketcham, Seidler, Van Gemmert, & Stelmach, 2002). While many agree that a kinematic analysis is critical for improving mouse use performance, the literature reports about a dozen different kinematic measures; however, it is not known how those measures correspond to actual performance. This research investigated the kinematics-performance relationship, as well as to determine how movement kinematics can affect the eventual mouse use performance.

4.2. Cursor Movement Kinematics

Kinematics is the study of motions without considering the forces that may cause the motion. Sometimes known as movement microstructure, this information allows characterization of the movement process. Literature shows that kinematic analysis is more prevalent in basic research on aiming movements of the upper limbs (e.g., Carlton, 1979; Carlton, 1994; Chua & Elliott, 1993; Elliott et al., 1991; Helsen et al., 1998; and Ricker et al., 1999). More recently, kinematic analysis began to take a foothold in a number of studies involving computer input devices (MacKenzie et al., 2001; Phillips, Triggs, & Meehan, 2005; Slocum, Chaparro, McConnell, & Bohan, 2005; and Slocum, Thompson, & Chapparo, 2005).

There are a host of different kinematic measures reported in the literature. These measures are often computed based on kinematic landmarks such as peak velocity, peak acceleration, and zero crossings in the velocity and acceleration profiles. There are generally two families of kinematic measures: spatial and temporal. Spatial kinematic measures include peak velocity, peak acceleration, proportion of distance traveled at peak velocity, and zero crossings. Some temporal kinematic measures reported in the literature include time to peak velocity, time from peak velocity until the end of movement, proportion of time to peak velocity, time to peak acceleration, and proportion of time to peak acceleration. Table 8 further describes these kinematic measures.

Table 8. Selected Kinematic Measures Reported in the Literature.

Kinematic Measure	Description	Reported in
Peak velocity (PV)	• The highest magnitude in velocity profile, usually occurs during primary submovement	Chua & Elliott (1993), Elliott et al. (1991), Helsen et al. (1998), Ketcham et al. (2002), Phillips et al. (2005), Ricker et al. (1999), Slocum, and Thompson, et al. (2005)
Time to PV (TPV)	• Difference between time at PV and time at the beginning of movement • Direct indicator for movement efficiency	Carlton (1994), Elliott et al. (1991), Helsen et al. (1998), Phillips et al. (2005), and Ricker et al. (1999)
Proportion of time to PV (PROPTPV)	• The ratio of time to PV (TPV) and movement time (MT)	Chua & Elliott (1993), Helsen et al. (1998), Ketcham et al. (2002), and Ricker et al. (1999)
Proportion of distance traveled at PV (PROPDPV)	• The ratio of distance traveled at time of PV and total distance • Also referred to as proportion of distance traveled in primary submovement • Some authors use it as a positive indicator for movement efficiency	Chua & Elliott (1993), Helsen et al. (1998), Ketcham et al. (2002), and Slocum, Chaparro, et al. (2005)
Peak acceleration (PA)	• The highest magnitude in acceleration profile, may occurs during primary or secondary submovements	Carlton (1994), and Helsen et al. (1998)
Time to PA (TPA)	• Difference between time at PA and time at the beginning of movement	Carlton (1994), and Helsen et al. (1998)
Proportion of time to PA (PROPTPA)	• The ratio of time to PA and the overall time	Helsen et al. (1998)
Time from PV until the end of movement (TPVEND)	• Difference between time at PV and time at the end of movement • Indicates time spent in homing phase	Elliott et al. (1991)

Many studies of movement kinematics are loosely based on the stochastic optimized submovement (SOS) model (Meyer et al., 1988; and Meyer et al., 1990). The model operates under the assumption that optimization of aiming movement requires a compromise between time and accuracy (i.e., speed-accuracy tradeoff). According to Elliott et al. (2001), the SOS model builds upon the deterministic iterative corrections model (Crossman & Goodeve, 1963/1983; and Keele, 1968) and the impulse variability model (Schmidt, Zelaznik, Hawkins, Frank, & Quinn, 1979). The best features from both models were incorporated in the SOS model: the feedback-control hypothesis of the deterministic corrections model, and the endpoint variability hypothesis of the impulse variability model. The feedback-control hypothesis posits that the detection of movement discrepancies (i.e., overshooting or undershooting) triggers corrective submovements. Visual sensory is the primary feedback mechanism, although kinesthetic sensory also plays a part to a lesser extent. The endpoint variability hypothesis is used to represent the notion of neuromotor noise. The hypothesis posits that movement endpoints are not deterministic but are normally distributed around the center of the target.

A typical aiming movement may consist of a primary submovement and a secondary submovement (Meyer et al., 1988). The primary submovement is the initial movement preprogrammed to end within the target. If the primary submovement ends as intended, the movement is completed. However, neuromotor noise may prevent the initial movement to arrive at the target as preprogrammed and in that case, a secondary submovement is initiated to correct the endpoint. In regard to the number of submovements, it was speculated that a typical aiming movement needs only one or two submovements. Tertiary and subsequent submovements are also possible, but in general they are part of the secondary submovement. In addition, higher-order submovements are quite unlikely and often observed in critical tasks requiring movements to extremely difficult targets or in tasks that require perfect performance (i.e., no tolerance for errors).

4.3. Research Rationales and Objectives

While the kinematics of aiming movement can be captured using different kinematic measures, the relationship of these measures to the eventual performance is often not discussed. Knowledge of the correlations between certain kinematic characteristics and performance is invaluable for understanding mechanisms that are likely effective in improving mouse use performance. For instance, Hwang, Keates, Langdon, & Clarkson (2004) proposed such a concept for the design of mouse input for motor-impaired users who demonstrate excessive submovements (i.e., pauses) during aiming movements. In this case, cursor stabilization could be activated to assist mouse use when necessary. Therefore, an adaptive user interface capable of detecting irregularities in movement kinematics can be used to invoke corrective measures to improve performance of mouse use.

This study seeks to determine the relationship between movement kinematics and the performance of a mouse-mediated aiming task. Correlation analyses between kinematic measures and movement time will identify the critical kinematic predictors of performance and will serve as validation of the works of various researchers who have suggested, but not demonstrated, a significant relationship. Additionally, it was predicted that the kinematics-performance relationship could differ from one age group to another. Therefore, the second objective was to determine whether the there is any differential impact of age on the kinematics-performance relationship.

4.4. Method

4.4.1. Participants

Forty-five healthy participants between 21 and 90 years of age were recruited from the local university community, as well as from an independent living center. To ensure a broad representation of age group, fifteen participants were recruited from three age groups: younger (M = 25.25 years old, SD = 2.89), middle-aged (M = 50.37 years old, SD = 5.01), and older (M = 80.62 years old, SD = 6.16). Participants were required to have normal or near-normal vision, with correction if necessary, with acuity of at least 20/60. Additionally, older participants were screened for dementia. All had experience using a computer mouse except for one middle-aged participant and two older participants. Inexperienced participants were given ample training in the pointing task.

4.4.2. Procedure

The study was conducted at both on-campus and off-campus locations. All tests were conducted in a quiet environment, and were administered on an individual basis. The testing environments provided adequate illumination and comfortable computer work areas. Informed consent was obtained from each participant prior to the study. Prior to testing a screening questionnaire (see Appendix A) was administered to characterize computer familiarity and any physical limitations that may impede performance of the mouse-based task. Then, participants' visual acuity was measured using a Snellen chart. Older participants were also screened for dementia using Folstein, Folstein, & McHugh's (1975) mini-mental state exam (see Appendix B). These criteria were used to exclude participants who scored less than 20 points out of 30 possible points.

Each participant performed six tasks (i.e., five psychomotor tests and a Fitts' pointing task). The testing order was randomized, with a break of about 2 minutes between each task. The experiment concluded after all tasks were completed.

4.4.3. Experimental Tasks

There were two types of experimental tasks: psychomotor tests and a mouse pointing task. Five psychomotor tests were used to measure various elemental psychomotor measures as suggested by Fleishman & Reily (1992). The psychomotor tests included the rotary pursuit test (Lafayette Model 2203ET), the grooved type steadiness test (Lafayette

Model 32010), the Minnesota manual dexterity test (Lafayette Model 32023), the Purdue pegboard (Lafayette Model 32020), and a tapping board (Lafayette Model 32012). The mouse pointing task was a multi-directional reciprocal Fitts' pointing task, similar to that described in Soukoreff & MacKenzie (2004). The Fitts' task was operationalized using the software program IDTest (International Business Machines [IBM], 1999) to generate stimuli for the pointing task. Participants performed all tasks with their dominant hand.

4.4.3.1. Psychomotor Tests

A rotary pursuit test was used to assess participant precision control. The light emitting target was set at 30 rpm rotating in a clockwise direction. Participants were instructed to track the rotating target using a stylus attached to the unit. Performance was measured using time-on-target (TOT) averaged from the four trials; higher TOT indicated better precision control. After two complete practice trials, four repetitions of the same duration were completed.

Participant arm-hand steadiness was measured using the grooved type steadiness test. The participants were required to move a stylus along a narrowing channel without touching the sides. After a complete practice trial, participants completed four repetitions. Error time, measured as the contact time between the stylus and the channel walls, was recorded and averaged across all four trials; lower error time indicated better arm-hand steadiness.

The Minnesota manual dexterity test was used to assess participant manual dexterity. Two test batteries were administered: turning and displacing. The turning battery required the participant to pick up a peg with one hand, turn the peg while passing it to the other hand and then return the peg back to its position with the bottom side facing up. The battery ended after all pegs were turned. The displacing battery began with an empty top-left hole. The participant was required to move the peg to the adjacent hole, until all the pegs were displaced. After a complete practice trial, both the turning and the displacing batteries were repeated four times. For each test battery, the sum of completion times from all four trials was used as the performance measure lower completion time indicated better manual dexterity.

The assessment of finger dexterity was conducted using the Purdue pegboard. Two test batteries were administered: insertion and assembly. The insertion battery required the participant insert as many pins as he could in 30 s, whereas the participant was given a minute to put together as many 4-pin assemblies. Participants were allowed to practice until they were comfortable with the routines. Four trials were completed of each battery. Thirty seconds were allowed to complete the insertion assembly; one minute was allowed for the assembly battery. The average number of pins inserted was recorded from the insertion battery, whereas the average number of parts assembled was recorded from the assembly battery. In both cases, a higher number indicated better finger dexterity.

Wrist-finger speed was measured using the tapping board. It was essentially a Fitts' pointing task with two metal plates at either end of the board. Participants were required to tap the metal plates with an attached stylus as fast as they could for 15 seconds. After two complete practice trials, participants performed four trials. The average number of taps per trial was recorded as the performance measure; a higher number of taps indicated better wrist-finger speed.

4.4.3.2. Mouse Pointing Task

A multidirectional reciprocal Fitts' pointing task was generated using IDTest (IBM, 1999) running on a Windows-based laptop computer with 1280-by-800 pixels screen resolution. The pointing device used was a neutral shaped Microsoft Optical Mouse connected to the computer via a universal serial bus (USB) port.

The targets were circular in shape with a diameter of 30 pixels and were separated by either 50, 100, 200, 400, or 650 pixels, thus producing five distance conditions. Using Shannon's formulation for index of difficulty (ID), $\log_2((D + W) / W)$, the combinations produced five ID values ranging from 1.42 to 4.50 bits. The targets, each colored black and red, were arranged along various angles (i.e., 0, 45, 90, and 135 degrees). The task required participants to point the cursor at the target and then select it using the left mouse button. The targets became transparent if successfully acquired. However, a beep would be audible if the participant missed the target.

Following a practice trial, each distance condition was tested five times at each angle. Therefore, each participant was subjected to 100 trials (i.e., 5 distances × 4 angles × 5 repetitions). The treatments (i.e., distance-angle combinations) were presented in random order (without replacement) for all trials and short breaks were allowed between treatments. In each trial, movement time (MT) was recorded as the performance measure. In addition, cursor x-y positions were sampled across time. Note the sampling of cursor positions was event-based. Each time a mouse movement was detected, the x-y position would be recorded by IDTest (B.A. Smith, personal communication, 1 December, 2006). As a result, the sampling rate varied for each trial.

4.4.4. Data Interpolation and Smoothing

Point-to-point cursor displacements were computed from the raw position data using the Pythagorean Theorem. The displacement data were then linearly interpolated at 200 Hz. The interpolation produced a dataset with a constant sampling rate, which was necessary for subsequent data smoothing. Data smoothing used a fourth order zero-phase shift Butterworth low-pass filter with a cut-off frequency of 6 Hz, which was determined using residual analysis. Data smoothing and the computations of velocities and accelerations were based on the techniques described in Winter (2005). The interpolation and smoothing processes were performed using a Microsoft Excel macro (Van Wassenbergh, 2005).

4.4.5. Cursor Kinematic Measures

Kinematics of cursor movement was characterized using eight measures: peak velocity (PV), peak acceleration (PA), time to peak velocity (TPV), time to peak acceleration (TPA), proportion of time to peak velocity (PROPTPV), proportion of distance traveled at the time of peak velocity (PROPDPV), proportion of time to peak acceleration (PROPTPA), and time from peak velocity until the end of movement (TPVEND). These measures are defined in Table 10. To avoid misinterpretation of initial jerk as PA, accelerations occurring within 10 ms of movement onset were disregarded.

4.5. Results and Analysis

Participant psychomotor ability was measured using seven measures, as suggested in Fleishman & Reily (1992). Table 9 provides the means and standard deviations of the psychomotor measures for each of the three age groups. In general the older group was associated with reduced psychomotor ability; however, the differences between the younger and the middle-aged group were less apparent.

Table 9. Participants' Psychomotor Measures.

Psychomotor Measure	Age Group[a]		
	Younger	Middle-Aged	Older
Precision control (time-on-target in seconds)			
M	11.91	11.05	6.34
SD	3.69	4.41	3.57
Arm-hand steadiness (error time in seconds)			
M	.31	.25	.71
SD	.20	.19	.64
Manual dexterity[b] (completion time in seconds)			
M	171.16	183.86	243.17
SD	13.62	24.18	31.85
Manual dexterity[c] (completion time in seconds)			
M	175.13	257.00	182.89
SD	15.64	47.02	23.57
Finger dexterity[d] (number of pins inserted)			
M	17.07	16.20	12.03
SD	1.87	1.60	2.44
Finger dexterity[e] (number of pins assembled)			
M	43.37	39.35	21.77
SD	4.87	7.29	5.73
Wrist-finger speed (number of taps)			
M	62.87	58.50	45.98
SD	9.50	9.44	10.15

[a]n = 15 for each group. [b]Minnesota manual dexterity test displacement battery. [c]Minnesota manual dexterity test turning battery. [d]Purdue pegboard insertion battery. [e]Purdue pegboard assembly battery.

4.5.1. Overall Analysis on Kinematics-Performance Correlation

One of the objectives of this study was to determine the kinematics-performance relationship. Even though kinematics is part of the movement, it was suspected that not all kinematic measures correlate with movement performance. In order to investigate the proposition further, a series of overall bivariate correlation (i.e., across all age groups) were computed for kinematic measures and movement time (MT), using a sample size of N = 4500 (i.e., 100 trials × 45 participants). Correlations with a magnitude larger than $|.35|$ were considered to be of practical value; those smaller than $|.35|$ were deemed to have little or no meaning. Based on that criteria, only TPV-MT (r = .68), TPA-MT (r = .61), and TPVEND TPVEND-MT (r = .96) were found to have practical meaning. The correlations PV-MT (r = .07), PA-MT (r = .16), PROPDPV-MT (r = .24), PROPTPV-MT (r = -.05), PROPTPA-MT (r = -.18) were of little importance.

4.5.2. ANOVAs on Kinematic-Peformance Correlations

In addition to understanding the overall kinematics-performance relationships, it was also of interest to determine whether the relationships differed between age groups. The bivariate correlations that were meaningful (i.e., TPV-MT, TPA-MT, and TPVEND-MT) were recalculated according to age group. For each distance condition (over all angles and repetitions), kinematics-MT correlations were computed for each participant. Because Pearson's correlations are known to be non-normally distributed, they were transformed to Fisher's z-scores (Fisher, 1970); the same technique was also reported in Chua & Elliott (1993) and Elliott et al. (1991). A series of 3 (between-subjects age group, AGE) × 5 (within-subjects distance condition, DIST) ANOVAs was performed on the z-scores (i.e., transformed kinematics-MT correlations). The between-subjects main effect age (AGE: younger, middle-aged, and older) was evaluated using $MS_{SUB(AGE)}$ as the error term, whereas the within-subjects main effect distance (DIST: 50, 100, 200, 400, 650 pixels) and the interaction AGE × DIST were evaluated using $MS_{COND*SUB(AGE)}$ as the error term. Moreover, all within-subjects effects were determined with numerator and denominator degrees of freedom adjusted using the Huynh-Feldt procedure to circumvent possible violation of the sphericity assumption.

The variances accounted for by the effects of interest were estimated by the partial $\hat{\omega}^2$. It should be noted that the computation of partial $\hat{\omega}^2$ was based on Olejnik & Algina's (2000) recommendation for a similar design (i.e., split-plot design) and is the proportion of effect variance to the sum of the error variance and the effect variance. Computation of effect size allows a way to determine whether statistical significance has any practical values. According to Cohen's (1988) guidelines, a value of 1% indicates a small effect, 6% indicates a medium effect, and 14% indicates a large effect. A small significant effect may means little from a practical standpoint. On the other hand, a significant large effect would be worthy in terms of its practicality.

4.5.2.1. TPV-MT Correlation

DIST and AGE × DIST were found to be significant in regard to the correlation magnitudes for TPV-MT, with $F_{4,\ 168} = 6.18$ ($p = .0001$, partial $\hat{\omega}^2 = .069$), and $F_{8,\ 168} = 2.43$ ($p = .0167$, partial $\hat{\omega}^2 = .048$), respectively. Post-hoc multiple comparison was conducted at each distance condition to determine if age differences exist. No practical results were obtained, it was concluded that the significant interaction effect AGE × DIST was driven more by the DIST effect.

4.5.2.2. TPA-MT Correlation

Only DIST was significant ($F_{8,\ 168} = 4.42$, $p = .0027$, partial $\hat{\omega}^2 = .057$) in regard to the TPA-MT correlation. Recall that the omnibus test showed non-significance for the main effect AGE and the interaction effect AGE × DIST, thus no further analysis was needed.

4.5.2.3. TPVEND-MT Correlation

The magnitudes of the TPVEND-MT correlations were found to vary significantly by AGE ($F_{2, 42} = 8.78$, $p = .0007$, partial $\hat{\omega}^2 = .515$) as well as by DIST ($F_{4, 168} = 13.49$, $p < .0001$, partial $\hat{\omega}^2 = .182$). Ryan's MCP was performed to determine pairwise differences between age groups, with familywise Type I error rate set at .05. The error term was $MS_{SUB(AGE)}$. The results showed that the TPVEND-MT correlation for the older group ($r = .90$) was smaller than for the younger ($r = .96$) and middle-aged ($r = .92$) groups. There was not a significant difference between the younger and middle-aged groups (see Figure 8).

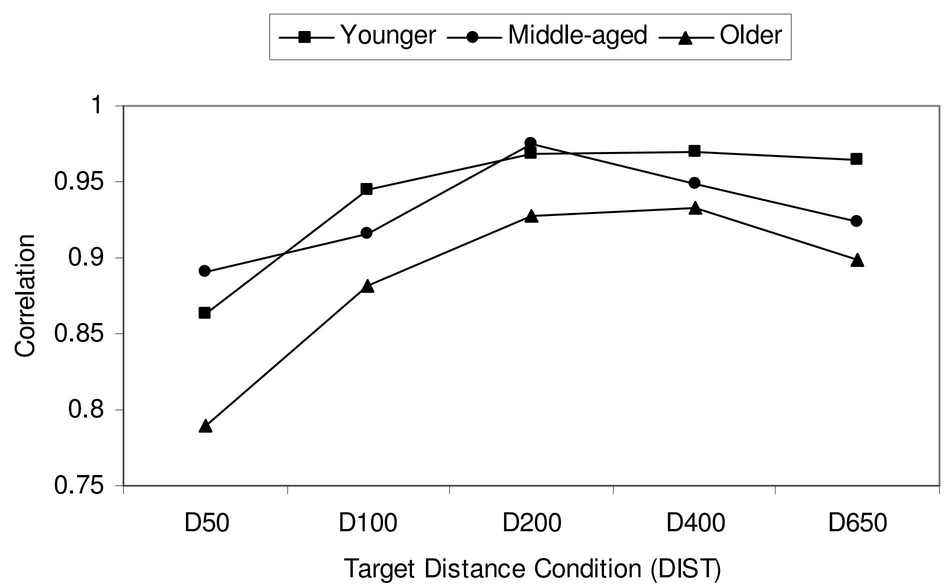

Figure 8. Plot of TPVEND-MT Correlations for AGE × DIST.

4.6. Discussion

This study examined whether kinematics measures can adequately predict task performance time. Most studies of movement kinematics employ a one-dimensional pointing paradigm whereby pointing movements have been restricted to one angle. A potential problem associated with this paradigm is the confounding between performance and movement angle (Phillips & Triggs, 2001). To avoid the bias due to movement angle, a multidirectional paradigm similar to that prescribed in ISO 9241-9 (International Organization for Standards [ISO], 2000) was used. The findings obtained from this multi-dimensional task are more generalizable because they do not restrict movement to one angle. This study also examined the impact of age on the kinematics-performance relationship. While many existing studies (e.g., Ketcham et al. 2002) have reported the relationship between age and movement kinematics, this study investigated the relationships from a within-group perspective. More specifically, it was of interest to investigate whether the kinematics-performance relationships determined from across age groups remain the same if computed from within each group.

Various kinematic-performance correlations computed across age groups showed time to peak velocity (TPV), time to peak acceleration (TPA), and time from peak velocity until the end of movement (TPVEND) were correlated with performance. A lack of relationship with performance was observed for other kinematic measures. Previous literature (e.g., Elliott et al., 1991; and Slocum, Chapparo, et al., 2005) had suggested PV, TPV, and PROPDPV as predictors for movement efficiency; however, this study was only able to confirm only the relationship between TPV and movement time. Despite being reported extensively in the literature, peak velocity (PV) was found to be uncorrelated with movement performance. The lack of correlation between PV and MT appeared to be driven by the minimal variance of MT accounted for by PV (see Ketcham et al., 2002). PV is a spatial kinematic measure, while on the other hand MT has to do with temporal kinematics;

and that may attribute to the dissociation between the two. The lack of correlation between PA and MT also can be explained with the same reasoning.

Findings from this study present two implications. First, if task performance is the focus, attention should be given to TPV, TPA, and TPVEND because the results suggested they were the determinants of movement time. Recall that both TPV and TPA are temporal kinematics associated with the primary submovement. Therefore, it is suggested that performance can be improved by facilitating quick attainment of PV and PA. On the other hand, TPVEND has to do with time spent in the secondary submovement (i.e., homing phase). To improve performance in this phase of movement, perhaps a stabilizing mechanism can be utilized to facilitate target homing. In the context of designing computer input devices, a common strategy for improving performance is to manipulate the parameters in Fitts' law (i.e., target width and distance). Such manipulation is often limited to modifying the design of the graphical user interface (see Balakrishnan, 2004). Now that pertinent kinematic measures have been identified, perhaps hardware can be enhanced to facilitate better movement kinematics, and consequently improve mouse use. Second, even though many kinematics measures were found to be uncorrelated with performance, these measures have been shown useful for characterizing the process of pointing movement. A number of studies have reported such kinematics differences along a host of different dimensions, such as age (e.g., Ketcham et al., 2002), index of difficulty (e.g., Ketcham et al., 2002), eye-hand coordination (e.g., Helsen et al., 1998), and type of input devices (e.g., Slocum, Chaparro, et al., 2005). It should be noted that this study was based on mouse-controlled pointing movements, and the kinematics-performance relationships identified here may not hold if a different pointing device is of interest. To further clarify these kinematics-performance relationships and to examine if the significant patterns identified in this study can be replicated, this study should be replicated using different pointing devices.

The age differences among these kinematics-performance relationships were somewhat unclear. In general, we were unable to determine the presence of TPV-MT and TPA-MT correlations in any particular age group. Nevertheless, a significant age effect was detected in TPVEND-MT correlations. For the older group, TPVEND (i.e., time spent in homing phase) accounted for 81% of variability in movement performance. This proportion increased to 88% for the younger and middle-aged groups. It was unclear what caused this difference. Perhaps this could be explained from the perspective of age differences in psychomotor ability. Reduced psychomotor ability among older adults might already account for considerable variability in performance, and as a result the contribution of age to TPVEND was reduced. This conjecture was not investigated further and thus it remains a question for future research.

CHAPTER 5

KINEMATICS OF MOUSE-MEDIATED AIMING MOVEMENT: EFFECTS OF AGE AND PSYCHOMOTOR ABILITY

5.1. Introduction

There are various user attributes affecting performance of mouse use. A variable of significant interest is age. Despite its apparent effects, Birren & Renner (1977) and Salthouse & Maurer (1996) suggested that age is only a surrogate variable in most cases. It is variables such as knowledge, skills, and abilities that have direct causal relationships with performance level. Such a conjecture has been confirmed by other researchers. For instance, Czaja & Sharit (1998) and Smith, Sharit, & Czaja (1999) found that age alone did not account for differences in performance of computing tasks, but it was the age-related changes in functional abilities that caused such differences. Following along that line, perhaps a more valid approach to studying mouse use is to focus on the functional abilities that directly affect mouse use performance.

5.2. Psychomotor Ability

Successful mouse use requires good psychomotor ability. From a human control system point of view, mouse use is a closed-loop system characterized by the collaboration between motor control (output) and visual function (input). Some researchers believe that psychomotor ability can be broken into several elemental components. In the past, there have been many attempts to identify and to classify these components. Of these, Fleishman's taxonomy of psychomotor abilities is the most extensive (Merrill, 1972). Originally developed for use in air force personnel training and selection, ten elemental abilities were listed in Fleishman & Reily (1992): control precision, multilimb coordination, response orientation, rate control, reaction time, arm-hand steadiness, manual dexterity, finger dexterity, wrist-finger speed, and speed-of-limb movement. These abilities are measurable using an array of standard psychomotor tests. For instance, control precision can be assessed using the rotary pursuit test, and multilimb coordination can be measured using a two-arm coordination test. Table 10 describes some elemental psychomotor abilities that maybe relevant to mouse use. Control precision and arm-hand steadiness were mentioned in Knight & Salvendy (1992) as important for mouse use. In addition, manual dexterity was found to correlate with mouse performance by Hwang (2001). Finger dexterity is thought to be pertinent because based on its definition in Fleishman's taxonomy, it may be vital for the operation of a mouse, particularly in pressing its buttons. Wrist-finger speed is thought to be relevant because similar movements are common in mouse use.

Table 10. Selected Elemental Psychomotor Abilities (Fleishman & Reily, 1992).

Psychomotor Ability	Description	Test Equipment
Control precision	• Ability to make highly controlled and precise adjustments that are quick or continuous.	Rotary pursuit test
Arm-hand steadiness	• Ability to keep arm and hand steady, either while moving the arm or while both arm and hand are in position.	Steadiness tester (grooved or hole type)
Manual dexterity	• Ability to handle fairly large objects with one or both hands. • May also include arm-hand movements.	Minnesota manual dexterity test
Finger dexterity	• Ability to make skillful, coordinated finger movements. • Usually involves handling of small, pin-sized objects.	Purdue pegboard
Wrist-finger speed	• Ability to make fast and repeated movements of the fingers, hands, and wrists. • May involves some degree of eye-hand coordination.	Tapping board

5.3. Characterizing Mouse Use with Cursor Movement Kinematics

The mouse affords several interaction techniques under the direct manipulation paradigm. These techniques are best captured using a concept known as task primitives (Foley, Wallace, & Chan, as cited in Hinckley, 2001). In essence, task primitives are the most elemental interaction techniques a mouse can perform: (1) pointing, (2) selecting, (3) dragging, (4) drawing or tracing, and (5) free-hand input. Pointing is an action where users move the cursor display from one point to another; selecting is often accomplished by clicking the mouse button. Dragging, on the other hand, can be thought as a combination of pointing and selecting; this action often involves holding down the mouse button while moving the cursor over some distance. Tracing is similar to the pointing and the dragging except the path of which the cursor moves is instrumental for task accomplishment (Douglas & Mithal, 1997). The fifth elemental task, free-hand input, is quite similar to tracing and can be thought as an action made up of several instances of tracing. An example of free-hand input is the action of entering text using the mouse. Among the primitives listed above, pointing and selecting are the most frequently used techniques.

Aiming movement is often referred to as spatially constrained goal-directed movement. When performed simultaneously, the actions of point and select resemble a type of aiming movement. For many years studies of aiming movement had been dominated by Fitts' law. However, as a performance prediction model for pointing tasks, Fitts' law does not explain what happens "during" the movement. Thus, alternative models were proposed to explain the process of the movement. Some notable models include the deterministic iterative corrections model proposed by Crossman & Goodeve (1963/1983) and Keele (1968), as well as the stochastic optimized submovement (SOS) model (Meyer, Abrams, Kornblum, Wright, & Smith, 1988; Meyer, Smith, Kornblum, Abrams, & Wright, 1990). To describe briefly, the deterministic model posits that aiming movement consists of several discrete ballistic phases (i.e., submovements); the model further assumes no variability in movement endpoints. In the contrast, the SOS model claims that the submovement endpoints are not deterministic and they normally distribute around the center of the target. Despite their apparent differences, both models focus on the kinematics of aiming movements.

There are more than a dozen kinematic measures reported in the literature. These measures can be computed from kinematic landmarks (e.g., distance traveled, peak velocity, peak acceleration, and zero crossings). Generally there are two families of kinematic measures: spatial and temporal. Spatial kinematic measures include peak velocity, peak acceleration, proportion of distance traveled at peak velocity, and zero crossings. Temporal kinematic measures include time to peak velocity, time from peak velocity until the end of movement, proportion of time to peak velocity, time to peak acceleration, and proportion of time to peak acceleration. Some of these measures were reported in mouse use studies. Even though not all were reported in mouse use literature, they remain relevant, particularly if the usage is operationalized using a pointing task. Table 11 summarizes various kinematic measures reported in the literature.

Table 11. Various Kinematic Measures.

Kinematic Measure	Description	Reported in
Peak velocity (PV)	• The highest magnitude in velocity profile, usually occurs during primary submovement	Chua & Elliott (1993), Elliott et al. (1991), Helsen et al. (1998), Ketcham et al. (2002), Phillips et al. (2005), Ricker et al. (1999), Slocum, and Thompson, et al. (2005)
Peak acceleration (PA)	• The highest magnitude in acceleration profile, may occur during primary or secondary submovements	Carlton (1994), and Helsen et al. (1998)
Time to PV (TPV)	• Difference between time at PV and time at the beginning of movement • Direct indicator for movement efficiency	Carlton (1994), Elliott et al. (1991), Helsen et al. (1998), Phillips et al. (2005), and Ricker et al. (1999)
Time to PA (TPA)	• Difference between time at PA and time at the beginning of movement	Carlton (1994), and Helsen et al. (1998)
Proportion of time to PV (PROPTPV)	• The ratio of time to PV (TPV) and movement time (MT)	Chua & Elliott (1993), Helsen et al. (1998), Ketcham et al. (2002), and Ricker et al. (1999)
Proportion of time to PA (PROPTPA)	• The ratio of time to PA and the overall time	Helsen et al. (1998)
Proportion of distance traveled at the time of PV (PROPDPV)	• The ratio of distance traveled at PV and total distance • Some authors suggested it as a positive indicator for movement efficiency	Chua & Elliott (1993), Helsen et al. (1998), Ketcham et al. (2002), and Slocum, Chaparro, et al. (2005)
Time from PV until the end of movement (TPVEND)	• Difference between time at PV and time at the end of movement • Indicates time spent in homing phase	Elliott et al. (1991)

5.4. Aging, Psychomotor Ability, and Performance of Computing Tasks

There is a host of studies that investigates the effects of aging on performance of computing tasks. However, only a few studies consider the perspectives of age-associated declines in functional abilities, and how that affects performance. In Czaja & Sharit (1998), subjects aged 20- to 75-years-old were tested with a computer data entry task over a period of five consecutive days. As predicted, the results indicated significant age differences in task performance. However, the age effect alone did not account for the differences in performance. Psychomotor ability, and to a lesser extent, cognitive ability were found to contribute to the variability of task performance as well. In another words, after the performance variance was accounted for by functional abilities, it was demonstrated that age had only minimal impact on performance. In a separate study, subjects of a similar age range were tested by Smith, Sharit, & Czaja (1999) on a series of computer mouse tasks (i.e., pointing, clicking, double-clicking, and dragging). As expected, performance differences were detected in regard to age. However, further investigation showed it was the age-related changes in psychomotor ability that accounted for such differences. Both studies demonstrated that when controlling for differences in psychomotor ability associated with age, a pure age effect no longer accounted for mouse use performance. In short, there is some evidence indicating that after controlling for basic functional abilities, the age effect on task performance diminishes. This evidence is consistent with the view that the age effect is only a surrogate variable, and that the underlying abilities are the true causal variables for performance differences (see Birren & Renner, 1977; and Salthouse & Maurer, 1996). However, it is not known whether the same proposition is also applicable to the kinematics of aiming movement.

5.5. Objectives

A number elemental psychomotor ability has been suggested to be predictive of computing task performance (e.g., Hwang, 2001; Knight & Salvendy, 1992; and Jacko & Vitense, 2001). It was the interest of this study to empirically examine this proposition. Although a similar question was addressed previously by Cheong, Pham, Phan, & Shehab (2005), this study extends that work by determining the predictability of mouse mediated movement kinematics based on various elemental psychomotor abilities.

Mouse use can be considered a complex psychomotor task; logically its performance is subject to age differences. While many studies (e.g., Smith, Sharit, & Czaja, 1999) found age effects in the performance of mouse tasks, it is not known if age differences are present in movement kinematics as well. Currently the effects of age on the kinematics of mouse-mediated aiming movements are not well-documented. Ketcham et al. (2002) was the only study of similar purpose; however, the aiming movements were mediated using a pen. Therefore, the second objective of this study was to determine age-related differences in regard to movement kinematics during aiming movements mediated by a mouse.

Some researchers believe that the effect of age on task performance is in fact associated with age-related changes in functional abilities, as demonstrated by Czaja & Sharit (1998) and Smith, Sharit, & Czaja (1999). However, it is not known whether the same is true in regard to movement kinematics. Therefore the current study attempted to separate age-related differences from differences in psychomotor ability in kinematic performance measures. It was hoped that age would show only minimal, if any, impact on kinematic differences after psychomotor ability was considered.

To summarize, this study has three objectives: (1) to determine whether psychomotor measures are predictive of certain kinematic measures of mouse-based cursor movement, (2) to determine age group differences in regard to movement kinematics, (3) to determine if a true age-effect exists in movement kinematic differences after psychomotor ability is considered.

5.6. Method

5.6.1. Participants

Forty-five healthy participants between 21 and 90 years of age were recruited from the University of Oklahoma community, as well as from an independent living center. Fifteen participants were recruited from three age groups: younger (*M* = 25.25 years old, *SD* = 2.89), middle-aged (*M* = 50.37 years old, *SD* = 5.01), and older (*M* = 80.62 years old, *SD* = 6.16). Participants were required to have normal or near-normal vision, with correction if necessary. Their binocular vision was at least 20/60 based on the Snellen chart. Additionally, older participants were screened for dementia. All participants were experienced mouse users except for one middle-aged participant and two older participants. Inexperienced participants were trained prior to performing the mouse task.

5.6.2. Procedure

All tests were conducted in a quiet environment, and were administered on an individual basis. Informed consent was obtained from the participants prior to the study. First, a questionnaire (see Appendix A) was administered to gather general demographic information and to screen out potential participants who have substantial injuries in their upper extremities. Then, participants' visual acuity was measured using a Snellen chart. In addition, older participants were screened for dementia using Folstein, Folstein, & McHugh's (1975) mini-mental state exam (see Appendix B). All participants initially recruited passed screening and proceeded to testing.

All participants performed five psychomotor tests and a pointing task. The order of testing was randomized, with a break of about 2 minutes between each task. The psychomotor tests were the rotary pursuit test (Lafayette Model 2203ET), the grooved type steadiness test (Lafayette Model 32010), the Minnesota manual dexterity test (Lafayette Model 32023), the Purdue pegboard (Lafayette Model 32020), and a tapping board task (Lafayette Model 32012). The pointing task was performed using a mouse under the Fitts' paradigm; IDTest (International Business Machines [IBM], 1999) was used for generating stimuli. The experiment concluded after all tasks were completed.

5.6.3. Experimental Tasks

Standardized psychomotor tests were used to measure various elemental psychomotor abilities (i.e., precision control, arm-hand steadiness, manual dexterity, finger dexterity, and wrist-finger speed) as suggested by Fleishman & Reily (1992). The mouse pointing task was operationalized using a multidirectional reciprocal Fitts' pointing task similar to that described in Soukoreff & MacKenzie (2004). Participants performed all tasks with their dominant hand.

5.6.3.1. Psychomotor Tests

Rotary Pursuit Test

A rotary pursuit test was used to assess participants' precision control. The test consisted of a light emitting target rotating beneath a circular glass template, at 30 rpm in a clockwise direction. The unit was attached with an impulse counter (Lafayette Model 58022) and a timer (Lafayette Model 54016), which were used to tally the number of revolutions made and to record total time-on-target (TOT), respectively. The unit was placed at waist height. Standing next to the unit, participants were instructed to track the rotating target using a stylus attached to the unit. To control for undesired variability, all participants were asked to position the stylus at the center of the template before each trial. After two practice trials lasting 30 s each, four repetitions of the same duration were completed. Short breaks were allowed between trials. The performance measure recorded was TOT averaged across the four trials.

Grooved Type Steadiness Test

Participants' arm-hand steadiness was measured using the grooved type steadiness test. The test unit consisted of a narrowing channel in which participants were required to move a stylus along without touching the sides. The unit was placed flat with the channel oriented horizontally to the participants, and that the wider end was on participant's weak hand side. All participants were asked to position the stylus at the wider end before the task began. After a practice trial, participants completed four repetitions. Error time (i.e., contact time between the stylus and the walls) was recorded using an attached timer (Lafayette Model 54016), and was averaged across four trials.

Minnesota Manual Dexterity Test

The Minnesota manual dexterity test was used to assess participants' manual dexterity. Participants were asked to stand next to the test board placed on a table directly in front of them. Two test batteries were administered: turning and displacing. The turning battery required the participant to pick up a peg with one hand, turn the peg while passing it to the other hand and then return the peg back to its position with the bottom side facing up. The battery ended after all pegs were turned. The displacing battery began with an empty top-left hole. The participant was required to move the peg to the adjacent hole, until all the pegs were displaced. To control for undesired variability, participants were asked to place their hand at the first peg before the trial began. After a practice trial, both the turning and the displacing batteries were repeated four times. Short breaks were allowed between trials.

Participants were reminded to complete both test batteries as fast as they could while ensuring all pegs were securely inserted. Performance measures recorded were completion times of both test batteries, each averaged across four trials.

Purdue Pegboard Test

The assessment of finger dexterity was conducted using the Purdue pegboard test. Participants were seated with the pegboard placed directly in front of them. Two test batteries were administered: insertion and assembly. The insertion battery required participants to use their dominant hand to pick up one metal pin at a time from the holding cup and then insert it into the holes arranged in two columns. The assembly battery required participants to make an assembly with both hands, using one pin, one collar, and two washers. Practice was allowed until participants were comfortable with the routines, then four trials of each battery were completed. Short breaks were allowed between trials. Participants were asked to place their hand near the holding cup before the test began. Participants were reminded to complete the test as fast as they could but making sure that all parts were securely inserted. Thirty seconds were given to complete the insertion assembly; one minute was allowed for the assembly battery. The average number of pins inserted was measured for the insertion battery; the average number of parts assembled was recorded for the assembly battery.

Tapping Board

Wrist-finger speed was measured using a tapping board. The unit was attached to an impulse counter (Lafayette Model 58022) for recording the number of taps made with the attached stylus. In a seated position, participants were required to alternately tap the metal plates with an attached stylus as fast as they could. After two practice trials, participants completed four 15-second trials. The average number of taps from four trials was the performance measure.

5.6.3.2. Mouse Pointing Task

A multidirectional reciprocal Fitts' pointing task was generated using IDTest (IBM, 1999) running on a Windows-based laptop computer with 1280-by-800 pixels screen resolution. The pointing device used was a neutral shaped Microsoft Optical Mouse connected to the computer via a universal serial bus (USB) port.

The targets were circular in shape with a diameter of 30 pixels; they were separated from each other by 50, 100, 200, 400, and 650 pixels. Using Shannon's formulation,

$$ID = \log_2\left(\frac{D+W}{W}\right)$$

the combinations produced five values of index of difficulty (ID) ranging from 1.42 to 4.50 bits. The targets were arranged along various angles (i.e., 0, 45, 90, and 135 degrees). The task required participants to point the cursor at the target and then select it using the left mouse button. The targets became transparent if successfully acquired. However, a beep sound was audible if the target was missed. Following a practice trial, each distance condition was tested five times at each angle. Therefore, participants completed 100 trials (i.e., 5 distances × 4 angles × 5 repetitions). The treatments (i.e., distance-angle combinations) were randomized for all trials. Short breaks were allowed between treatments. Movement time (MT) was recorded. In addition, cursor x-y positions were sampled across time. The sampling of cursor positions was event-based. Each time a mouse movement was detected, the x-y position of the cursor was recorded by IDTest (B.A. Smith, personal communication, 1 December, 2006). As a result, the sampling rate varied in each trial.

5.6.4. Data Interpolation and Smoothing

Cursor displacements were computed from the raw position data using the Pythagorean Theorem. The displacement data were then linearly interpolated at 200 Hz. The interpolation produced a dataset with a constant sampling rate, which was necessary for subsequent data smoothing. The interpolated data was smoothed using a fourth order zero-phase shift Butterworth low-pass filter with a cut-off frequency of 6 Hz. The cut-off frequency was determined using residual analysis. Data smoothing, selection of cut-off frequency, and the computations of velocities and accelerations were based on the techniques described in Winter (2005). The interpolation and smoothing processes were performed using a Microsoft Excel macro (Van Wassenbergh, 2005).

5.6.5. Movement kinematics Measures

Kinematics of cursor movement was characterized using nine measures: peak velocity (PV), time to peak velocity (TPV), proportion of time to peak velocity (PROPTPV), proportion of distance traveled at peak velocity (PROPDPV), peak acceleration (PA), time to peak acceleration (TPA), proportion of time to peak acceleration (PROPTPA), and time from peak velocity until the end of movement (TPVEND). To avoid misinterpretation of initial jerk as PA, accelerations that occurred within 10 ms of movement onset were disregarded during the identification process of PA.

5.7. Results and Analysis

5.7.1. Age Differences in Psychomotor Ability

Participants' psychomotor ability was assessed using seven measures from standard psychomotor tests as suggested by Fleishman & Reily (1992). A series of one-way ANOVAs were performed to compare differences among age groups in regard to various psychomotor measures. As expected, age groups were found to be significantly different in regard to all psychomotor measures (see Table 12). Ryan's multiple comparison procedure (MCP) was performed to determine pairwise differences in age group. In general, the results revealed lower psychomotor ability in the older age group when compared to the younger and the middle-aged groups. There was no significant difference between the younger and the middle-aged groups in regard to psychomotor ability, such a trend in age differences was observed across all psychomotor measures (see Table 12).

Table 12. ANOVAs and Ryan's MCP on Psychomotor Measures.

Source	*df*	ANOVA *F*	Group Means (Standard Deviation)		
		Precision Control (time-on-target, TOT in seconds)			
Age group (AGE)	2	8.82	11.91	11.05	6.34
			Younger	Middle-aged	Older
Error	42	(15.26)			
		Arm-Hand Steadiness (error time, ET in seconds)			
Age group (AGE)	2	5.90	.25	.31	.71
			Middle-aged	Younger	Older
Error	42	(.16)			
		Manual Dexterity[a] (completion time, CT-D in seconds)			
Age group (AGE)	2	37.26	171.16	183.86	243.17
			Younger	Middle-aged	Older
Error	42	(594.83)			
		Manual Dexterity[b] (completion time, CT-T in seconds)			
Age group (AGE)	2	30.53	175.13	182.89	257.00
			Younger	Middle-aged	Older
Error	42	(1003.51)			
		Finger Dexterity[c] (number of pins inserted, PIN-I)			
Age group (AGE)	2	27.12	17.07	16.20	12.03
			Younger	Middle-aged	Older
Error	42	(4.00)			
		Finger Dexterity[d] (number of pins assembled, PIN-A)			
Age group (AGE)	2	54.09	43.37	39.35	21.77
			Younger	Middle-aged	Older
Error	42	(36.60)			
		Wrist-Finger Speed (number of taps, TAP)			
Age group (AGE)	2	12.24	62.87	58.50	45.98
			Younger	Middle-aged	Older
Error	42	(94.10)			

Note. Values in parentheses represent mean square error. Underlined groups are not significantly different at $\alpha = .05$.
[a]Minnesota Manual Dexterity Test displacement battery. [b]Minnesota Manual Dexterity Test turning battery. [c]Purdue Pegboard insertion battery. [d]Purdue Pegboard assembly battery.

5.7.2. Age Differences in Movement kinematics

Each kinematic measure was evaluated using a 3 (between-subjects age group, AGE) × 5 (within-subjects distance condition, DIST) × 4 (within-subjects movement angle, ANGLE) × 5 (within-subjects repetition, REPEAT) analysis of variance (ANOVA). The test on the between-subjects effect used $MS_{SUB(AGE)}$ as the error term; the tests on the within-subjects effects were determined using their respective error terms. To circumvent possible violation of the sphericity assumption, within-subjects effects were determined with numerator and denominator degrees of freedom adjusted using the Huynh-Feldt procedure. Effect size was also computed for each significant effect. According to Olejnik & Algina (2000), effect size can be defined as the proportion of the sum of the error variance and variances of all other effects in the model, $\hat{\eta}^2 = SS_{effect} / SS_{total}$. An effect size of 1% is considered a small effect, 6% a medium effect, and 14% indicates a large effect (Cohen, 1988).

Subsequent to the omnibus tests, Ryan's multiple comparison procedure (MCP) was performed if age group was significant. When dealing with the between-subjects effect, the error term was approximated using the between-subjects error, or $MS_{SUB(AGE)}$. For multiple comparisons of the simple between-subjects effect at a fixed level of the within-subjects factor (i.e., distance condition, movement angle, and trial), the error term was approximated using the pooled within-cells error term at that particular level (Maxwell & Delaney, 1990). For instance, $MS_{SUB(AGE)\text{ at D400}}$ was used as the error term when conducting MCP on the between-subjects age effect at D400 (a within-subjects effect).

5.7.2.1. Peak Velocity

Peak velocity (PV) was significantly different in regard to AGE ($F_{2, 42}$ = 22.75, p < .0001, $\hat{\eta}^2$ = .086), ANGLE ($F_{3, 126}$ = 16.2, p < .0001, $\hat{\eta}^2$ = .005), and DIST ($F_{4, 168}$ = 214.43, p < .001, $\hat{\eta}^2$ = .394). Significance was also detected for the interactions AGE × DIST ($F_{8, 168}$ = 17.99, p < .0001, $\hat{\eta}^2$ = .066) and DIST × ANGLE ($F_{12, 504}$ = 2.76, p = .0128, $\hat{\eta}^2$ = .003).

A series of Ryan's MCPs was performed on the simple effect AGE at all DIST levels (i.e., D50, D100, D200, D400, and D650), using a Bonferroni adjustment of $\alpha = .05/5 = .01$ for each level of distance condition. The older group attained significantly lower PV across all distance conditions; however, there was no significant different between the younger and the middle-aged groups (see Table 13). As shown in Figure 9, the older group is increasingly disadvantaged as the distance increases.

Table 13. Age Differences in Peak Velocity at Various Distance Conditions.

Distance Condition	Group Means in pixels/s (Standard Deviation)		
D50	35.82 (25.64) Younger	28.54 (14.47) Middle-aged	19.16 (27.13) Older
D100	66.09 (23.52) Younger	61.15 (83.27) Middle-aged	37.80 (29.19) Older
D200	132.71 (145.52) Younger	101.00 (45.45) Middle-aged	62.06 (42.59) Older
D400	240.82 (240.83) Younger	186.68 (107.56) Middle-aged	102.65 (88.55) Older
D650	391.66 (174.72) Younger	313.94 (200.22) Middle-aged	132.91 (98.43) Older

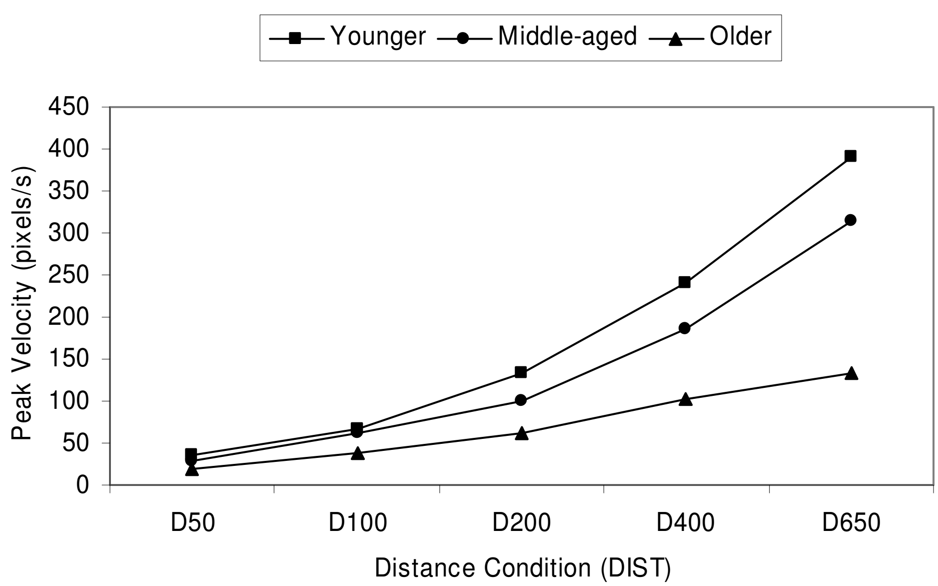

Figure 9. Plot of Peak Velocities for AGE × DIST.

5.7.2.2. Time to Peak Velocity

ANOVA indicated significant AGE effects ($F_{2, 42}$ = 33.71, p < .0001, $\hat{\eta}^2$ = .201), as well as DIST effects ($F_{4, 168}$ = 43.90, p < .001, $\hat{\eta}^2$ = .043) on time to peak velocity (TPV). Ryan's MCP on the main effect AGE revealed significant differences between all age groups. As depicted in Figure 10, TPV increased with age from the younger group (M = .129 s, SD = .049), to the middle-aged group (M = .182 s, SD = .125), and the older group (M = .325 s, SD = .252).

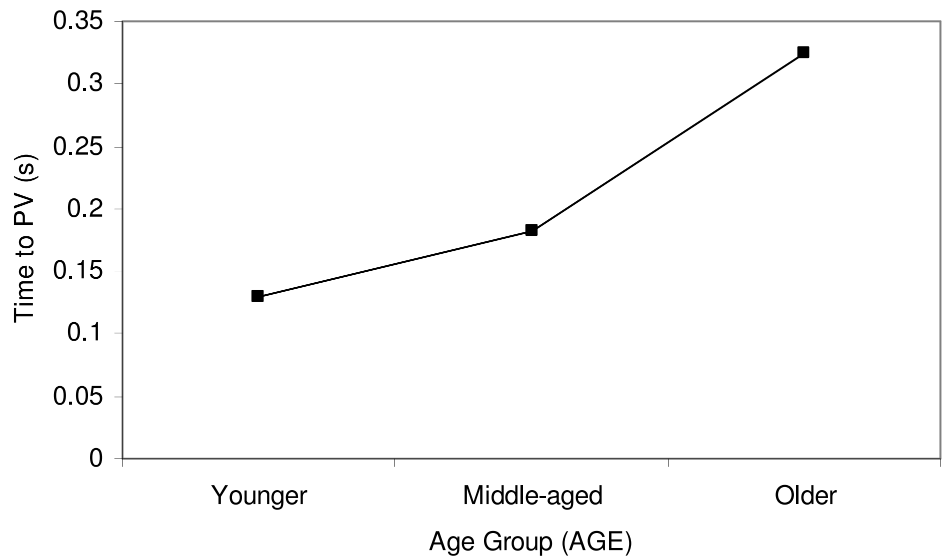

Figure 10. Plot of Time to Peak Velocity for AGE.

5.7.2.3. Proportion of Time at Peak Velocity

Proportion of time at PV (PROPTPV) was not significantly different in regard to AGE. Nevertheless, the results showed significant effects for DIST ($F_{4, 168}$ = 39.44, p < .0001, $\hat{\eta}^2$ = .054), REPEAT ($F_{4, 168}$ = 5.68, p = .0003, $\hat{\eta}^2$ = .005), DIST × ANGLE ×

REPEAT, ($F_{48,\,2016}$ = 1.56, p = .0342, $\hat{\eta}^2$ = .012), and AGE × DIST × ANGLE × REPEAT ($F_{96,\,2016}$ = 1.45, p = .0208, $\hat{\eta}^2$ = .023).

5.7.2.4. Proportion of Distance Traveled at Peak Velocity

ANOVA showed significant age effects ($F_{2,\,42}$ = 9.23, p = .0005, $\hat{\eta}^2$ = .011) in regard to proportion of distance traveled at peak velocity (PROPDPV). The remaining effects were insignificant. Ryan's MCP on the main effect AGE revealed the older group produced larger values (M = .717, SD = 2.59) than younger (M = .226, SD = .15) and middle-aged (M = .447, SD = 2.13). There was no significant difference between the younger and the middle-aged groups (see Figure 11).

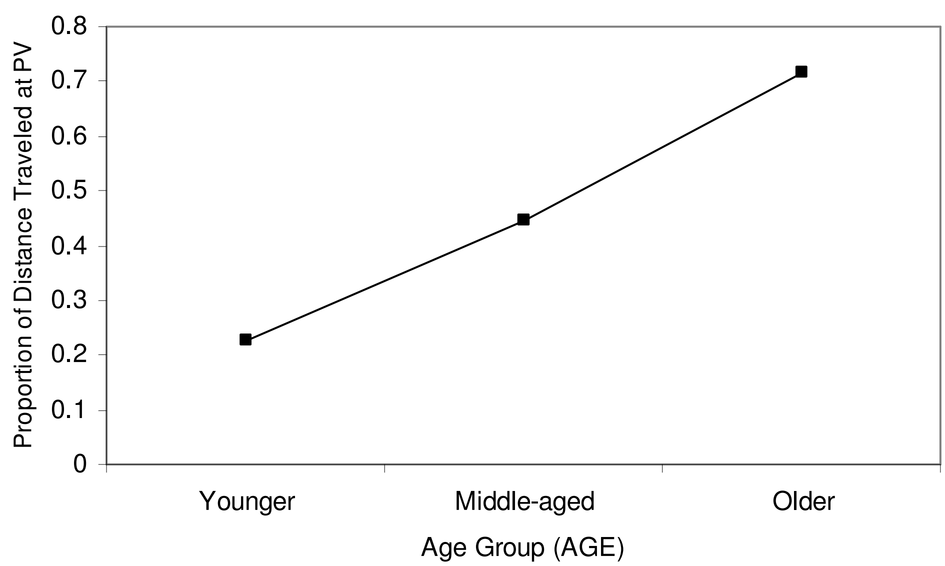

Figure 11. Plot of Proportion of Distance Traveled at Peak Velocity for AGE.

5.7.2.5. Peak Acceleration

Peak acceleration (PA) was significantly affected by AGE ($F_{2, 42}$ = 4.26, p = .0206, $\hat{\eta}^2$ = .013) and DIST ($F_{4, 168}$ = 44.77, p < .0001, $\hat{\eta}^2$ = .012). Ryan's MCP was performed to determine pairwise differences in AGE. Again, PA for the older group (M = 1570.9 pixels/s^2, SD = 4106.67) was significantly lower than for the younger (M = 2833.3 pixels/s^2, SD = 3060.52) and the middle-aged (M = 2884.2 pixels/s^2, SD = 7836.83) groups, and there there was no difference between the latter two (see Figure 12).

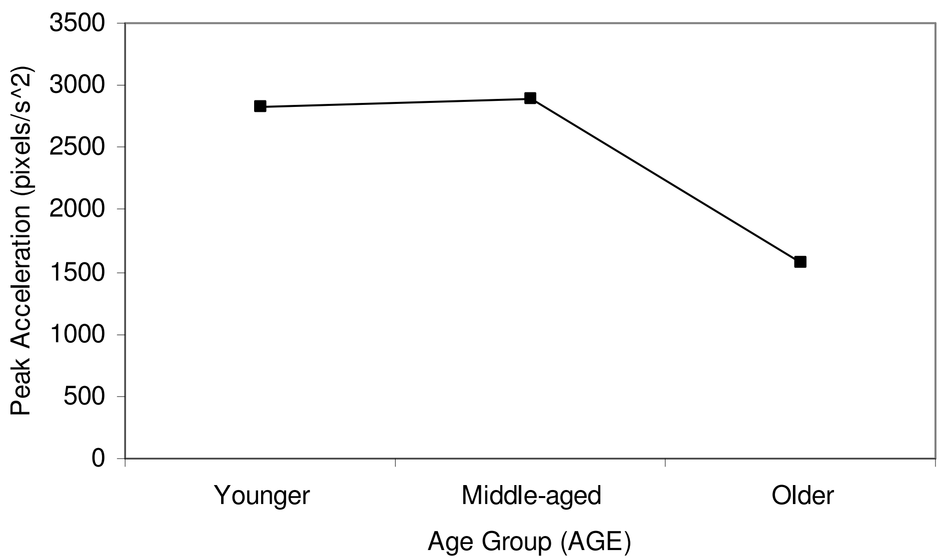

Figure 12. Plot of Peak Acceleration for AGE.

5.7.2.6. Time to Peak Acceleration

In regard to time to peak acceleration (TPA), significant differences were detected for AGE ($F_{2, 42}$ = 38.64, p < .0001, $\hat{\eta}^2$ = .198), ANGLE ($F_{3, 126}$ = 5.39, p = .0025, $\hat{\eta}^2$ = .004), DIST ($F_{4, 168}$ = 21.58, p < .0001, $\hat{\eta}^2$ = .021), AGE × DIST ($F_{8, 168}$ = 4.16, p = .0013, $\hat{\eta}^2$ = .008), and AGE × ANGLE ($F_{6, 126}$ = 3.81, p = .0026, $\hat{\eta}^2$ = .006).

Ryan's MCP on age with α = .01 (e.g., Bonferroni adjusted for the levels of distance) revealed all three age groups were significantly different at D50. Furthermore, the older group had longer TPA than the younger and the middle-aged groups across all other distance conditions; however, there was no significant difference between the younger and the middle-aged groups (see Table 14 and Figure 13).

Table 14. Age Differences in Time to Peak Acceleration at Various Distance Conditions.

Distance Condition	Group Means in s (Standard Deviation)		
D50	.171 (.107) Younger	.272 (.174) Middle-aged	.438 (.249) Older
D100	.196 (.097) Younger	.254 (.113) Middle-aged	.430 (.246) Older
D200	.182 (.105) Younger	.241 (.129) Middle-aged	.394 (.228) Older
D400	.212 (.122) Younger	.267 (.175) Middle-aged	.434 (.338) Older
D650	.224 (.123) Younger	.324 (.292) Middle-aged	.570 (.381) Older

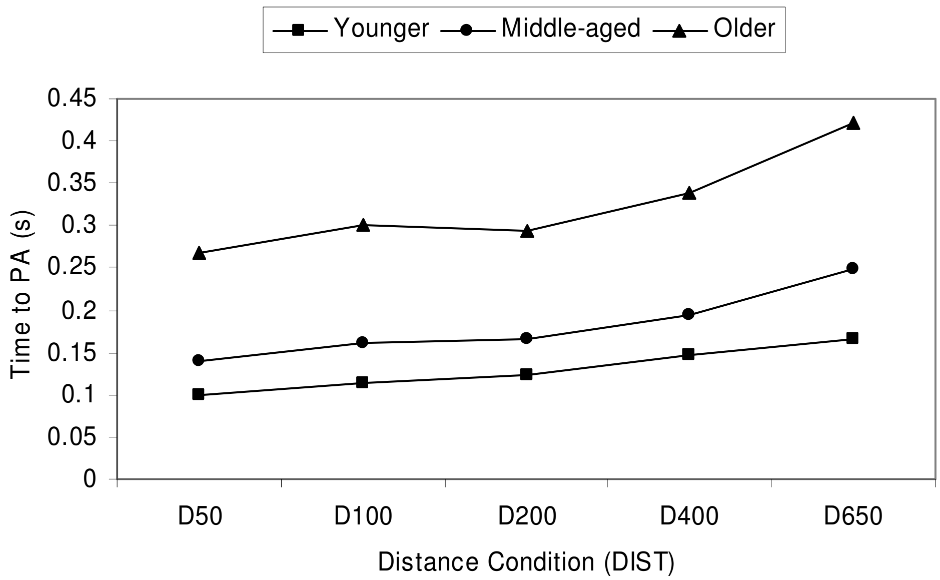

Figure 13. Plot of Time to Peak Acceleration for AGE × DIST.

Due to the significant AGE × ANGLE effect, a second Ryan's MCP was performed on age with $\alpha = .0125$ (e.g., Bonferroni adjusted for levels of angle) to examine the AGE by ANGLE interaction. Across all movement angles, the older group had longer TPA values than the younger and the middle-aged groups; however, there were no significant differences between the younger and the middle-aged groups. The only exception was when ANGLE = 90°, all three age groups were significantly different than each other (see Table 15 and Figure 14).

Table 15. Age Differences in Time to Peak Acceleration at Various Movement Angles.

Movement Angle	Group Means in s (Standard Deviation)		
0°	.205 (.114) Younger	.249 (.151) Middle-aged	.413 (.244) Older
45°	.195 (.107) Younger	.279 (.202) Middle-aged	.493 (.359) Older
90°	.187 (.117) Younger	.293 (.207) Middle-aged	.483 (.287) Older
135°	.200 (.113) Younger	.266 (.188) Middle-aged	.414 (.291) Older

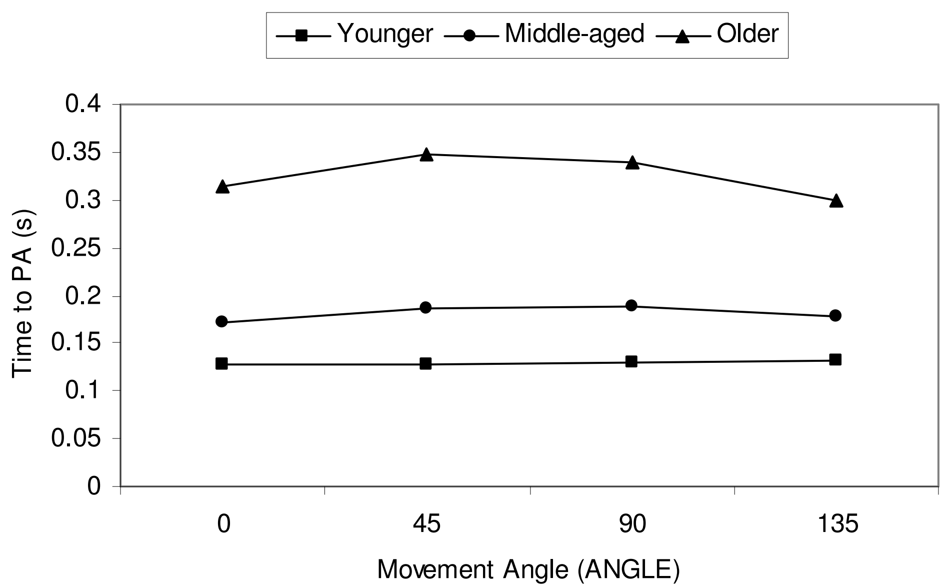

Figure 14. Plot of Time to Peak Acceleration for AGE × ANGLE.

5.7.2.7. Proportion of Time to Peak Acceleration

AGE was not significantly different in regard to proportion of time to peak acceleration (PROPTPA). However, ANOVA detected significance for DIST ($F_{4, 168}$ =

128.49, p < .0001, $\hat{\eta}^2$ = .150), REPEAT ($F_{4, 168}$ = 3.52, p = .0089, $\hat{\eta}^2$ = .002), and AGE × ANGLE ($F_{6, 126}$ = 4.04, p = .0010, $\hat{\eta}^2$ = .006).

5.7.2.8. Time from Peak Velocity until the End of Movement

In regard to time from peak velocity until the end of movement (TPVEND), AGE was significantly different ($F_{2, 42}$ = 28.07, p < .0001, $\hat{\eta}^2$ = .277), as were DIST ($F_{4, 168}$ = 393.25, p < .0001, $\hat{\eta}^2$ = .219), REPEAT ($F_{4, 168}$ = 8.58, p < .0001, $\hat{\eta}^2$ = .003), and AGE × DIST ($F_{8, 168}$ = 17.67, p < .0001, $\hat{\eta}^2$ = .020). Results from Ryan's MCP with α = .01 (e.g., Bonferroni adjusted for levels of distance) indicated that the older group had longer TPVEND compared to the younger and the middle-aged group across all distance conditions; there were no differences between the latter two groups (see Table 16 and Figure 15).

Table 16. Age Differences in Time from Peak Velocity until the End of Movement at Various Distance Conditions.

Distance Condition	Group Means (Time to Peak Acceleration in s)		
D50	.319	.466	.729
	(.084)	(.243)	(.313)
	Younger	Middle-aged	Older
D100	.425	.565	.883
	(.095)	(.217)	(.361)
	Younger	Middle-aged	Older
D200	.543	.722	1.071
	(.172)	(.314)	(.409)
	Younger	Middle-aged	Older
D400	.656	.861	1.378
	(.148)	(.332)	(.544)
	Younger	Middle-aged	Older
D650	.745	1.003	1.551
	(.150)	(.367)	(.578)
	Younger	Middle-aged	Older

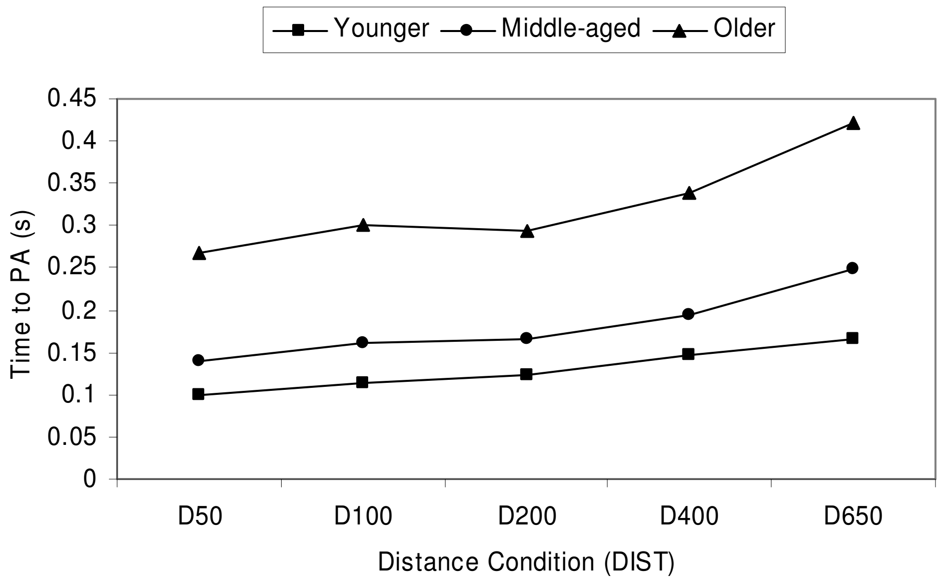

Figure 15. Plot of Time from Peak Velocity to End of Movement for AGE × DIST.

5.7.3. Effect of Age on Movement kinematics Controlling for Psychomotor Ability

Recall that one of the objectives of this study was to determine whether age still exerted significant effect on kinematic measures after functional abilities such as psychomotor ability were taken into account. Only kinematic measures that were significantly different in regard to the main age effect were included, i.e., peak velocity (PV), time to PV (TPV), proportion of distance traveled at PV (PROPDPV), peak acceleration (PA), time to PA (TPA), and time from PV until the end of movement (TPVEND). Other measures (i.e., proportion of time at peak velocity (PROPTPV) and proportion of time at peak acceleration (PROPTPA)) were excluded because the fact that the age main effect was not significant rendered them irrelevant in the current context. For computation purpose, the kinematic measures were aggregated across the 20 trials (i.e., 4 angle × 5 repetition) of each distance condition.

Recall that seven psychomotor measures were recorded. However, both CT-D and CT-T were measures of manual dexterity obtained from the Minnesota manual dexterity test; and PIN-I and PIN-A were measures of finger dexterity obtained using the Purdue pegboard test. For the sake of simplicity, only one measure (i.e., CT-D and PIN-I) from each test were used in subsequent analysis. Precision control (as measured using time-on-target (TOT)), manual dexterity (as measured using completion time from displacing battery (CT-D)), finger dexterity (as measured using number of pins inserted (PIN-I)), and wrist-finger speed (as measured using number of taps (TAP)) were evaluated for their contribution to each kinematic measure using stepwise regression analysis with $\alpha = .05$ for variable entrance and $\alpha = .2$ for deletion. The results indicated that CT-D was the only good contributor for all kinematic measures, except for TPVEND whereby TAP was also found to be a good contributor.

A series of hierarchical multiple regression was performed with each of the kinematic measures as the dependent variable. As explained in Czaja & Sharit (1998), the technique involved computing age-related variances using two regression models. In the first regression, age was entered as the only predictor in the model; this allows the determination of total age-related variance accounted for in the dependent variable (i.e., kinematic measures). In the second regression, unique age-related variance was computed by entering age after the psychomotor measures had been entered. Subsequently, the proportion of unique age-related variance to total age variance (i.e., [total age variance – unique age variance]/total age variance) was computed to determine the specific age effect on the kinematic measures. A high proportion indicates a large overlap between age and psychomotor ability, and age alone does not explain the differences in kinematic measures

(Salthouse, 1996). Using this ratio of age-related variances, a high proportions of shared variance (i.e., larger than .8) was detected in PV, TPV, PA, and TPA. Such a high proportion indicated that despite the apparent influence of the age effects, differences in these measures were in fact caused by age-related changes in psychomotor ability (i.e., manual dexterity). Simply said, age was only a surrogate variable. However, the results were less apparent for PROPDPV and TPVEND and thus the same suggestion did not apply. Table 17 summarizes the regression analyses for various kinematic measures.

Table 17. Hierarchical Multiple Regression for Various Kinematic Measures.

Dependent Variable	Predictor	β	R^2	Unique R^2
Peak velocity (PV)	CT-D (Manual dexterity)	-.764*	.137	.137
	Age	-.812	.146	.009
	Total age		.124	
	Unique age		.009	
	Proportion variance shared		.927+	
Time to PV (TPV)	CT-D (Manual dexterity)	.001*	.465	.465
	Age	.002*	.524	.059
	Total age		.481	
	Unique age		.059	
	Proportion variance shared		.877+	
Proportion of distance at peak velocity (PROPDPV)	CT-D (Manual dexterity)	.000	.068	.068
	Age	.010*	.115	.047
	Total age		.115	
	Unique age		.047	
	Proportion variance shared		.591	
Peak acceleration (PA)	CT-D (Manual dexterity)	-21.744*	.056	.056
	Age	6.343	.057	.001
	Total age		.030	
	Unique age		.001	
	Proportion variance shared		.967+	
Time to PA (TPA)	CT-D (Manual dexterity)	.002*	.558	.558
	Age	.002*	.609	.051
	Total age		.541	
	Unique age		.051	
	Proportion variance shared		.906+	
Time from PV until the end of movement (TPVEND)	CT-D (Manual dexterity)	.006*	.455	.455
	TAP (Wrist-finger speed)	.005*	.466	.011
	Age	.004*	.486	.020
	Total age		.395	
	Unique age		.202	
	Proportion variance shared		.489	

Note. β's are from final regression model.
* Significant at $\alpha = .05$.
+ Proportion larger than .8.

5.8. Discussion

Several authors have suggested a linkage between psychomotor ability and performance of mouse use. Among the earliest proponents is Knight & Salvendy (1992), who suggested that mouse use is dependent on precision control. Hwang (2001) found manual dexterity to correlate with mouse use performance. The current study differs from the previous ones in two ways. First, various elemental psychomotor measures were obtained from across a wide age range. Also, unlike previous studies where only movement time was investigated, this study investigates the relationship between psychomotor ability and movement kinematics.

Age differences were detected in regard to all psychomotor measures, namely: precision control, arm-hand steadiness, manual dexterity, precision control, and wrist-finger speed. Decrements in psychomotor ability were only apparent in the older group, and that the younger and the middle-aged group were not significantly different. These results agreed with previous findings whereby psychomotor ability was found to be stable across the age groups until older ages whereby the deficit becomes apparent (e.g., Kerr, Blais, & Toward, 1996).

Age differences were detected in all kinematic measures except for proportion of time at peak velocity (PROPTPV) and proportion of time at peak acceleration (PROPTPA). In general, post-hoc analysis attributed the overall differences to the older group. As evidenced by age differences in peak velocity (PV) and peak acceleration (PA), it was concluded that the primary submovement reduces in the older group. The data also showed time needed to achieve PV and PA (i.e., TPV and TPA) increased as a function of age, which was particularly apparent in the older group. Consequently, the longer time spent in the primary submovement translated to a longer distance traveled at peak velocity (i.e., PROPDPV) in the older group. Many existing studies have reported similar trends in the older adults (see Ketcham et al., 2001; and Vercruyssen, 1996) but the current study demonstrated that changes in movement kinematics only become clearer in the older age group compared to the younger and the middle-aged groups. During the homing phase, the data indicated that the time needed for adjusting the cursor for target acquisition (i.e., TPVEND) increased significantly in the older group, albeit no difference was detected between the younger and the middle-aged groups. The homing phase is characterized by corrective movements used to adjust overshoots or undershoots. The corrective movements are enabled by visual feedback and kinethestic feedback to a lesser extent (Keele & Posner, 1968). Note that all pariticpants regardless of age group had good vision. Nonetheless, even with a good control of the vision, the age effect was rather significant. Thus, it may indicated that there were other factors such as executive control (e.g., the ability to process visual information and the subsequent output) may play an important role in this phase.

The inability to detect significant age effects on proportion of time to peak velocity (PROPTPV) can be attributed to the positive correlation between TPV and MT (see Chapter 4), and that the differences in TPV in the numerator were occluded by differences in MT in the denominator. As a result, despite the age differences in TPV and MT, the PROPTPV in one age group did not deviate much by age group. A similar argument is also applicable in explaining the insignificant age effects on proportion of time to peak acceleration (TPA), because TPA and MT are also positively correlated (see Chapter 4). Despite their inability to reveal age effects in this study, PROPTPV and PROPTPA have been shown useful in other settings such as the determination of visual feedback during aiming movement (see Chua & Elliott, 1993; Helsen et al., 1998; and Ricker et al., 1999).

Even though age differences were detected in kinematic measures, they did not necessarily translate to poorer performance (i.e., longer movement time). Note that not all kinematic measures were correlated with movement time (MT). Correlation with MT was only found in TPV, TPA, and TPVEND. Hence, this led to a question: how could age-related differences be present in some kinematic measures and in movement time, but at the same time some of them were uncorrelated (see Chapter 4)? It is believed that the dissociation could be explained by investigating the effects of factors other than age on movement kinematics, following the proposition that overt age-related performance deficiencies may be in fact caused by age-related changes in functional abilities, and that age is only a surrogate variable (Birren & Renner, 1977; Salthouse, 1996; and Salthouse & Maurer, 1996).

Psychomotor ability seemed a plausible functional ability that might cause variability in mouse use. Thus, it was of interest to learn whether age still contributed to the variability in kinematic measures after psychomotor ability was taken into account. Hierarchical multiple regression confirmed that an overt age effect shared variance with psychomotor ability in respect to several kinematics measures, i.e., PV, TPV, PA, and TPA. Since these measures were also associated with the primary submovment, thus, the results suggested that age was not a major contributor to the kinematics of the primary submovement. Instead, the differences could be attributed to age-related changes in psychomotor ability. However, we were unable to make the same conclusion in regard to PROPDPV and TPVEND. To summarize further, the data indicated that, in general, ballistic submovements were affected by age-related differences in psychomotor ability, and not age per se. However, it was unclear as to whether the differences in the secondary submovement, the homing phase, were due to age, or due to age-related changes in psychomotor ability.

It is generally believed that the ballistic primary submovement is preprogrammed towards arriving within the target, and that there is little or no involvement of sensory feedback. Manual dexterity (as measured using the Minnesota test) accounted for a large portion of the variance in the kinematics of the primary submovement, suggesting that differences in this phase could be attributed to the effects of psychomotor ability. Psychomotor ability is generally thought of as a hybrid of various functional abilities (i.e., vision, motor control, and physical ability). The next logical steps would be to determine whether motor control and other fundamental abilities that makes up psychomotor ability are indeed contributing to differences in movement kinematics. Visual and kinesthetic sensory feedback are additional contributing factors during the secondary homing submovement (Crossman & Goodeve, 1963/1983; Chua & Elliott, 1993; and Keele, 1968). The presence of additional contributing factors may explain the small shared variance between age and psychomotor ability. Because data on visual feedback, thought to be an important factor, was not observed in this study, it was unclear whether a larger variance could be captured should vision be included.

CHAPTER 6

EFFECTS OF LOW VISION ON THE KINEMATICS OF MOUSE-MEDIATED POINTING MOVEMENT

6.1. Introduction

Low vision is an umbrella term that describes a diverse population of people with visual impairments. Some authors refer to low vision as conditions whereby despite use of corrective devices, visual limitations are still profound (Mehr, 1975). It should be made clear that low vision does not necessarily translate to blindness; rather, it is a collection of visual impairments. Only 10% of those who suffer from vision loss are functionally blind (Nelson & Dimitrova, as cited in Kraut & McCabe, 2000). Functional blindness refers to conditions where individuals no longer have useful vision and that they have to rely on other sensory systems to perform daily activities. On the other hand, people with low vision still retain some useful vision (Lighthouse International, 2001). Also referred to as people with partial sight, these individuals often rely on corrective techniques and devices in their daily activities. The Eye Diseases Prevalence Research Group (2004) reported a steady increase of low vision conditions among adults aged 40- to 80-year-old. A similar trend of visual impairments in the older population was also reported by Desai, Pratt, Lentzner, & Robinson (2001, March). According to the report, 19% of individuals 70 years of age and older were visually impaired and that such impairment increased with age. Despite the statistics, aging itself does not necessarily lead to vision loss. Although there are physiological changes in the eyes with aging (Kline & Scialfa, 1996), some of these changes are not a major cause for low vision. For instance, certain aging ocular structures, such as the cornea, present negligible effects on visual functions.

There are numerous causes for low vision. In most cases it is pathological. Low vision is often caused by conditions such as macular degeneration, cataracts, glaucoma, and diabetic retinopathy (Kraut, 2000). These conditions cause a host of different vision problems. Macular degeneration is a condition caused by deterioration of the central part of the retina that is responsible for visual acuity in the central visual field. Cataracts are caused by clouding of the lens. Common cataracts-related conditions include blurred and hazy vision in high illumination environments. Glaucoma is caused by pressure build-up inside the eyeball that damages the optic nerve, which in turn causes loss of peripheral vision. Diabetic retinopathy is caused by the leaking of retinal blood vessels. Blurred vision and increased sensitivity to glare are common problems associated with diabetic retinopathy. Note that the list mentioned above is not exhaustive; they are only a fraction of the numerous conditions associated with low vision.

6.2. Classification of Low Vision

Since low vision is often associated with one or more eye conditions, a person with certain medical conditions may experience a host of different vision losses. For instance, a diabetic patient may suffer from both cataracts and diabetic retinopathy because both diseases have been linked to diabetes. In order to meet the needs for a cohesive way of describing consequences of disease, the International Classification of Impairments, Disabilities and Handicaps (ICIDH) and the International Classification of Functioning, Disability and Health (ICF) were developed by the World Health Organization (WHO). The frameworks, particularly ICIDH, have been shown useful for describing partially sighted vision from multiple perspectives. Although often used interchangeably, the terms "disorder", "impairment", "disability", and "handicap" are used in ICIDH for differentiating various aspects of medical condition. Disorder refers to anatomical or physiological changes due to the pathology; impairment refers to functional changes to the organ; disability focuses on the functional abilities of the individual; handicap is related to the socioeconomic consequences caused by the condition (Colenbrander, 2000).

Visual condition is often measured along the functional vision dimension in applied settings. Eligibility for assistance and intervention programs (e.g., educational assistance, tax benefits, and social security assistance) are often based on measures of functional vision. Functional vision refers to a person's ability to use his vision in order to perform daily tasks effectively (Flom, 2004). Common measures of functional vision include visual acuity, visual field, color sensitivity, and contrast sensitivity. Some less common measures include light sensitivity, oculomotor control, and accommodation. Among these, visual acuity, visual field, and contrast sensitivity are the greatest determinants of the ability to accomplish daily tasks (Flom, 2004). Visual acuity is the ability to see fine details; it is expressed using the Snellen ratio. The numerator of the fraction represents the distance between the person and the object, whereas the denominator is the distance at which a person with normal eyesight could correctly recognize the object. Thus, a person with 20/40 vision can only resolve objects at 20 ft., but the same objects can be resolved by a person with normal vision at 40 ft. Visual field is a three-dimensional sensitivity to differential light at various positions, often measured in degree-radius or degree-diameter (Colenbrander, 2000). Color sensitivity is the ability to differentiate colors; it often involves the ability to discern two different colors such as green and red, or the ability to discriminate a normal range of colors. Finally, contrast sensitivity is the ability to discern the differences in luminance (brightness) between an object and its background. Contrast sensitivity is typically measured using a Pelli-Robson chart and is expressed as the proportion of the difference between the object and its background, and the brightness of the background.

In the United States, the most common classification scheme for visual condition is ICD-9-CM (U.S. Department of Health and Human Services [DHHS], 1980), which involves ordinal grouping of visual acuity scores. It is in fact the American adaptation of the International Classification of Diseases (9th Revision), or ICD-9, by the WHO (1977). A person is considered visually impaired when his visual acuity falls beyond 20/80. There are two broad ranges of visual impairments as defined in ICD-9-CM, namely: low vision and blindness. Low vision comprises of acuity scores from 20/80 to 20/1000, whereas a person is considered near-blindsighted if the acuity score is 20/1250 or above. At the end of the continuum is total blindness; that is, no light perception is possible in the eyes. Another classification scheme is based on visual field. A person is considered as being visually impaired when his visual field is less than 30º; and the severity increases as the degree-radius becomes narrower (Colenbrander, 2000). Similar to that of the visual acuity scheme, the extreme is total vision loss.

6.3. Low Vision and Computing

Despite the advances of computing technology, most computing tasks rely heavily on visual perception. While novel interaction techniques such as voice dictation are beginning to appear, they are still uncommon in home computers. In addition, most of these techniques require additional learning time; thus rendering it less appealing to users who could still rely on residual vision to complete the task. In other words, the benefits using the voice-dictated user interface do not outweigh the additional cost in learning time. Many still opt to use graphical user interface (GUI), albeit sometimes the interaction is augmented with accessibility features. On top of that, the availability of built-in accessibility features on modern computer environments has made it more difficult for people with residual vision to discard the GUI for alternative interaction paradigms.

In a GUI paradigm, the mouse remains the primary device for interacting with computers. Successful use of a mouse requires well-coordinated motor movements, as well as good visual feedback. From a human control system point-of-view, mouse use is a closed-loop system characterized by collaboration between motor control (output) and visual ability (input). The mouse cursor on the screen provides visual feedback to the user who subsequently exerts control on the mouse to move the cursor to a desired screen location.

There are many studies that investigate the contribution of vision in non-mechanized, direct hand movements (e.g., Elliott, Carson, Goodman, & Chua, 1991; Helsen, Elliott, Starkes, & Ricker, 1998; Ricker, Elliott, Lyons, Gauldie, Chua, & Byblow, 1999) and in mouse-mediated pointing movements (e.g., Chua & Elliott, 1993). However, participants with limited visual ability are rarely included. Jacko and colleagues (e.g., Jacko, et al., 1999; Jacko et al., 2003; Jacko, Barreto, et al., 2000; Jacko, Rosa, et al., 2000) were among the handful of researchers who investigated computer users with visual impairments. Working with participants suffering from retinitis pigmentosa, albinism, optic neuritis, and myopia, Jacko et al. (1999) investigated performance differences along various GUI attributes. Participants' visual condition was characterized using visual function measures, i.e., visual acuity, visual field, contrast sensitivity, and color discrimination. The results indicated that measures of visual function were significant predictors of task performance, particularly in terms of icon size and background color. In another study involving participants diagnosed with macular degeneration, Jacko, Barreto, et al. (2000) found that, in general, characteristics of cursor movement (i.e., movement time and velocity) change as visual acuity changes. In addition to longer movement times, participants with macular degeneration had lower movement velocities. Because participants with macular degeneration were significantly older than those with normal vision, it was not clear whether the difference in movement velocity was due to the visual condition, or merely due to a general aging effect. In other words, it was possible that the differences were confounded by the aging effect, instead of a direct effect of visual condition per se.

6.4. Kinematics of Pointing Movement

Most studies of pointing movement are dominated by Fitts' law. However, as a prediction model for performance of pointing movement, Fitts' law cannot explain what happens "during" the movement. Thus, alternative models were proposed to explain the process of the movement. Some notable models include the deterministic iterative corrections model proposed by Crossman & Goodeve (1963/1983) and Keele (1968), as well as the stochastic optimized submovement (SOS) model (Meyer, Abrams, Kornblum, Wright, & Smith, 1988; and Meyer, Smith, Kornblum, Abrams, & Wright, 1990). At present time the consensus indicates that the SOS model is the most appropriate model for describing the process of aiming movement. The model operates under the assumption that optimization of aiming movement requires a compromise between time and accuracy (i.e., speed-accuracy tradeoff). An attribute that sets the SOS model apart from previous models is the notion of neuromotor noise. It posits that due to such noise, submovement endpoints are normally distributed around the center of the target. Feedback systems (i.e., visual sensory, and kinesthetic sensory in a lesser extent) detect discrepancies (i.e., overshooting or undershooting) and invoke corrective submovements.

A typical pointing movement may consist of one or two components: the primary movement and secondary submovement (Meyer et al., 1988). The primary movement is preprogrammed to end within the target. If the primary movement ends as intended, no secondary submovements are needed. However, neuromotor noise may prevent such accuracy. In that case, one or more secondary submovements are initiated to correct the endpoint. The SOS model posits that a typical aiming movement needs only one or two submovements. Third- and higher-order submovements are also possible; but these higher order submovements would be absorbed by the secondary submovement. Further, higher-order submovements are quite unlikely and often observed in extra-ordinary situations such as movements involving extremely difficult targets and those require error-free performance.

A way to understand the process of pointing movement is by investigating the kinematics of the movement. Kinematics is the study of motions without considering the forces that cause the motion. The kinematics approach has been reported in recent studies involving computer input devices (MacKenzie et al., 2001; Phillips, Triggs, & Meehan, 2005; Slocum, Chaparro, McConnell, & Bohan, 2005; and Slocum, Thompson, & Chapparo, 2005). There are various kinematic measures reported in the literature, which can be grouped into two families: spatial and temporal. Spatial kinematic measures usually appear in distance units such as distance and amplitude, and include peak velocity, peak acceleration, proportion of distance traveled at peak velocity, and zero crossings (see Table 18). Temporal measures are strictly time-based and some temporal kinematic measures reported in the literature include time to peak velocity, time from peak velocity until the end of movement, proportion of time to peak velocity, time to peak acceleration, and proportion of time to peak acceleration (see Table 19).

Table 18. Spatial Measures of Movement Kinematics.

Kinematic Measure	Description	Reported in
Peak velocity (PV)	• The highest magnitude in velocity profile, usually occurs during primary submovement	Chua & Elliott (1993), Elliott et al. (1991), Helsen et al. (1998), Ketcham et al. (2002), Phillips et al. (2005), Ricker et al. (1999), Slocum, and Thompson, et al. (2005)
Proportion of time to PV (PROPTPV)	• The ratio of time to PV (TPV) and movement time (MT)	Chua & Elliott (1993), Helsen et al. (1998), Ketcham et al. (2002), and Ricker et al. (1999)
Proportion of distance traveled at PV (PROPDPV)	• The ratio of distance traveled at time of PV and total distance • Also referred to as proportion of distance traveled in primary submovement • Some authors use it as a positive indicator for movement efficiency	Chua & Elliott (1993), Helsen et al. (1998), Ketcham et al. (2002), and Slocum, Chaparro, et al. (2005)
Peak acceleration (PA)	• The highest magnitude in the acceleration profile, may occur during primary or secondary submovements	Carlton (1994), and Helsen et al. (1998)
Proportion of time to PA (PROPTPA)	• The ratio of time to PA to the overall time	Helsen et al. (1998)

Table 19. Temporal Measures of Movement Kinematics.

Kinematic Measure	Description	Reported in
Time to PV (TPV)	• Difference between time at PV and time at the beginning of movement • Direct indicator for movement efficiency	Carlton (1994), Elliott et al. (1991), Helsen et al. (1998), Phillips et al. (2005), and Ricker et al. (1999)
Time to PA (TPA)	• Difference between time at PA and time at the beginning of movement	Carlton (1994), and Helsen et al. (1998)
Time from PV until the end of movement (TPVEND)	• Difference between time at PV and time at the end of movement • Indicates time spent in homing phase	Elliott et al. (1991)

6.5. Research Rationales and Objectives

Given that vision is still the primary sensory feedback for computer users with low vision, it is important to understand the impact of low vision on computing. To be more specific, the objective of this study was to investigate the impact of low vision on mouse use. In the past, studies of mouse use often focused on endpoint measures such as movement time and target misses. While a great deal had been learned from these studies (e.g., Jacko, et al., 1999; Jacko et al., 2003; Jacko, Barreto, et al., 2000; Jacko, Rosa, et al., 2000), it was believed that further insight could be obtained by examining the kinematics of mouse-mediated pointing movement. It was hoped that by understanding changes in movement kinematics due to limited visual ability, novel techniques could be designed to improve the experiences of mouse users with low vision.

Investigation of mouse use is incomplete without taking into consideration into the interrelated factors such as age and psychomotor ability. There are countless studies that report age-related performance differences. However, some researchers (Birren & Renner, 1977; and Salthouse & Maurer, 1996) suggest that, in most cases, the age effect is only a surrogate variable and that the causality is driven more by relatively immediate factors such as knowledge, skills, and functional abilities. This conjecture had already been shown true by Czaja & Sharit (1998) and Smith, Sharit, & Czaja (1999), who concluded that age alone did not account for differences in performance of computing tasks, but the differences were caused by age-related changes in functional abilities. A similar conclusion was also reported for movement kinematics (see Chapter 5). The age factor was found to contribute minimally to the variance in certain kinematic measures and that the differences in kinematic measures were better explained by psychomotor ability (i.e., manual dexterity). As a result, this study investigated the impact of low vision on the kinematics of pointing movement while controlling for the effects of psychomotor ability and age.

6.6. Method

6.6.1. Participants

Ten participants were recruited to form two groups of equal size: low vision and normal vision. Following the strategy reported in Jacko, Rosa, et al. (2000), participants from each group was matched individually on age. As a result, the low vision group had a mean age of 47.82 years old (*SD* = 29.59), and the mean age in the normal vision group was 47.17 years old (*SD* = 30.15). Low vision participants were recruited with assistance from an on-campus disability service and a local independent living center. Potential participants were first screened to include only those who experienced less than near-normal vision after correction. However, there was no restriction on the type of condition that caused vision problem; thus low vision participants reported a wide range of visual conditions (see Table 20). Participants in the normal vision group were required to have at least 20/60 after-correction Snellen visual acuity. On the other hand, visual acuity of the low vision participants ranged from 20/60 to 20/2400 after correction. In addition, older participants were screened for dementia. All participants were experienced mouse users.

Table 20. Profiles of Low Vision Participants.

Participant	Age (years)	Diagnosis and Consequent Condition	Visual Acuity Left	Visual Acuity Right
1	81.0	• Cataracts in left eye o Blurred and hazy vision • Age-related macular degeneration (AMD) in the right eye o Reduced central visual field	20/60	Unknown
2	77.9	• Age-related retina degeneration in both eyes o Multiple possible conditions, including perception of flashing lights	20/85	20/2100
3	18.8	• Albinism o Astigmatism • Retina pigmentosa in both eyes o Reduced peripheral visual field	20/2400	20/2200
4	25.2	• Cataracts in both eyes o Blurred and hazy vision • Macular degeneration and lens removed in right eye o Reduced central visual field o Distorted light perception	20/50	20/2350
5	36.0	• Cataracts, detached retina, and retinitis pigmentosa in both eyes o Blurred and hazy vision o Reduced peripheral visual field	Unknown	Unknown

Note. Visual acuity reflects Snellen score after correction.

6.6.2. Procedure

All tests were conducted in a quiet environment and on an individual basis. Informed consent was obtained from each participant prior to the study. First, a screening questionnaire (see Appendix A) was administered. Then, participant's visual acuity was obtained using a Snellen chart. Because the chart had an upper threshold of 20/60, low vision participants were asked to provide their visual acuity score, if known. They were also asked about their diagnosis, history of the condition, and the usage of assistive devices. Additionally, older participants were screened for dementia using Folstein, Folstein, & McHugh's (1975) mini-mental state exam (see Appendix B).

During the experiment, each participant was asked to perform a psychomotor test and a pointing task, with a break of about 2 minutes between each task. The psychomotor test was performed on the Minnesota manual dexterity test (Lafayette Model 32023). The pointing task was performed using a mouse under the Fitts' paradigm; IDTest (International Business Machines [IBM], 1999) was used for generating stimuli for the pointing task. The experiment concluded after all tasks were completed.

6.6.3. Experimental Tasks

Participants were required to perform two types of experimental tasks: the displacing battery of the Minnesota manual dexterity test and a mouse pointing task. The test was used to measure manual dexterity as suggested by Fleishman & Reily (1992). The mouse pointing task was operationalized using a multidirectional reciprocal Fitts' pointing task similar to that described in Soukoreff & MacKenzie (2004). Participants performed all tasks using their dominant hand.

6.6.3.1. Minnesota Manual Dexterity Test

The Minnesota manual dexterity test unit consisted of wooden pegs arranged in four rows. A displacing test battery was chosen because it was found to account for the largest variability in movement kinematics (see Chapter 5). To perform the test, participants were asked to stand next to the test unit placed on a table directly in front of them. The test began with the top-left hole emptied. Then the participants were required to fill the top hole with the peg directly below it, until the bottom hole of the column is empty. The bottom hole was then filled with the peg from the second column. For the second column, participants were required to fill the empty hole with the peg directly above it until the top hole is emptied. Similarly, the top hole of the second column had to be filled with the peg from the third column. The test continued in this manner across the board until the bottom-right hole was emptied. After a practice trial, four actual trials were performed. Short breaks were allowed between trials. In addition, participants were asked to place their hand at the peg below the top-left hole before the trial began. Finally, they were reminded that if the peg was dropped; it should be picked up and placed in the intended position. They were also reminded to complete the test as fast as they could but in the mean time they should ensure all pegs were securely placed in the intended holes. Performance measures recorded were completion time averaged from four trials.

6.6.3.2. Mouse Pointing Task

A multidirectional reciprocal Fitts' pointing task was generated using IDTest (IBM, 1999) running on a Windows-based laptop computer with 1280-by-800 pixels screen resolution. The pointing device used was a neutral shaped Microsoft Optical Mouse connected to the computer via a universal serial bus (USB) port.

The targets were circular in shape with a diameter of 30 pixels; they were separated 50, 100, 200, 400, and 650 pixels from each other. Using Shannon's formulation of Fitts' Law, the combinations produced five conditions with index of difficulty (ID) [$\log_2((D + W) / W)$] values ranging from 1.42 to 4.50 bits. The targets, each colored black and red, were arranged along various angles (i.e., 0, 45, 90, and 135 degrees). The task required participants to point the cursor at the target and then select it using the left mouse button. The targets became transparent if successfully acquired. However, a beep sound was audible should the intended target was missed. Following a practice trial, each distance condition was tested five times at each angle. Therefore, each participant was subjected to 100 trials (i.e., 5 distances × 4 angles × 5 repetitions). The treatments (i.e., condition-angle combinations) were presented in random order for all trials. Short breaks were allowed between treatments. Movement time (MT) was recorded as the performance measure. In addition, cursor x-y positions were sampled across time using IDTest. Note that the sampling of cursor positions was event-based (i.e., mouse movement). Each time a mouse movement was detected, the x-y position would be recorded by IDTest (B.A. Smith, personal communication, 1 December, 2006). As a result, the sampling rate varied in each trial.

6.6.4. Data Interpolation and Smoothing

Point-to-point cursor displacements were computed from the raw position data using the Pythagorean Theorem. The displacement data were then linearly interpolated at 200 Hz. The interpolation produced a dataset with a constant sampling rate, which was necessary for subsequent data smoothing. The interpolated data was smoothed using a fourth order zero-phase shift Butterworth low-pass filter with a cut-off frequency of 6 Hz. The cut-off frequency was determined using residual analysis. First derivatives were obtained from the smoothed displacement data to obtain velocities; second derivatives were computed to produce accelerations. Data smoothing, selection of cut-off frequency, and the computations of velocities and accelerations were based on the techniques described in Winter (2005). The interpolation and smoothing processes were performed using a Microsoft Excel macro (Van Wassenbergh, 2005).

6.6.5. Movement kinematics Measures

In addition to movement time (MT), six kinematic measures were recorded including: peak velocity (PV), time to peak velocity (TPV), proportion of distance traveled at peak velocity (PROPDPV), peak acceleration (PA), time to peak acceleration (TPA), and time from peak velocity until the end of movement (TPVEND). The measures were extracted from the displacement, velocity, and acceleration profiles of each repetition of the pointing movements, based on the definitions in Table 21. To avoid misinterpretation of the initial jerk as PA, accelerations occurred within 10 ms of movement onset were excluded from the identification process of PA.

6.7. Results and Analysis

A series of 2 (between-subjects visual condition, VISION) × 5 (within-subjects distance condition, DIST) × 4 (within-subjects movement angle, ANGLE) × 5 (within-subjects repetition, REPEAT) analysis of covariance (ANCOVA) were conducted with age and manual dexterity (as measured using the Minnesota manual dexterity test) as the covariates. Movement time (MT) and the kinematic measures (i.e., peak velocity (PV), time to peak velocity (TPV), proportion of distance traveled at peak velocity (PROPDPV), peak acceleration (PA), time to peak acceleration (TPA), and time from peak velocity until the end of movement (TPVEND)) were the dependent variables. The ANCOVAs were analyzed with SAS PROC MIXED, using a first-order auto-regressive covariance structure (i.e., AR(1)).

The AR(1) model assumes observations measured repeatedly from a subject are highly correlated, and the correlation tends to be stronger particularly when the observations are closer to each other in time. On the other hand, a simple covariance structure, also known as compound symmetry, contains a matrix where all variances and covariances are equal (Milliken & Johnson, 2002). As a result, AR(1) is usually preferred over the compound symmetry covariance structure in repeated measures analysis.

In order to probe for the practical importance of various effects, selected effect size was computed. According to Cohen (1988), an effect size of 1% is considered a small effect, 6% a medium effect, and 14% indicative of a large effect. An effect found to be statistically significant is of little practical value if the corresponding effect size is negligible (Olejnik & Algina, 2000). Thus, effect size offers a way for determining the practical impact of an effect on the dependent variable. In this study, effect size was calculated as the proportion of the variance associated with that effect divided by the total variance of all the pertinent effects in the model, $\hat{\eta}^2 = SS_{effect} / SS_{total}$ (Olejnik & Algina, 2000). Effect size was computed for effects significant at $\alpha = .05$.

Recall that the impact of low vision on the process of pointing movement was of interest in this study; therefore, the analysis was focused on the main effect VISION. As indicated in Table 21, the main effect VISION was significant in regard to movement time (MT), time to peak acceleration (TPA), and time from peak velocity until the end of movement (TPVEND). On the other hand, vision was not significant in regard to peak velocity (PV), time to peak velocity (TPV), and proportion of distance traveled at peak velocity (PROPDPV). Compared to the normal vision group, the low vision group took longer to complete the Fitts' task. Subsequent investigation of movement kinematics revealed the main effect VISION was significant in regard to TPA and TPVEND; a longer TPA and TPVEND was also observed in the low vision group. However, no group differences were detected in regard to other kinematic measures.

The main effect DIST (i.e., distance amplitude) was significant in regard to several measures, including MT, PV, PA, and TPVEND (see Table 21). The significant DIST effect detected in MT was in accordance with Fitts' law, which states that MT has a direct relationship with DIST. In regard to PV and PA, the observed distance effect revealed an increase in both measures as DIST increased. The difference in TPVEND due to distance follows with the previous correlation analysis (see Chapter 4) which showed a large portion of the variability of MT was contributed by TPVEND. Finally, the remaining main effects (i.e., ANGLE and REPEAT), as well as the relevant interaction effects, were not significant.

Subsequent to the omnibus analysis, post-hoc multiple comparisons were conducted as necessary (i.e., when the interaction effect VISION × DIST was significant). To control for Type I error per comparison, a Bonferroni adjustment, $\alpha' = .01$ was used. In regard to MT, the significance in both the main effect VISION and the interaction effect VISION × DIST indicated that the low vision group produced higher MT compared with the normal vision group, and that the difference became more profound for the larger target distances (i.e., D400 and D650; see Figure 16).

Table 21. Summary of ANCOVAs.

Dependent Variable	Effect	F-ratio[a]	p-value[b]	Effect Size, $\hat{\eta}^2$
Movement time (MT)	VISION	36.57	.0009*	.102
	DIST	23.56	<.0001*	.094
	VISION × DIST	3.27	.0234*	.013
Peak velocity (PV)	VISION	2.27	.1830	Not computed
	DIST	83.71	<.0001*	.358
	VISION × DIST	6.32	.0007*	.028
Time to PV (TPV)	VISION	5.18	.0632	Not computed
	DIST	.61	.6600	Not computed
	VISION × DIST	.94	.4527	Not computed
Proportion of distance traveled at peak velocity (PROPDPV)	VISION	.19	.6790	Not computed
	DIST	2.20	.0911	Not computed
	VISION × DIST	2.71	.0473*	.012
Peak acceleration (PA)	VISION	5.08	.0652	Not computed
	DIST	43.80	<.0001*	.161
	VISION × DIST	4.92	.0033*	.018
Time to PA (TPA)	VISION	13.68	.0101*	.053
	DIST	1.77	.1593	Not computed
	VISION × DIST	.46	.7615	Not computed
Time from PV until the end of movement (TPVEND)	VISION	40.64	.0007*	.087
	DIST	29.72	<.0001*	.108
	VISION × DIST	4.93	.0033*	.018

Note. A series of 2 × 5 × 4 × 5 ANCOVAs was performed. Only VISION, DIST, and their interaction were reported because all other effects and corresponding interactions were not significant.
[a] VISION $df_{num} = 1$, $df_{den} = 6$; DIST $df_{num} = 4$, $df_{den} = 32$; VISION × DIST $df_{num} = 4$, $df_{den} = 32$ [b] $\alpha = .05$.

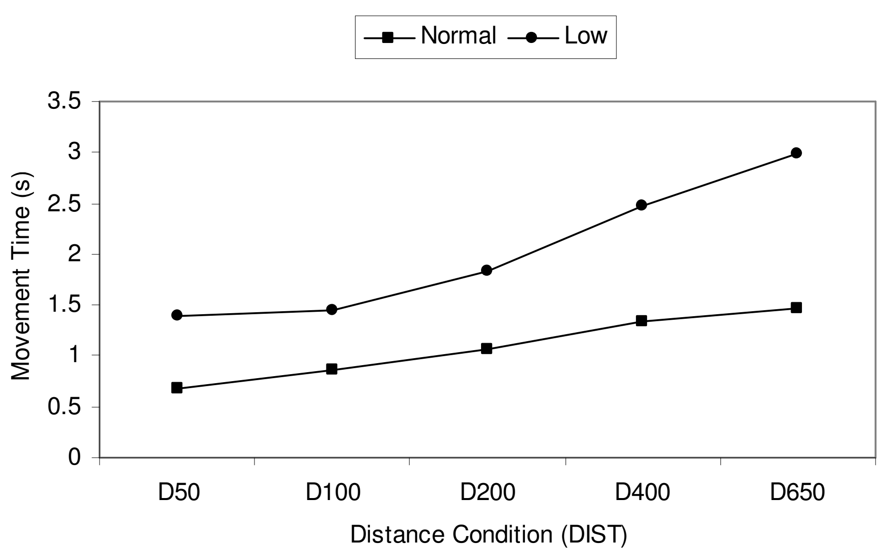

Figure 16. Plot of Unadjusted MT for VISION × DIST.

Even though the main effect VISION was not significant in regard to PV and PA, the interaction effect VISION × DIST was significant (see Table 21). Post-hoc analysis revealed the interaction effect was mainly driven by significant group difference at D650 for PV (see Figure 17), and at D400 and D650 for PA (see Figure 18). Note the main effect VISION was not significant in both cases but on the other hand the DIST effect was significant. Thus the data suggested that both PV and PA were more profoundly influenced by movement amplitude, rather than visual condition. Although significant VISION × DIST was detected on PROPDPV, no group differences were detected at any movement amplitudes.

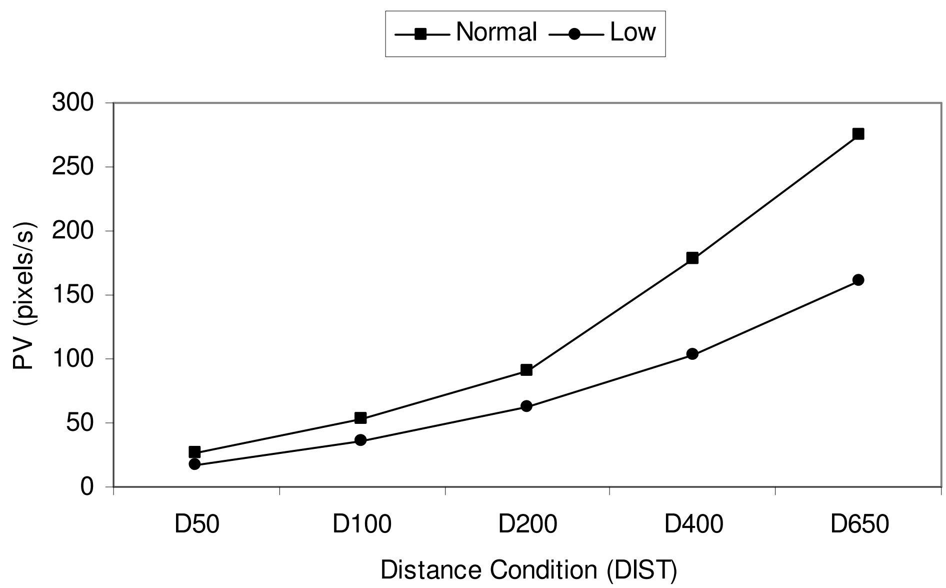

Figure 17. Plot of Unadjusted PV for VISION × DIST.

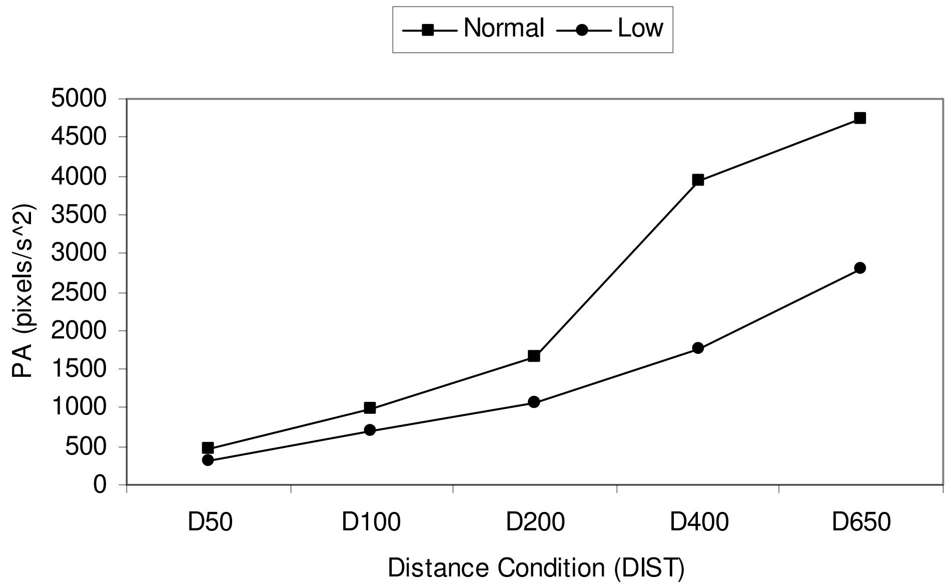

Figure 18. Plot of Unadjusted PA for VISION × DIST.

Post-hoc analysis also revealed that group difference in regard to TPVEND was more profound at large movement amplitudes (i.e., D400 and D650). Note that both main effects VISION and DIST were significant. When coupled with the significant interaction VISION × DIST, the data suggested while both visual condition and movement amplitude affected time spent homing in on the target, the difference between the two visual groups was more profound when the targets were further apart (see Figure 19). In other words, the low vision group spent longer time during the homing phase than the normal vision group, particularly when the participants had to move a longer distance.

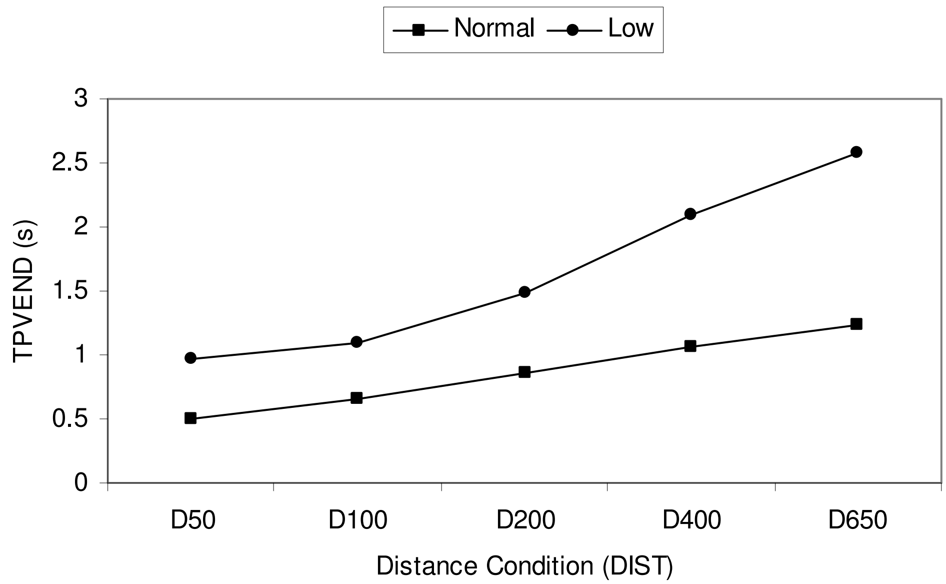

Figure 19. Plot of Unadjusted TPVEND for VISION × DIST.

In summary, the results indicated group differences in movement performance and the kinematics were more profound for larger movement amplitudes. Longer temporal measures (i.e., MT and TPVEND) were observed in the low vision group compared to the normal vision group. These same measures were differentially affected by the combination of visual condition (i.e., VISION) and movement amplitude (i.e., DIST). The differences were generally more subtle from D50 through D200, and they became more profound starting from D400. Although no vision group differences on spatial kinematics were detected (i.e., PV, PA, and PROPDPV), some differences were detected along the DIST effect, particularly at larger movement amplitudes (e.g., D400 and D650).

6.8. Discussion

Jacko and colleagues (e.g., Jacko, et al., 1999; Jacko et al., 2003; Jacko, Barreto, et al., 2000; and Jacko, Rosa, et al., 2000) reported a series of investigation on the effects of low vision on mouse-based interaction with graphical user interface. In the studies, low vision was characterized using various visual function dimensions (e.g., visual acuity and visual field). As expected, the results indicated participants with low vision performed less optimally compared to those with normal vision. However, like many performance-based studies, only endpoint measures (i.e., movement time and error rate), were analyzed. Unfortunately, endpoint measures are limited in providing intermediary information on the movement itself. In order to gain additional insight about the process of the movement, this study employed a multidirectional Fitts' paradigm, during which movement kinematics were captured. It was hoped that the effects of low vision on the process of mouse use could be better understood by investigating the differences in movement kinematics.

Some vision group differences in movement kinematics were detected. In general, findings from this study were in line with the characterization of goal-directed pointing movements using a two-component stochastic optimized submovement (SOS) model (see Meyer et al., 1988; and Meyer et al., 1990). While it was not surprising that the low vision group needed more time to complete the pointing task, the fact that the homing phase (as measured using time from peak velocity until the end of movement) was slower in the low vision group was an interesting finding. Homing time has been identified (see Chapter 4) as a major contributor to overall movement time, thus affecting performance. Such a notion is further verified in the current study because the results indicated that the low vision group spent more time during the homing phase. Because the analyses accounted for psychomotor ability, it seems likely that the additional time spent during this phase can be attributed to inadequate visual feedback for an efficient homing phase.

The results revealed a lack of vision group difference in regard to peak velocity (PV), time to peak velocity (TPV), proportion of distance at PV (PROPDPV), and peak acceleration (PA). Following the SOS model, these measures would be representative of the initial primary submovement, characterized by its ballistic nature and requiring minimal or no visual feedback (Chua & Elliot, 1993). Both vision groups appeared to achieve peak velocity at the same time (i.e., as indicated by the insignificant difference in TPV). Reduced visual function did not deter participants from completing the primary submovement in similar time as the normal vision group. Similar arguments seem to be applicable to findings for PROPDPV. Recall that PROPDPV is indicative of the distance traveled at the end of the primary submovement. Since minimal visual feedback is needed during this phase, differences in visual conditions should not result in significant differences on distance; this was confirmed by the current study.

Although debatable, TPA is sometimes used by researchers as an alternative way to indicate time spent in the primary submovement. Therefore, the vision group difference in TPA challenges the proposition that the primary submovement is not dependant upon visual ability. It was not known whether TPA was in fact a valid indicator of the primary submovement. Without further investigation, it was difficult to explain why differences were detected in TPA.

Despite differences in movement time, neither the low vision group nor the normal vision group differed in terms of PV and PA. The dissociation with movement performance was not surprising because neither of the kinematic measures were correlated with movement time as reported in Chapter 4. The lack of correlation was partly attributed to the fact that MT is a temporal measure, whereas PV and PA are both spatial measures. In a subsequent study (see Chapter 5), both measures were found to be highly influenced by psychomotor ability, by which lower PV and PA were observed among participants with reduced psychomotor ability. Recall in the current study psychomotor ability was a covariate, and thus its effect was controlled for during the analysis. The fact that no vision group differences were detected in the current study suggests that both measures were related only to psychomotor ability and not influenced by visual condition.

The results also indicated movement time and kinematics were influenced by visual condition and movement amplitude (i.e., distance between targets), with profound differences detected in larger movement amplitudes. Low vision had a stronger impact when a larger distance had to be traversed. This was observed not only in the overall movement (as seen from MT), a similar impact of visual condition and movement amplitude was also seen in the secondary submovement (as seen from TPVEND). However, the same was not true for the primary submovement because the corresponding kinematics (i.e., TPV) appeared to be the same regardless of visual condition and movement amplitude. Perhaps the impact in the secondary submovement was due to the low vision group's limited visual feedback, particularly when they had to traverse over a long distance. The effect was likely compounded by having to hone in on the intended target. It is speculated that the additional time observed during the homing phase was due to the need to refocus visual attention from the initial point to the intended target. Since the low vision group was less effective in that regard, they needed more time to visually locate the intended target. Even though a significant interaction of vision and distance was also detected along PV and PA, post-hoc analysis showed both measures were chiefly influenced by movement amplitude only.

When the results are taken together, the following speculation is offered. When presented with a target, the participant first obtains a rough visual identification of the target location. The low vision group retains some residual vision, which was enough to allow for the initial target identification. This may explain why no significant difference was detected in the primary submovement time (i.e., TPV). At the same time, the knowledge of the general target location would also allow the participant to exert the initial jerk that was deemed necessary to arrive at the target. Note that the psychomotor ability in both groups was essentially the same, thus the related kinematics (i.e., PV and PA) were not different. On the contrary, visual feedback is an important feedback mechanism during the secondary submovement. Hence, the low vision group performed less effectively during this stage compared to the normal vision group, as demonstrated by the difference detected in TPVEND.

An obvious limitation of the current study is that various low vision conditions were treated as one group. There is no doubt that the limitations associated with different low vision conditions differ from each other. Following the framework of the International Classification of Impairments, Disabilities and Handicaps (ICIDH), the implications are multi-faceted, including the anatomical, functional, skills and abilities, and socio-economical (Colenbrander, 2000). Quantification of low vision along dimensions of functional vision such as visual acuity, visual field, contrast sensitivity, and color sensitivity has been successfully employed by Jacko and colleagues (e.g., Jacko, et al., 1999; Jacko et al., 2003; Jacko, Barreto, et al., 2000; and Jacko, Rosa, et al., 2000) in distinguishing performance differences in mouse use. Low vision is also distinguishable along the quality of the "picture" as seen from the eyes. For instance, a person with macular degeneration may have more trouble with his central vision compared to a person with retinitis pigmentosa whereby the peripheral vision is reduced. Therefore, it is expected that differences in movement kinematics can exist even within the low vision group. Due to the limited number of low vision participants in the current study, it was not feasible to further subdivide the group. Despite a diverse low vision group was tested, it is worth noting that in general the results conformed to the propositions brought forward by the SOS model. For future research, perhaps only a homogeneous low vision group that sees the same "picture" from the eyes, thus allowing further understanding of how specific low vision condition can affect aiming movement.

CHAPTER 7

GENERAL DISCUSSION

Mouse use is one of the most studied topics in ergonomics research of computer systems. Perhaps the mouse has been the subject of such extensive research because of its endemic use. The direct manipulation paradigm of the mouse is so robust that even the relatively new touchpad had to be redesigned to match that of a mouse (MacKenzie, 2003). Efficient mouse use requires high-level interaction between motor control (output) and visual function (input). In other words, the cursor on the screen provides visual feedback to the user who subsequently controls the mouse to produce desired results. Many studies have examined the effects of aging, psychomotor ability, and visual ability on mouse use. Movement time and error rates are often analyzed in similar studies. However, these measures only provide information about the outcomes of the movements; they are unable to reveal details of what happens "during" the movement. This dissertation research fills the gap by investigating the effects of various functional abilities (i.e., psychomotor and visual) on the process of mouse use, via its movement kinematics.

Based on the kinematic profiles (i.e., the velocity and the acceleration profiles), movement kinematics can be characterized using various measures. The kinematic measures broadly exist in two forms: spatial and temporal. Spatial kinematic measures are usually presented in distance units such as distance and amplitude, whereas temporal measures are strictly time-based (see Section 4.2). Since kinematic measures are captured from the process of the movement, it might be expected that they would correlate with movement performance (i.e., movement time). However, an omnibus correlation analysis confirmed that was not the case. The results indicated only temporal kinematics (i.e., time to peak velocity, time to peak acceleration, and time from peak velocity until the end of movement) correlated with movement performance (i.e., movement time); none of the spatial kinematics showed strong correlation with performance (see Section 4.5.1).

It was also of interest to determine whether the kinematics-performance correlation magnitudes differed from one age group to another. Selected kinematics-performance correlations (those with strong overall correlation) were examined by age group (i.e., younger, middle-aged, and older). Some of these correlations (i.e., time to peak velocity-movement time and time to peak acceleration-movement time) became inconsequential, suggesting that the age effect was a driving factor, rather than the inherent relationship between the kinematics and performance. The only exception was the correlation between the homing time (i.e., time from peak velocity until the end of movement) and performance (i.e., movement time), in which strong correlations were observed when separated by age.

A second study was performed to investigate the effects of age and psychomotor ability on movement kinematics. ANOVAs revealed age differences across different kinematic measures. Overall, kinematics in the older group were significantly different from the younger and the middle-aged groups; there were no differences between the younger and the middle-aged groups. Age differences were detected in regard to peak velocity, peak acceleration, and proportion of distance traveled at peak velocity. The older group demonstrated lower peak velocity and peak acceleration but a larger proportion of distance traveled at peak velocity compared to the younger and the middle-aged groups. Since it is commonly known that movement time is also influenced by age, one maybe tempted to draw a linkage between movement time and peak velocity, peak acceleration, and proportion of distance traveled at peak velocity, however, none of the three kinematic measures correlated with movement time (see Section 4.5.1). Note the SOS model states that the primary submovement is usually ballistic in nature. Also note that the older group demonstrated lower psychomotor ability compared to the younger and the middle-aged groups. Hence, the age differences in kinematics related to the primary submovement (i.e., peak velocity, peak acceleration, and the proportion of distance traveled at peak velocity) can be attributed to the older group's execution of the initial movement, which is less ballistic and explosive compared to the younger participants. This proposition is further supported by the significant age effect on temporal measures that are pertinent to the primary submovement. Specifically, time to peak velocity was found to increase with age (see Section 5.7.2.2).

Typical movement velocity and acceleration profiles for the three age groups are shown in Figures 20 and 21. Even though all three groups exhibited stereotypical profiles for the primary submovement, the peak velocity (i.e., indicator for the ballistic motion) is lower in the older group. The longer time spent and the larger distance covered during the initial submovement (see Section 5.7.2.4) indicates the older group might be using a compensation strategy by traversing a larger distance before homing in on the target. Another possibility is that the older group simply lacks the ability to move the cursor effectively towards the target; this can be attributed to reduced psychomotor ability in the older group. In regard to the deceleration phase, all groups spent a considerable amount of time homing in on the target. Similar to the ballistic phase, the age difference in the secondary submovement was attributed to the longer time in the older group. The longer time associated with the older group may be indicative of the reduced ability to coordinate visual feedback with the subsequent motor output (i.e., executive control). However, without the pertinent data, this suggestion remains speculative.

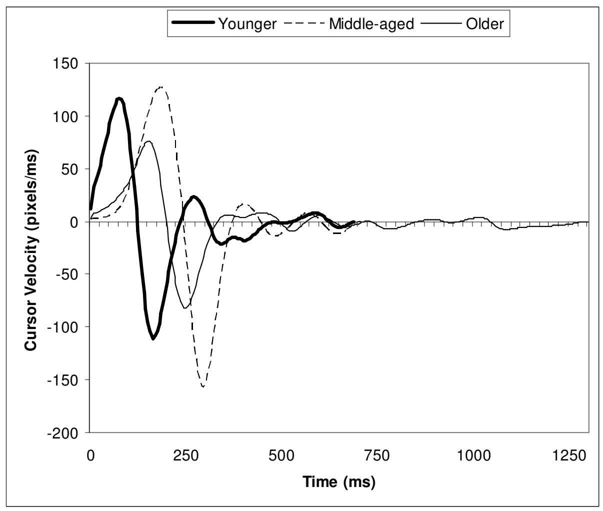

Figure 20. Selected Individual Velocity Profiles.

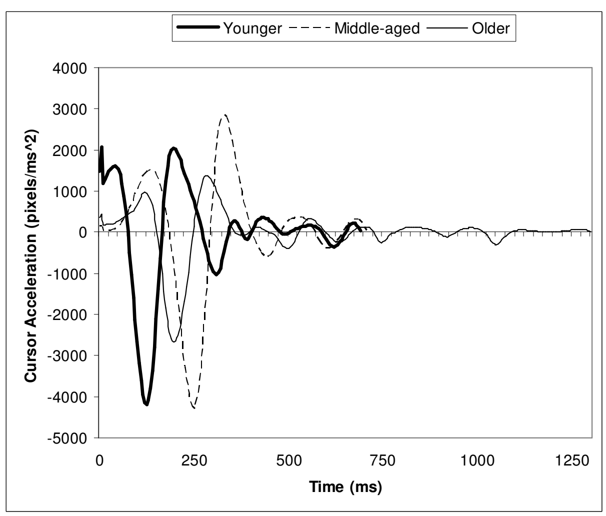

Figure 21. Selected Individual Acceleration Profiles.

It was also of interest to determine whether age was in fact a surrogate variable to the kinematic differences. In other words, the question was whether age was still a significant contributor to differences in movement kinematics after psychomotor ability was taken into account. Since reduced psychomotor ability has been associated with aging, the question arose as to whether changes in movement performance and kinematics were directly caused by changes in functional ability rather than changes in age. Subsequent analyses showed age was not a major contributor to differences in movement kinematics, and indeed the differences (except for proportion of distance traveled at peak velocity and time from peak velocity until the end of movement time) were attributed to the effects of psychomotor ability. Further investigation indicated there were other factors in addition to the age and psychomotor ability that influenced both kinematic measures. Other possible contributing factors may include target parameters such as target size and distance amplitude; however, without further analysis it remains speculation.

A subsequent study was performed to investigate the effects of visual ability on movement kinematics. The results indicated that visual ability did not affect the primary submovement, as indicated by the minimal changes to pertinent kinematic measures (i.e., peak velocity, proportion of distance traveled at peak velocity, peak acceleration, and time to peak velocity). Even though the low vision group was clearly disadvantaged in terms of visual function, their primary submovement was similar to that of the normal vision group. This finding was consistent with the proposition of the SOS model that visual feedback plays a minimal role during the ballistic phase of movement. On the other hand, significant differences were detected in the homing phase, for which the low vision group was observed to spend significantly more time in this secondary submovement. Again, the findings are supported by the SOS model because the model assumes the homing phase is profoundly characterized by the feedback-control mechanism, which requires a high degree of visual feedback.

Based on the findings gathered thus far, an overall picture of mouse-mediated aiming movements can be drawn around the SOS model. Before starting with the aiming movement, the participant takes a quick glance at the location of the intended target; a similar eye-lead-hand proposition was also suggested by other researchers (e.g., Abrams, 1992; Abrams, Meyer, & Kornblum, 1990; and Eliott et al., 2001). Then, based on the initial visual estimation, the participant propels the mouse (i.e., cursor) towards the target. The preprogrammed motor movement is highly influenced by the psychomotor ability of the participant, which is subject to various factors including the age effect. Since the initial ballistic phase does not require visual feedback, the kinematics remains similar even if the participant has reduced visual functions. Due to neuromotor noise, the preprogrammed movement is likely to either overshoot or undershoot. In either case, the feedback-control mechanism begins to operate in the deceleration phase. The deceleration phase is characterized by corrective submovements for error adjustment. These submovements are often aided by visual feedback, and kinethestic feedback to a lesser extent (Keele & Posner, 1968). And as suggested, results from this research indicated that visual ability was vital for efficient target homing.

Note that only two of many mouse task primitives were investigated in the current research. In addition to pointing and selecting, there exist other task primitives for mouse-based computer tasks, including dragging, drawing or tracing, and free-hand input. Future kinematic analyses of mouse use should of necessity include a wider variety of mouse task primitives.

Certain characteristics of pointing devices are believed to have influence over mouse use. In particular, gain setting (or control-display ratio) is an influential factor in mouse use. Gain refers to the amount of control movement needed to produce the desired output movement (Kantowitz & Sorkin, 1983). It has been long established that gain setting is not an important factor for influencing mouse performance (see Jellinek & Card, 1990; Kantowitz & Elvers, 1988; and Lin, Radwin, & Vanderheiden, 1992). However, recent studies (Thompson, McConnell, Slocum, & Bohan, 2007) report the effects of gain setting on certain movement kinematics. Gain setting was not considered in this research because the mouse was operating in the Windows environment which effectively made it a rate-control mouse. As a result, gain setting was irrelevant. Because most mice are rate-control devices, it is believed that findings from this research have a greater external validity compared to those obtained from a more controlled environment.

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APPENDIX A

SCREENING QUESTIONNAIRE

This questionnaire is part of the screening process designed to recruit participants from the desired population. Please answer all questions to the best of your ability. Information obtained from this questionnaire will be maintained confidential and will be used only to determine your eligibility to participate in this study. Feel free to ask the administrator if you have any questions.

1. Gender:
   - ☐ Male
   - ☐ Female

2. Which of the following age groups you belong to?
   - ☐ 18-29
   - ☐ 40-59
   - ☐ 65-80
   - ☐ None of the above

   If so, what is your age? ___ years ___ months

3. What is your highest educational level?
   - ☐ Some high school
   - ☐ High school graduate
   - ☐ Some college
   - ☐ College graduate (i.e., Associate's or Bachelor's)
   - ☐ Some graduate school
   - ☐ Post-baccalaureate (i.e., Master's or Doctoral)

4. Do you use a computer?
   - ☐ Yes
   - ☐ No

   If YES, how many hours in a week do you typically use a computer?
   - ☐ 0 – 2 hours
   - ☐ 3 – 5 hours
   - ☐ 6 – 10 hours
   - ☐ over 10 hours

   If YES, which of the following tasks you do with a computer? Select all that apply.
   - ☐ Internet (e.g., e-mail, web browsing)
   - ☐ Using spreadsheet (e.g., financial planning, inventory control)
   - ☐ Word processing (e.g., writing letter, creating posters and flyers)
   - ☐ Other, please specify: ______________________________

5. Have you had injury in these? Select all that apply.
   - ☐ Neck
   - ☐ Shoulder
     Which side? ☐ Left ☐ Right
   - ☐ Arm
     Which side? ☐ Left ☐ Right
   - ☐ Hand
     Which side? ☐ Left ☐ Right
   - ☐ Wrist
     Which side? ☐ Left ☐ Right

   If so, when did that injury occur? ___ years ___ months ago.

   If so, please describe the nature of the injury.

   ____

   Are you still experiencing the symptoms?
   - ☐ Yes
   - ☐ No

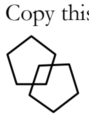
6. Do you have any limitations due to:
   - ☐ Celebral palsy
   - ☐ Cumulative trauma disorder (CTD)
   - ☐ Parkinson's disease

-- END --

APPENDIX B

MINI-MENTAL STATE EXAM

(ADAPTED FROM FOLSTEIN, FOLSTEIN, AND MCHUGH, 1975)

Orientation	**Max. Score**	**Score**	**Instructions**
What is the (year) (season) (date) (day) (month)?	5		As for the date. Then proceed to ask other parts of the question. One point for each correct segment of the question.
Where are we: (state) (county) (town) (hospital) (floor)?	5		As for the facility then proceed to parts of the question. One point for each correct segment of the question.
Registration			
Name three objects (bed, apple, shoe). Ask the patient to repeat them.	3		Name the objects slowly, one second for each. Ask him to repeat. Score by the number he is able to recall. Take time here for him to learn the series of objects, up to 6 trials, to use later for the memory test.
Attention and Calculation			
Count backwards by 7s. Start with 100. Stop after 5.	5		Score the total number correct. (93, 86, 70, 72, 65)
Alternate question. Use if subject refuses or is unable to count backward by 7s.			
Spell the word "world" backwards.	5		Score the number of letters in correct order. (dlrow = 5, dlorw = 3)
Recall			
Ask for the objects used in question 2 to be repeated.	3		Score one point for each correct answer. (Bed, apple, shoe)
Language			
1. Naming: Name this object: Watch, pencil.	2		Hold the object. Ask patient to name it.
2. Repetition: Repeat the following – "No ifs, ands, or buts."	1		Allow one trial only. Score one point for correct answer.
3. Follow a 3-state command: "Take the paper in your right hand, fold it in half, and put it on the floor."	3		Use a blank sheet of paper. Score one point for each part correctly executed.
4. Reading: Read and obey the following: Close your eyes.	1		Instruction should be printed on a page. Allow patient to read it. Score by a correct response.
5. Writing: Write a sentence.	1		Allow patient to write any sentence. It must contain a noun, verb, and be sensible.
6. Copying: Copy this design. 	1		All 10 angles must be present. Figures must intersect. Tremor and rotation are ignore.
	Total Score		Maximum 30. Test is not timed. Scores below 20 indicate probable dementia.