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METHODOLOGY FOR THE SELECTION AND EVALUATION OF COMPUTER INPUT DEVICES FOR PEOPLE WITH FUNCTIONAL LIMITATIONS

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METHODOLOGY FOR THE SELECTION AND EVALUATION OF COMPUTER INPUT DEVICES FOR PEOPLE WITH FUNCTIONAL LIMITATIONS

A DISSERTATION APPROVED FOR THE

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ABSTRACT

Many computer users with motor impairments frequently use standard input devices even though these devices are not best suited for them. A methodology for specifying alternative assistive input devices as a function of type and degree of functional limitation is important for improving access to computer technology. The current research developed a matrix for matching assistive technology input devices to the assessed level of functional limitation. Since there are few reliable input device assessment instruments for people with impairments, this research also developed and validated a methodology for assessing the level of impairment for people with upper-limb motor impairments.

Computer pointing task performance for 23 unimpaired participants (mean = 28.2 years, SD = 5.7 years) and 11 participants with upper extremity impairments (mean = 25.8 years, SD = 10.0 years) was evaluated using three input devices (joystick, trackball, and mouse) and a Fitts' Law test. Impairments represented in this study included cerebral palsy, spina bifida, head injury, muscular dystrophy, spinal cord injuries, and multiple disabilities. The Minnesota Manual Dexterity Test (MMDT) was used to assess manual dexterity. Each Fitts' Law target was square in shape with a width of 5, 15, or 25 mm. Movement amplitude from the start point to the center of the target was 40, 80, or 160 mm. Movement directions for the unimpaired group were 0 (East), 90 (North), and 225 (Southwest) degrees, but were limited to 0 and 90 degrees for participants with impairments. The control-display (CD) gains used in this study were 0.5 and 1.0. There was one practice session and two main sessions. In each run, each combination of target size, movement amplitude and movement direction appeared four times in random order. A separate run was conducted for each device and CD gain combination. Each unimpaired participant pointed to 108 targets per run and participants with impairments pointed to 72 targets per run.

Fitts' Law was a valid model of performance for assessing the levels of impairment for both groups. Movement time (MT) and Fitts' Law index of performance (IP) correlated strongly with the MMDT scores and served as valid metrics for assessing the use of computer input devices by people with upper-limb motor impairments. This research developed and validated a sound approach to input device selection and functional limitation assessment to improve the match between computer pointing task requirements and the capabilities of challenged users.

METHODOLOGY FOR THE SELECTION AND EVALUATION OF COMPUTER INPUT DEVICES FOR PEOPLE WITH FUNCTIONAL LIMITATIONS

CHAPTER 1

INTRODUCTION

At the beginning of the 21st century, people are already experiencing the fast-moving world of high technology in their workplace, on the road, and at home. High technology is particularly evident in the development and use of computer systems. According to the United States Census Bureau in 1997, almost three quarters (74.4%) of U.S. children (ages 3 to 17 years) used a computer at home or at school. Nearly half of all American adults (47.1%) used a computer at home, work, or school; compared to 1984 statistics, the rate of computer use has tripled (Newburger, 1999).

Since human beings rely more and more on the applications of computers, such as email, the World Wide Web, and information processing, it is becoming increasingly important that computer access be universal. This is especially true for people who are unable to fully use their hands and/or arms due to some level of motor impairment. In recent years, new laws have created additional motivation for the investment of resources in the development and testing of advanced assistive technologies allowing access to computer technology by people with disabilities. The most pertinent laws are Section 508 of the 1986 Federal Rehabilitation Act (FRA) and the 1992 Americans with Disabilities Act (ADA). The ADA extends responsibility for providing accessible work places and equipment to the job environment, including private and government sectors (Albrecht, 1992; Allen, 1998; DeJong & Brannont, 1998; Elkind, 1990; Lazzaro, 1996; Orlin, 1995; Vanderheiden, 1990; Williges & Williges, 1995). The most recent legislation for electronic product design is the Telecommunications Act, signed by the President in February 1996. The goal of the Telecommunications Act is to improve the accessibility of consumer products to more users with disabilities without reducing the usability or attractiveness for the mass or core of consumers of the products without impairments (TAAC, 1997).

Additionally, the number of older people in the population is dramatically increasing in the United States. According to Howell (1997), the percentage of older adults in the population will grow from nearly 13% in 1990 to 22% by the year 2030. The population projection for people who are elderly shows a similar pattern in the European Community. Howey (1995) estimated that the percentage of elderly people in Europe will grow from 14% to 22% by the year 2040. The main reason for this growth is the aging of the baby boom generation (Vanderheiden, 1990). Since most people who are elderly (86% of American people over age 65) are likely to have one or more mobility impairments (Vercruyssen, 1997), more careful attention must be focused on the mobility impairment issues of the elderly.

Bergman and Johnson (1995, p. 11) defined the term *physical disability* as "disabilities that affect the ability to move, manipulate objects, and interact with the physical world." Hindrances to the use of current computers by people with motor impairments should be minimized in a way that promotes accessibility regardless of the user's age, computer knowledge, strength, agility and degree of impairment. Until the mid-1990s, "design for disability" was not a main concern in computer development due to a lack of interest by most researchers (Glinert & York, 1992; Newell, 1995). According to Newell (1995), the major reason for this lack of interest was insufficient understanding and a lack of information regarding the special needs of people with functional limitations. Another reason may be that it is economically infeasible for the manufacturers of assistive computer input devices to fully research and design devices for special populations. If the causes of this lack of interest can be addressed, researchers can make considerable strides towards embracing consumer populations with disabilities into the highly beneficial computer technology society.

According to Trewin and Pain (1999), many computer users with impairments frequently use traditional computer input devices, even though these devices are not ideal for them. Identification of alternative assistive technologies for different types of impairments is important to guide the development of more accessible hardware and software. Recently, a series of research efforts to improve computer access for people with disabilities was conducted by IBM researchers incorporating new technologies such as personal computer (PC) oriented cameras and speech recognition software (Costlow, 2000). According to Costlow (2000), IBM researchers found that their efforts toward improving accessibility benefit everyone, not just people with impairments.

People with motor impairments have widely ranging abilities. People who have complete paralysis below the waist may not have any problem using computers because their upper body is unimpaired. Some people may have limited range of motion, and still possess fine motor control within the limited range. Others may not be capable of keyboard input due to the total loss of use of their arms. Some people with arthritis or rheumatoid arthritis may have joint movement limitation or may be limited by pain.

Human-computer interaction (HCI) is a currently thriving area in computer graphics, human factors, cognitive psychology, and artificial intelligence. Until recently, however, sufficient effort did not exist to improve accessibility to assistive hardware and software for people with disabilities (Shaw, Loomis, & Crisman, 1995). In many cases, users with disabilities were overlooked during the HCI design process due to a lack of awareness, increased production cost, or inadequate market volumes from consumers with impairments (Bergman & Johnson, 1995). To enhance accessibility, HCI designers must consider the needs of people with disabilities throughout all design stages. Additionally, better information interchange must occur between HCI organizations and consumers with disabilities (Bergman & Johnson, 1995).

The primary goal of this dissertation was to develop a matrix for recommending solutions which match the assistive technology input devices to the assessed level of functional limitations. To date, few assessment instruments designed for people with impairments or the elderly demonstrate reliability and validity. Therefore, there existed a need to develop an assessment tool for predicting functional performance in computer input tasks. A secondary goal of this study was to develop and validate a methodology for assessing the level of impairment for people with upper-limb motor impairments.

The following chapter reviews the literature related to the general issues of people with disabilities, including causes and a taxonomy of motor impairments, various computer assistive technologies, and computer task requirements using input devices. Chapter 3 presents the issues that were the focus of this dissertation. Chapter 4 describes the development of a model framework that can quantify the difficulties encountered by people with functional limitations and provide solutions that allow them to effectively use computer technology. Chapter 5 presents a validation methodology for evaluating a selection matrix for people with motor impairments using a manual dexterity task to assess the level of impairment and a computer-based cursor movement task based on Fitts' Law. Chapter 6 presents the analysis procedures that were conducted in this dissertation and discusses the results of the experiment. Finally, Chapter 7 concludes with several proposed implications and recommendations for future research.

CHAPTER 2

LITERATURE REVIEW

This chapter reviews the literature defining the various issues of people with disabilities using computer assistive technology. Among the various types of disabilities, motor impairment is the primary focus of this dissertation. Various diseases and causes of mobility impairments along with specific definitions are, therefore, the focus of this review. The first section presents a review of general definitions of disabilities and demographics. Legal requirements addressing access by people with disabilities are also presented. The next section presents a taxonomy of functional limitations that are usually classified as severe or moderate. Currently available computer assistive technologies are carefully reviewed to provide information that will allow the matching of specific technologies to the impairment categories. To conclude the literature review, computer task elements and requirements are summarized.

2.1 People with Disabilities

The number of people with disabilities is steadily increasing because of advanced modern medical technology that can save more people who might die without modern medical treatment. Many of those who survive, however, have disabilities and become regarded as a minority group in their communities (Albrecht, 1992). Allen (1998) reported that since more than 80% of people with disabilities live in the community (not in an institution), the development of optimal support tools is critical for people with disabilities to enjoy a normal social life.

In this section, general issues and population demographics for people with disabilities are reviewed. Government efforts, that is, legal requirements, to maximize access to computer technology by people with disabilities are also reviewed.

2.1.1 Impairment and Disability

Definitions of disability have been ambiguous because various fields provide operational definitions within each background and discipline, often with a different intended use (Albrecht, 1992; Bouisset & Rossi, 1991). In the 1980s and early 1990s, the World Health Organization (WHO), the American Medical Association (AMA) and the Institute of Medicine (IOM) independently worked to formulate consistent definitions addressing the conceptualization and measurement of disability (Albrecht, 1992; Edwards, 1995; Kane & Boult, 1998; Mor, 1998).

According to the classification scheme developed by the WHO in 1980, *impairment* is defined by physiological causes, while *disability* reflects the functional consequences of impairment. On the other hand, *handicap* is defined with reference to a specific situation (Bouisset & Rossi, 1991). Therefore, a person with a disability may be regarded as either handicapped or not handicapped depending on the situation.

Gardner-Bonneau (1990, p. 379) clarified the distinction between *functional impairment* and *disability*. A functional impairment is "a disability only when it prevents an individual from carrying out activities he or she could otherwise do." A person who is paralyzed in both arms may have a mobility impairment with respect to using computer input devices, but this impairment is not disabling when he/she can use alternative input devices such as speech input, sip-and-puff, or eyegaze. Therefore, issues of precisely matching assistive technology tools to people with motor impairments are critical in order to minimize the number of people with disabilities.

According to Albrecht (1992) and Vercruyssen (1997), *functional limitations* are operationally defined most frequently in terms of the difficulties in performing activities of daily living (ADL) and less often in terms of instrumental activities of daily living (IADL). The ADLs are considered essential for everyday functioning: bathing, dressing, eating, using the toilet, walking/mobility and transferring between positions (Albrecht, 1992; Kennedy, LaPlante, & Kaye, 1997). The IADLs represent more complex tasks and include handling personal finances, preparing meals, shopping, doing light housework, using the telephone, and taking medications (Albrecht, 1992; Vercruyssen, 1997).

The number of people who experience activity limitations in daily living is steadily increasing due to: (1) advanced modern medical technology and practices that save more lives, but leave survivors with various limitations, and (2) extended life expectancy resulting in an increasing population of people who are elderly and more prone to experiencing diseases and disabling consequences (Albrecht, 1992).

Since the same disease can cause different types of disability, large barriers exist in disability research. Moreover, the functional limitations associated with a disability can be removed in various ways depending on the type of assistive tools used. Stolov (1981) addressed three characteristics of disability:

(1) there is no direct correlation between a disease and the spectrum of associated disability problems,
(2) there is no direct relationship between a disease and the amount of residual disability, and
(3) the patient's residual capacity for physiological and psychological adaptation determines the ability to overcome the disability.

The critical distinction between impairment and disability is that "impairment refers to an organically based disturbance in the person's bodily structure or processes, while disability is grounded in the individual's inability to perform major activities" (Albrecht, 1992, p. 20). Figure 1 shows the relationships between the concepts of pathological lesion, impairment, functional limitation, and disability (integrated from the concepts of Albrecht, 1992; Institute of Medicine, 1991, 1997; Kane & Boult, 1998; Mor, 1998). From the conceptual model in Figure 1, a pathological lesion impairs the normal operation of a bodily system (impairment), which in turn causes difficulty in performing tasks (functional limitation), leading to a state of not being able to perform tasks in daily life (disability). Human factors professionals have a great role to play in preventing functional limitations from becoming disabilities by developing appropriate assistive tools and technologies. Kane and Boult (1998) further extended their model to include two additional concepts, the need for supportive services and the demand for services.

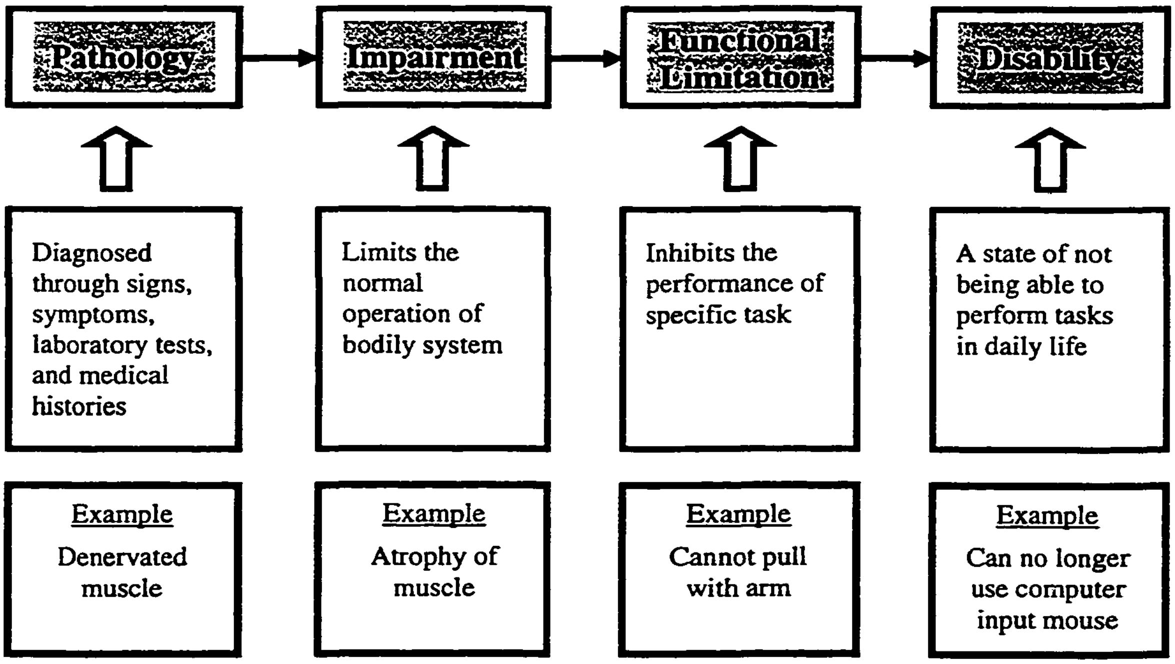


Figure 1. Conceptual Model of Disability (Integrated from Albrecht, 1992; Institute of Medicine, 1991, 1997; Kane & Boult, 1998; Mor, 1998).

Three general barriers to people who have disabilities or elderly were addressed by Bowe (1980). The first barrier is a *social barrier*, encompassing a lack of knowledge and understanding of disability and aging. The second barrier is an *architectural barrier.* The architectural barrier is a structural barrier in which the person cannot access work or home without the help of assistive tools or structural changes. The final barrier is a *communication barrier*, that is, an interaction barrier between the person and the work tools or environment.

By providing access to computer technology through assistive input devices, these three barriers can be breached. Computer software can be used to assist with everyday tasks, such as time and finance management. The Internet provides the user with access to essentially unlimited resources: entertainment, education, shopping, news and information systems, and communication through electronic mail and real-time conversations. Moreover, Roulstone (1998) suggested that new user-friendly technology will overcome technical barriers for people with disabilities.

2.1.2 Demographics

More than 70% of the 12 million working-age Americans with disabilities are unemployed (Howey, 1995; Williges & Williges, 1995). In a survey conducted by Williges and Williges (1995), most unemployed people responded that the main reason for their unemployment was their disability. If appropriate assistive tools can be provided to employees with disabilities, their productivity could be similar to that of their counterparts who are not disabled (Williges & Williges, 1995).

In many cases, disabling conditions occur in people under 35 years of age because younger people are more frequently involved in accidents than older people, and their unemployment causes critical poverty (Bowe, 1980). The onset of disability in a worker most often produces a traumatic loss in earning power. Bowe (1980) reported that only one-half of all people with disabilities and one-fourth of people with severe disabilities had any earnings. Disability problems, therefore, are closely linked with problems of poverty in many countries. In part to address this problem, the U.S. government initiated more visible legislative efforts to provide better access to computer technology for people with disabilities.

The U.S. Census Bureau estimated the total U.S. population in 1992 at 256.3 million. More than 24% (61 million) of the population had impairments or diseases that contributed to activity limitations (Institute of Medicine, 1997). According to Howey (1995), approximately 11.3% to 15.1% of the European Community had some form of disability. Table 1 summarizes the prevalence of consumer populations with impairments in the United States (Institute of Medicine, 1997) and Table 2 summarizes the populations with impairments in the European Community (Sandhu & Wood, 1990).

The number of elderly people is dramatically increasing in the United States. Howell (1997) estimates that the population of older adults will grow from nearly 13% in 1990 to 22% by the year 2030. The elderly population projection in the European Community shows a similar pattern. Howey (1995) estimates that the elderly population in the European Community will grow from 14% to 22% by the year 2040. The main reason for this growth is the aging of the baby boom generation. This group is becoming a large user of computer products (Vanderheiden, 1990). In the European Community, approximately one-third of the people with some disability are over age 60. Moreover, they may also have multiple age-related impairments, such as impaired vision, hearing, and/or motor control.

Since 86% of American people over age 65 are likely to have one or more impairment problems (Edwards, 1995; Vercruyssen, 1997), more careful attention must be focused on meeting the needs of consumers who are elderly. According to Edwards (1995), approximately 5% of people aged 30 are disabled in the United Kingdom. The proportion rises to 30% by age 60, and reaches almost 70% by age 80 and above.

Table 1. Prevalence of Impairments in the U.S. in 1992 (Institute of Medicine, 1997).

Impairment & Disease or Disorder	Number (thousands)	Percent (%)
All impairments and diseases or disorders	61,043	100.0
Impairments Total	16,327	26.7
Visual	1,294	2.1
Hearing	1,175	1.9
Speech	545	0.9
Impairment of sensation	141	0.2
Learning disability-mental retardation	1,575	2.6
Absence of body part	788	1.2
Paralysis	1,071	1.8
Deformities	900	1.5
Orthopedic impairments	8,608	14.1
Other	230	0.4
Diseases or Disorders Total	44,716	73.3
Infectious diseases or disorders	378	0.6
Neoplasms	1,628	2.7
Endocrine, nutritional, metabolic, and immunologic	3,409	5.6
Blood and blood-forming organs	217	0.4
Mental disorders	2,035	3.3
Nervous system & sensory organs	4,373	7.2
Circulatory system	10,170	16.7
Respiratory system	4,774	7.8
Digestive system	1,727	2.8
Genitourinary system	778	1.3
Skin & subcutaneous tissue	362	0.6
Musculoskeletal & connective tissue	10,530	17.2
Congenital anomalies	287	0.5
Symptoms, signs, and ill-defined conditions	2,843	4.7
Injuries & poisonings	1,205	2.0

Table 2. Prevalence of Impairments in the European Community (Sandhu & Wood, 1990).

Impairment	European Community
Impairment Total	36 - 49 million
Physical Impairment	24.8 million (50.6 - 68.9%)
Hearing	8.7 million (17.8 - 24.2%)
Vision	6.5 million (13.3 - 18.1%)
Speech	3.6 million (7.3 - 10.0%)
Cognitive	7.4 million (15.1 - 20.6%)

According to Elkind (1990), the statistics overestimate the population of consumers with disabilities by an unknown amount because they count people with multiple disabilities in multiple categories. On the other hand, Elkind (1990) also insisted that the numbers are sufficiently large to warrant careful attention to the capabilities of people with functional limitations in the design of systems to be used by all consumers.

2.1.3 Legal Requirements for Access by People with Functional Limitations

For the last two decades, new laws have created visible incentives for the development of access to computer technology by people with disabilities (Albrecht, 1992; Allen, 1998; DeJong & Brannont, 1998; TAAC, 1997; Williges & Williges, 1995). The most pertinent laws are (1) Section 508 of the 1986 Federal Rehabilitation Act (FRA) authorized from the 1973 FRA, (2) the Technology-Related Assistance for Individuals with Disabilities Act of 1988, (3) the Americans with Disabilities Act (ADA) passed in July 1990, and (4) the Telecommunications Act of 1996.

According to Williges and Williges (1995), beginning in July 1990 the Americans with Disabilities Act (ADA) required employers to make reasonable accommodations for workers with disabilities. The act covers all businesses with at least 25 employees. Complying with the federal law can be costly for some employers unless low-cost accommodations that yield productive employees are available. Specific areas of the ADA legislation include reasonable accommodation for using computer input devices.

The legal requirements have provided legislative directives to ensure that people with disabilities have *equal access* to computer technology. According to Brown (1992, p. 36), the ADA legislation particularly states that "employers will need to provide *reasonable accommodations* to people with disabilities including steps such as job restructuring and modification of equipment." According to Williges and Williges (1995), the legislation provides positive motivation for the government and the private sector to consider the capabilities and limitations of people with disabilities in the design of computer hardware and software.

The most recent legislation for electronic product design is the Telecommunications Act, signed by the President in February of 1996. In accordance with this Act, the Federal Communications Commission formed the Telecommunications Access Advisory Committee (TAAC) to address the issues for incorporating universal design into the development process of telecommunications products (TAAC, 1997). This Act influenced improving the access to consumer products by users with disabilities without reducing the usability or attractiveness for the mass or core of consumers of the products without disabilities.

2.2 Motor Impairments

The disabled population includes a large and diverse group of people with mobility impairments (Bopp, 1984). According to the Institute of Medicine (1997), approximately one of every seven Americans (about 49 million) has some type of disabling condition. About one-third of those people (16 million) have severe disabilities (that is, they are unable to carry out major activities such as working or attending school). Another 16 million people with disabilities are restricted in their major activities, and the remaining people are limited in other types of activities due to motor deficits, missing, deformed or paralyzed limbs, or spinal deformity.

This section presents information about prevalent diseases that produce motor impairments. Appendix A presents descriptions and incidence rates of these various diseases. In terms of upper limb usage, a clinically applied taxonomy of impairments may identify three categories: (1) moderate difficulty, (2) severe difficulty, and (3) inability to use limbs. In addition, the relationships between people with functional limitations and computer use are reviewed to determine how people with impairments can accomplish their desired computer activity.

2.2.1 Diseases and Causes of Motor Impairments

Among the causes of motor impairments are congenital conditions such as cerebral palsy, injuries such as spinal cord injury and amputation, and numerous diseases, including multiple sclerosis (MS), poliomyelitis and arthritis. Various degrees of limitation in mobility may also result from a stroke or any of a number of neurological or orthopedic diseases and disorders. In this section, various diseases and causes of mobility impairments are reviewed.

2.2.1.1 Spinal Cord Injury

More than half a million Americans have experienced spinal cord injuries, with ten thousand new injuries occurring annually (Bowe, 1980; Institute of Medicine, 1997). The major causes of these spinal cord injuries are automobile accidents, falls, and contact sports such as football and soccer. The National Spinal Cord Statistical Center at the University of Alabama at Birmingham estimated that the average yearly health care and living expenses for people with spinal cord injuries were $198,000 for the first year and $24,154 for each subsequent year (Institute of Medicine, 1997).

Figure 2 illustrates the relationship of spinal nerve roots to vertebrae and the corresponding sensory components of each spinal nerve. Table 3 summarizes some disorders caused by spinal cord injury.

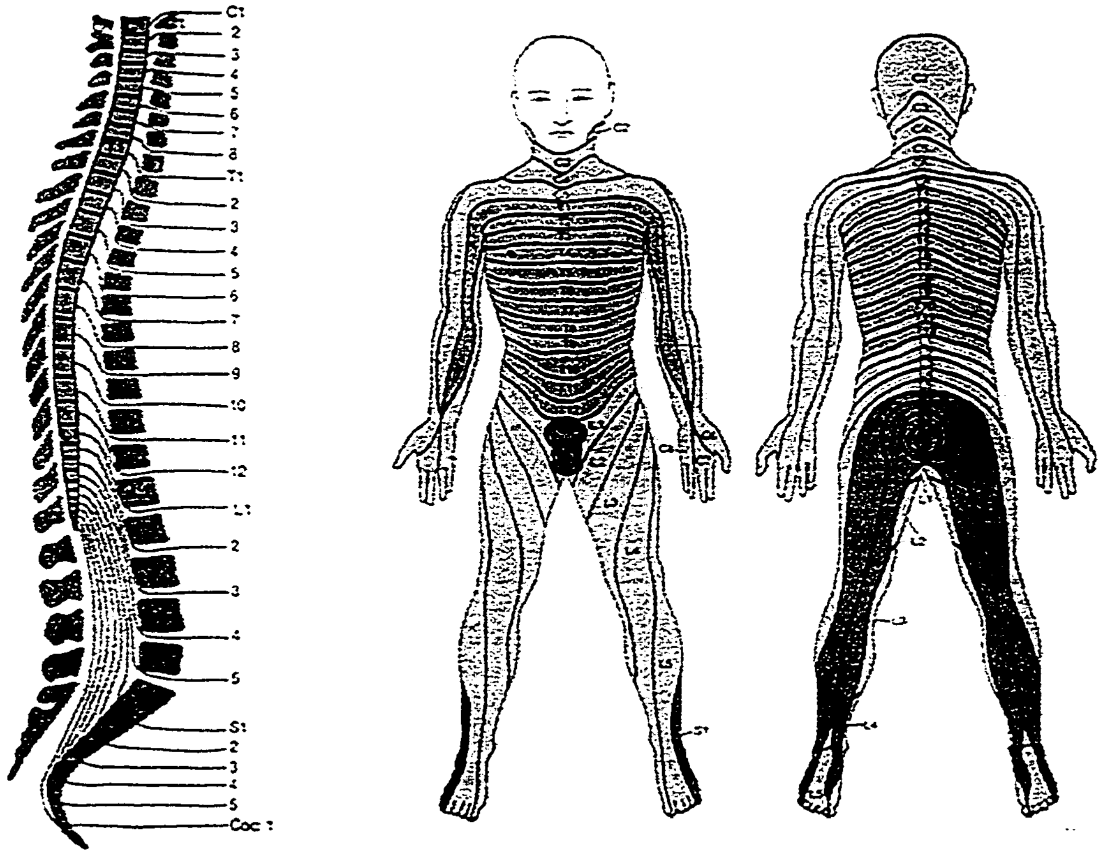


Figure 2. Relationship of Spinal Nerve Roots to Vertebrae and the Corresponding Sensory Components of Each Spinal Nerve (Donovan, 1981).

2.2.1.2 Neuromuscular Difficulties

According to Robinault and Denhoff (1973), every 53 minutes a child is born in the U.S. with multiple neuromuscular difficulties. The impairments caused by neuromuscular diseases are limited mainly to the motor system (Corcoran, 1981). Children with these conditions may have weakness or clumsiness in voluntary motion,

Table 3. Some Disorders of the Spinal Cord (Kalat, 1995).

Disorder	Description	Causes
Paralysis	Lack of voluntary movement in part of the body.	Damage to motor neurons in the spinal cord or their axons in the periphery.
Flaccid paralysis	Inability to move one part of the body voluntarily, accompanied by low muscle tone and weak reflexive movements.	Damage to motor neurons in the spinal cord. Can be temporary result of damage to axons from brain to spinal cord.
Spastic paralysis	Inability to move one part of the body voluntarily, although reflexive movements and tremors remain. Muscles are stiff and muscle tone is higher than normal. Reflexes are strong and jerky.	Damage to axons from the brain to the spinal cord. (Such damage initially causes flaccid paralysis, which eventually gives way to spastic paralysis.)
Quadriplegia	Loss of sensation and muscle control in all four extremities.	Cut through the spinal cord above the level controlling the arms.
Hemiplegia (in the arm)	Loss of sensation and muscle control in the arm on one side.	Cut halfway through the spinal cord or damage to one of the hemispheres of the cerebral cortex.
Poliomyelitis	Acute virus infection of the spinal cord often followed by residual paralysis of muscles.	Virus that damages cell bodies of motor neurons.
Amyotrophic lateral sclerosis (Lou Gehrig's disease)	Gradual weakness and paralysis, starting with the arms and later spreading to the legs. Both motor neurons and axons from the brain to the motor neurons are destroyed.	Degeneration of motor nerve cells and their axons, leading to replacement of corticospinal tracts by scar tissue (Sclerosis).

as well as troublesome involuntary movements. Each disease's description and incidence is shown in Appendix A.

Since multiple sclerosis, cerebral palsy, and cerebral trauma (i.e., stroke) produce a variety of other neurological limitations in addition to motor system impairments, these diseases are individually described in the following sections. Table 4 summarizes various disorders causing neuromuscular dysfunction.

2.2.1.3 Multiple Sclerosis

Multiple sclerosis, one of the most common neurological diseases in the world, is defined as a progressive disease of the central nervous system (CNS) characterized by the destruction of the insulating material covering nerve fibers (Kraft, 1981). Resulting impairments related to using computer input devices include poor muscle control, weakness and fatigue, talking, seeing, and sensing or grasping objects (Kraft, 1981; Petajan & White, 1999). In the U.S., more than 350,000 individuals have MS (Petajan & White, 1999). Most commonly, the onset of MS starts between the ages of 20 and 40, with a peak incidence occurring around age 30. MS is more common in females than males at a ratio of 1.7:1 (Petajan & White, 1999).

2.2.1.4 Cerebral Palsy (Multiple Dysfunctions)

Cerebral palsy (CP) refers to disorders of movement resulting from damage to the brain (Easton & Halpern, 1981). Robinault and Denhoff (1973) described the condition in more detail. CP is a general term applied to a group of disabilities resulting directly or indirectly from damage to the developing brain that may occur before, during, or after birth. A primary characteristic of CP is loss or impairment of control over voluntary muscles in arms, legs, tongue, eyes, or overall body movements. In terms of motor dysfunction, balance and coordination may be impaired in a range from mild to severe.

Table 4. Some Disorders of Neuromuscular Dysfunction (Corcoran, 1981).

Disorder	Description	Causes
Friedreich's Ataxia	A hereditary disease characterized by clumsiness and incoordination (ataxia), fatigability, atrophy, and muscle imbalance.	Spinocerebellar degeneration. Usually beginning in children or teenagers with signs of spinal cord and cerebellar degeneration.
Gullain-Barre Syndrome	A disorder involving progressive muscle weakness or paralysis, causing the conduction of nerve impulses to slow down.	A preceding infection of the upper respiratory or gastrointestinal tracts, but no definite cause has yet been established.
Huntington's Disease	A hereditary disease of the brain with onset usually in adult life, characterized by jerky involuntary movements and mental deterioration.	Widespread degeneration throughout the brain, with shrinkage of the brain tissue and enlargement of the fluid-filled cavities inside the brain.
Multiple Sclerosis	A disorder of the central nervous system involving decreased nerve function associated with the formation of scars on the covering of nerve cells.	A complex interaction of infection, immune, and genetic factors.
Muscular Dystrophy	A family of hereditary diseases that cause degenerative changes in the muscles, leading to progressive weakness and disability.	Abnormal function of a number of enzymes found in muscles.
Myasthenia Gravis	A disease that causes weakness and fatigability of the muscles.	A decrease in the amount of acetylcholine at the neuromuscular junction due to a form of disimmune disorder.
Parkinson's Disease	A progressive disease of older adults characterized by muscle rigidity, slowness of movements, and a unique type of tremor.	A deficiency in the neurotransmitter chemical dopamine in affected areas of the brain.
Spinal Muscular Atrophy	A group of hereditary diseases characterized by the weakness and flaccidity of the trunk and limb muscles.	Progressive degeneration of the anterior horn cells.

Rao (1998) categorized cerebral palsy by the type of movement such as spastic, athetoid, or ataxic (Table 5). In addition, CP is known as a neuromuscular disorder that takes five characteristic forms (Easton & Halpern, 1981; Robinault & Denhoff, 1973):

- ***Spasticity*** (50%, the most frequently occurring form), the motor symptom of cerebral palsy wherein the voluntary muscles overcontract, causing awkward postures.
- ***Athetosis*** (25%), marked by a constantly recurring series of slow, wormlike involuntary movements throughout the body.
- ***Ataxia*** (7%), lack of balance from failure of coordination.
- ***Tremor*** (1% to 5%), coarser movements than in athetosis.
- ***Rigidity*** (7%), recognized by resistance to a limb being moved.

Table 5. Type of Movement Categorizations of Cerebral Palsy (Rao, 1998).

Classification	Characteristics
Spasticity	Rigidity in the muscles, which causes stiffness and restricted movement. • ***Hemiplegia***: one arm and one leg on the same side of the body. • ***Diplegia***: both legs. • ***Quadriplegia***: all four extremities as well as trunk and neck muscles.
Athetosis	Slow, writhing, involuntary movements that lack fixed amplitude, rhythmicity, or direction.
Ataxia	Inability to appropriately activate or inhibit muscles with sufficient rapidity and accuracy.

2.2.1.5 Amputation

Friedmann (1981) defined the term amputation as the complete loss of all limb elements below a certain point. The major causes of upper extremity amputation are trauma, vascular disorders, neoplasms, infections, and malfunctioning extremities (Lewis, 1973). In terms of computer use, congenital limb deficiency is also included in this category. According to the Amputation Fact Sheet (2001), there are 350,000 amputees living in the U.S., with approximately 135,000 new amputees added each year. The most common causes of amputation of extremities are dysvascular disease without mention of diabetes (16.3%), diabetes (14.4%), trauma (33.6%), cancer (8.2%), congenital or birth defects (6.9%), and other causes (6%) (Limb Loss Researchers Poised for Leap Forward, 2000). For daily living, orthotics and prosthetics are essential for people who have experienced an amputation. In addition, Lewis (1973) found that people who are older are more prone to lose an extremity due to a vascular disorder or infection.

2.2.1.6 Stroke and Cerebral Trauma

In general, the terms cerebral vascular accident (CVA), stroke, and cerebral trauma are interchangeably used with brain damage because the results and effects from each incident are very similar (Fowler, 1981). According to Anderson (1981), stroke is defined as a sudden onset of weakness or other neurological symptoms as a result of injury to a blood vessel in the brain (cerebrum, cerebellum, or brain stem). In many cases, a stroke results in some level of permanent neurological damage. Three main causes of stroke are prevalent in the literature (Anderson, 1981):

- ***Thrombosis***, the most common cause, occurs when a blood clot (thrombus) forms in a blood vessel and reduces or blocks the blood flow past that point.
- ***Hemorrhage***, caused by a rupture of a blood vessel resulting in bleeding into the brain tissue.
- ***Embolism*** occurs when a large blood clot breaks off and blocks an artery (Figure 3).

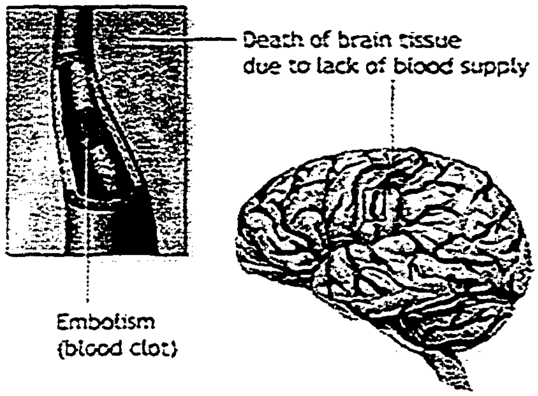


Figure 3. Stroke Caused by Embolism (Source: Disease, Condition or General Health Topic, 2001).

Stroke most commonly causes hemiplegia or hemiparesis. Unique differences exist between hemiplegia and hemiparesis. Hemiplegia is total paralysis of the arm, leg, and trunk on the same side of the body, while hemiparesis is weakness on one side of the body. Based on the area of the cerebrum damaged, right or left hemiplegia will result. According to Anderson (1981), damage to one side of the brain generally affects the opposite side of the body. Right hemiplegia is a motor and sensory paralysis of the right side of the body. Based on Anderson's theory, people with left hemisphere damage may be unable to understand spoken or written language because the left cerebral hemisphere is associated with language function. On the other hand, people with right cerebral hemisphere damage may be unable to accurately interpret visual information or may be unable to properly orient themselves with respect to the environment (Fowler, 1981).

While the incidence rate of strokes is stable, the prevalence of cerebral trauma is steadily increasing in modern society due to frequent accidents involving automobiles and motorcycles. According to Rubinstein (1993), a survey conducted in San Diego County estimated that about 44% of brain injuries were secondary to automobile accidents. For this reason, the average age of patients with cerebral trauma is younger than the average age of patients who have had a stroke. Even though the mechanisms of stroke and cerebral trauma may differ, the results and effects on the person are very similar (Anderson, 1981).

Stroke has received much attention because it ranks third as a fatal disease in the U.S. Stroke is frequently accompanied by one or more other medical problems associated with diseases of the blood vessels, including hypertension, heart disease, diabetes mellitus, atherosclerosis, elevated blood cholesterol, and peripheral vascular disease. The acutely damaged brain, resulting either from a disruption in blood flow or from tissue damage caused by a blow or a lesion of any sort will almost always result in behavioral deficits that may include decreases in physical abilities, intellectual performance, social functioning, emotional control, or any combination of the four (Fowler, 1981).

2.2.1.7 Arthritis and Repetitive Strain Injuries (RSI)

Arthritis is defined as pain in the joints, usually reducing range of motion and causing weakness (Nicholas, 1981). Rheumatoid arthritis is a chronic syndrome. Osteoarthritis is a degenerative joint disease. Approximately 37 million people in the U.S. have arthritis of some kind, which is almost one out of every seven people. In general, women are more likely to suffer from osteoarthritis among people over 55 years of age. The most common risk factors for osteoarthritis are obesity, a history of trauma, and various genetic and metabolic diseases (Disease, Condition or General Health Topic, 2001).

On the other hand, repetitive strain injuries (RSI) or cumulative trauma disorders (CTD) are caused by frequent and regular intervals of repetitive action (Bergman & Johnson, 1995). In 1992, the Occupational Safety and Health Administration (OSHA) collected injury data in all work places and found that almost 56% of the injuries were RSIs (Furger, 1993). Tendonitis and carpal tunnel syndrome (CTS) are the most common RSI types. Since people with RSI suffer from headaches, radiating pain, numbness, tingling, and a reduction of hand function, they need alternative assistive technologies for computer input tasks, including alternative pointing devices, screen keyboard, predictive dictionary and speech recognition (Bergman & Johnson, 1995).

2.2.1.8 Origin of Physical Disability

LaPlante (1998) studied the origin of physical disability from 1990 National Health Interview Survey data. As shown in Table 6, the main causes of musculoskeletal and sensory impairments are accident or injury (45.5%), congenital in origin (11.1%), stroke, cancer, diabetes, and polio together (over 3%), and unknown origin or other conditions (40.1%). In many cases, orthopedic impairments (60%) and deformity or impairment of extremities (73.6%) are due to accident or injury. More than half of the paralysis cases are also due to accident or injury (58.8%), with cerebrovascular disease as the second highest cause, accounting for 20% of quadriplegia, paraplegia, or hemiplegia. Cancer is a primary cause of amputation (28.2%). Around 8% of blindness and over 11% of leg losses are caused by diabetes. The most frequent cause of cerebral palsy is congenital disease (65.3%).

2.2.2 Taxonomy of Functional Limitations for Computer Use

According to Cunningham and Coombs (1997), four different groups of people with mobility impairments exist: (1) those who use wheelchairs, (2) those who use motorized scooters, (3) those who use crutches or walking canes, and (4) those who have impaired upper body mobility of the hand or arm due to missing digits, hands, or arms, or due to conditions such as arthritis or cerebral palsy. For the use of computer input devices, the fourth group is the focus group of this dissertation.

With respect to the design of telecommunications or computer input devices, the term disability is better defined functionally than clinically (Kaplan, Witt, & Steyaert, 1992). When using computer input devices and controls, impairments may be described or divided in three categories: (1) unable to use limbs due to paralysis or

Table 6. Origin of Musculoskeletal, Neuromuscular, and Sensory Impairments: The United States in 1990 (LaPlante, 1998).

(Numbers are in Thousands)

	All Origins	Accident or Injury	Cerebrovascular Disease	Cancer	Diabetes	Polio	Congenital	Other Conditions	Unknown Etiology
Musculoskeletal and sensory impairments	9772	4448	109	98	56	59	1087	1935	1980
Blind in both eyes	247	16	4	4	19	0	28	134	42
Impaired in both eyes	254	16	14	0	12	0	6	165	41
Blind/impaired in one eye	220	87	0	0	4	0	27	72	30
Deaf in both ears	126	6	0	0	0	0	24	69	27
Impaired in both ears	228	11	0	3	0	0	23	131	60
Deaf/impaired in one ear	146	13	0	6	0	0	12	64	51
Absence of legs	115	45	0	3	13	0	4	46	4
Absence of bone, joint, or muscle of extremities	106	30	0	2	0	0	4	66	4
Amputation	195	76	2	55	8	0	14	27	13
Paralysis (Quadriplegia/paraplegia/hemiplegia)	119	70	23	0	0	7	3	10	6
Cerebral Palsy	193	6	0	0	0	0	126	12	49
Other paralysis, complete or partial	232	104	56	4	0	34	7	9	18
Curvature of back or spine	367	64	0	0	0	8	99	68	128
Deformity/impairment of back	2636	1715	0	2	0	0	70	399	450
Deformity/impairment of upper extremities	700	570	2	3	0	0	32	42	51
Deformity/impairment of lower extremities	2060	1460	4	0	0	6	106	276	208
Orthopedic impairment	110	66	0	3	0	2	2	18	19
Speech impairments	254	7	2	6	0	0	29	80	130
Mental retardation	1069	30	2	7	0	0	359	160	511
Learning disability	150	4	0	0	0	0	24	29	93
Other impairments	247	52	0	0	0	2	88	60	45

absence of limbs, (2) severe difficulty in using or controlling limbs, and (3) moderate difficulty in using limbs. These categories for impairment were created using a somewhat different approach than the categories for clinical purposes. People with clinically moderate impairments who have significant difficulties using input devices and controls should functionally be placed in the severe difficulty category.

In this section, the types of disorders that were reviewed in the previous section are assigned to the three impairment categories. Since people with disabilities should be included in the design and evaluation of assistive technologies (Bergman & Johnson, 1995), reviewing the three categories is important.

2.2.2.1 Unable to Use Limbs

For computer input devices, the absence of upper limb body parts or upper extremities that are unusable due to paralysis or discoordinated movement may be the most severe form of impairment (Edwards, 1995). Brain damage or damage to the spinal cord often causes paralysis. Paraplegia refers to paralysis of the legs, while tetraplegia and quadriplegia refer to paralysis of all four limbs. Paralysis can also affect one side of the body – usually when damage has occurred to the opposite side of the brain. Paralysis is not always complete, but may result in reduction in the movement of the limb or limbs (Edwards, 1995).

Several assistive tools for computer input exist for people who are unable to use limbs (Table 7). These tools include mouthsticks, headsticks, eyegaze, sip-and-puff and speech recognition systems (Edwards, 1995). Bouisset and Rossi (1991) found great benefit in using these alternative tools for people who have lost the ability to speak or who cannot adequately read or write.

Table 7. Assistive Technology Strategies for People Unable to Use Upper Limbs.

Impairment	Functional Limitation	Needed Features/Capabilities
Loss of limbs, loss of hands or paralyzed limbs	Cannot use input devices with limbs or hands	Eyegaze, speech recognition, or sip-puff controlled input device (because typical input devices, such as keyboard, mouse, or touch screen, cannot be used)

2.2.2.2 Severe Difficulty Using Limbs

Edwards (1995) mentioned that numerous forms of brain damage may cause severe difficulty in using limbs due to problems of motor control. Cerebral palsy and stroke are examples of partial paralysis. Alternative mouse devices, such as head-controlled pointers and locators, are intended to help people with cerebral palsy or upper-spinal cord injuries (Berliss, Borden, & Vanderheiden, 1989).

Casali (1995) proposed several solutions for assisting in typing. To make the selection of a particular key easier, keyguards that fit over the keyboard have been developed for people who inadvertently bump extra keys. People who have severe tremor can use input devices with keyguard assistance. In addition, people with severe tremor may use a voice recognition system to completely replace the keyboard and mouse (Lazzaro, 1996).

For people who have difficulty with eye/finger coordination, useful alternative tools include a force joystick, a trackball, and a touchpad. Table 8 represents several assistive technology strategies for people who have severe difficulty in using their upper limbs.

Table 8. Assistive Technology Strategies for People Severe Difficulty Using Upper Limbs.

Impairment	Functional Limitation	Needed Features/Capabilities
Muscle or skeletal deformities, muscle rigidity (stiffness), or numbness and tingling (loss of sensation)	Lack of dexterity	Eyegaze, speech recognition, or sip-puff controlled input device (because typical input devices, such as keyboard, mouse, or touch screen, could be hard to use)
Tremor	Inadvertently bump extra keys	Keyguard or voice input device
Poor coordination (ataxia)	Difficulty in eye/finger coordination	Force joystick, trackball, or touchpad

2.2.2.3 Moderate Difficulty Using Limbs

People with severe weakness in their limbs may be unable to operate controls at all, or may have great difficulty performing constant, uninterrupted input tasks. People with mild weakness, however, may properly perform input tasks by using an ergonomically designed keyboard and mouse. To reduce pain and risk of injury in the wrist area due to repetitive motion tasks, and to increase comfort, accuracy, and productivity, the ergonomic keyboard is a good alternative input device for people with moderate weakness or joint pain in the wrist (Lazzaro, 1996).

Adjustable keyboard repeat-rate features are beneficial for people with muscle spasticity, muscle atrophy, uncontrolled slow movement, and dysfunctional movement (Trace Center, 1988). To help people who have difficulty selecting the small keys of a standard keyboard, enlarged keyboards may be used. To augment the skills of people with severely limited range of motion or the use of only one hand, reduced size keyboards may be helpful (Casali, 1995).

People who can use only one hand are unable to activate multiple buttons or keys at the same time. An available alternative assistive tool is a "sticky key" that can transform two-handed keystrokes into single-handed keystrokes (Lazzaro, 1996). For people with limited range of motion, a remote controllable keyboard or mouse may be used to perform computer input tasks without moving the body or reaching with the arms. Another assistive tool for people with limited range of motion is the trackball. Since a trackball remains stationary, relatively little range of motion is needed for its operation (Lazzaro, 1996).

According to Berliss et al. (1989), modern computers are much easier to learn and use due to the advanced development of computer input pointing devices including joysticks, light pens, mice, tablets, touch pads, touch screens and trackballs, and graphical user interfaces using iconic images. These advancements, however, may cause more difficulty for people with movement impairments such as motor coordination disorders, paralysis, or spasticity. Berliss et al. (1989) suggested that since these computer input devices require a certain degree of motor control, upper extremity weakness and reduced manual dexterity might decrease the usability for people with mobility impairments. Therefore, the required features in Table 9 should be carefully considered in developing appropriate assistive tools for people with moderate motor impairments.

2.2.3 Functional Assessment of the Degree of Impairment

Upper extremity performance typically plays a critical role in a human being's daily activities. Manual dexterity tests are typically used to assess upper extremity performance. Dexterity is measured by the time required to complete a manipulation task involving fine, voluntary movement of small objects (Maiden & Dyson, 1997). Casali (1991) claimed that various measures of motor ability including the strength, speed, accuracy, range of motion, steadiness, and sensory performance of muscle groups or body segments in the upper extremities can be quantitatively assessed by existing functional assessment tests.

Table 9. Assistive Technology Strategies for People Moderate Difficulty Using Upper Limbs.

Impairment	Functional Limitation	Needed Features/Capabilities
Muscle spasticity	Lack of dexterity	Adjustable keyboard repeat rate
Joint pain	Lack of dexterity	Ergonomically designed keyboard and mouse
Muscle atrophy, or uncontrolled slow movement	Problem completing timed responses	Adjustable keyboard repeat rate
Missing one hand	Unable to activate multiple buttons/keys at the same time	Sticky key and minikeyboard
Jerky unpredictable movement (chorea)	Inadvertently bump extra keys	Keyguard or voice input devices
Dysfunction movement (apraxia)	Problem completing timed responses and fine movement	Adjustable keyboard repeat rate
Limited range of motion	Difficulty in reaching	Remote controllable keyboard and mouse (Trackball may be used)
Weakness (lack of strength)	Difficulty in grasping or handling	Ergonomically designed keyboard and mouse

Traditionally, many different types of functional assessment tests have been used to measure the manual skills of people with mobility impairments. Some examples of the tests for assessing hand and finger dexterity are (1) Jebsen Hand Function Test, (2) Minnesota Manual Dexterity Test, (3) Nine Hole Peg Test, (4) Purdue Pegboard, (5) Box and Block Test, (6) Morrisby Manual Dexterity Test, (7) Crawfords Small Parts Dexterity Test, (8) Bennett Hand Tool Dexterity Test, and (9) Smith Hand Function Test (Casali, 1991; Maiden & Dyson, 1997; Verdino & Dingman, 1998).

Casali (1991, 1995) pointed out that traditional standardized tests for evaluating gross muscle performance and range of motion focused mainly on measuring the force and range of motion of various movements. A need existed to develop new assessment tools for predicting functional performance in computer input tasks. Desrosiers, Hebert, Bravo, and Dutil (1995) identified three limitations in existing traditional functional tests: (1) the tasks are naturally too artificial, not highly related to daily activities, not bilateral but unilateral, and focused only on hand functional performance instead of proximal movements, (2) the time of execution was the primary measurement criterion, even though the execution process by which the task was completed is important, and (3) few assessment instruments designed for people with disabilities or the elderly demonstrate reliability and validity.

Fess (1990) suggested that a standardized test should consider several elements, including (1) a statement that defines the purpose or intent of the test, (2) correlation statistics or another appropriate measure of instrument validity and reliability, (3) detailed descriptions of the equipment used in the test, (4) normative data, drawn from a large population sample, which is divided into categories according to appropriate variables, such as hand dominance, age, sex or occupation, and (5) specific instructions for administering, scoring and interpreting the test. Maiden and Dyson (1997) agreed with the suggestion by Fess because many hand function tests have not fully met the standardization criteria.

Since each of the available tests assesses different sets of functional capabilities, Casali (1991, 1995) developed a functional assessment test, the Virginia Engineering Assessment Center's Small Parts Manipulation Test. The test was developed for people with mobility impairments of the upper extremities. The test was also designed to be easy and inexpensive to construct and administer for assessing the usage capabilities of various computer input devices by people with mobility impairments. However, the test has not yet been widely accepted or used as a standard test by other researchers.

Among various tests, the Minnesota Manual Dexterity Test may serve as a fairly good test for assessing manual functional dexterity of people with disabilities. Most functional assessment tests require too high a degree of fine manual dexterity. However, since the Minnesota Manual Dexterity Test uses relatively large objects manipulated with the hands and fingers, this test can possibly be used to assess the functional dexterity of people with upper-limb impairments. No existing normative data for impaired populations were found.

2.3 Computer Assistive Technology for People with Motor Impairments

According to Lazzaro (1996), the personal computer (PC) and assistive technology correspond to an "electronic bill of rights" for people with disabilities. The most common computer input devices are the keyboard and the mouse. People with motor impairments, however, need alternative assistive tools to interact with computers. To date, numerous computer assistive technologies have been developed. When designing new assistive technology tools for people with impairments, the role of human factors specialists should be emphasized (Bouisset & Rossi, 1991). As Edwards and Hancock (1995) suggested in their design guideline, the latest assistive technology should be assessed to iterate to improved designs.

The loss of motor control or lack of mobility may be a critical reason for difficulty in operating advanced computer technology (Howey, 1995). The Institute of Medicine (1991, p. 225) defined assistive technologies as "devices and techniques that can eliminate, ameliorate, or compensate for functional limitations." People with motor impairments can interact with the social and physical elements of their environment more efficiently and more effectively using assistive technology (Institute of Medicine, 1991). To expand access to information technology (IT) computer systems, special interfaces using assistive technology devices might be used by people with motor impairments to perform needed and desired tasks. These assistive technology devices are even more critical for people with severe impairments.

Even though assistive technology will not perfectly eliminate an impairment, it will possibly improve daily function and independence (Russell, Hendershot, LeClere, Howie, & Adler, 1997). That is, the assistive technology may enable people with functional limitations to use computer input devices more effectively. According to Russell et al. (1997), the advanced development of computer technology plays the most important role for the improvement of assistive devices to make input devices easier to use, safer, and less expensive.

The Technology-Related Assistance for Individuals with Disabilities Act (TRAIDA) of 1988, Public Law 147, had a major impact on the development of assistive technology (Brown, 1992; DeJong & Brannont, 1998). According to DeJong and Brannont (1998), however, the primary focus was on physical assistive devices rather than computer assistive devices. Greater development efforts in computer devices are critically necessary. Howey (1995) suggested that better designed assistive tools affect more users and reach larger markets.

In many cases, highly advanced assistive technology tools have been initiated based on professional perceptions of user needs. Figures 4 and 5 describe user needs with respect to assistive devices. Some gaps may exist when people with functional limitations perform computer tasks using computer assistive devices (Figure 4). Once the elements of the gaps are defined and removed, people with functional limitations can efficiently use the devices. Computer assistive devices that are well-matched with the types of functional limitations will provide a better interface for the people with those functional limitations (Figure 5).

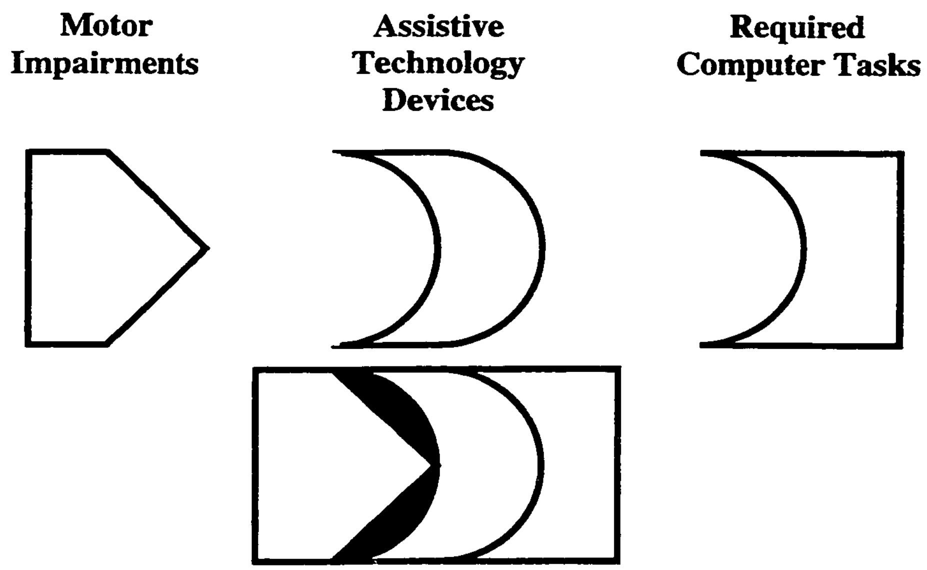


Figure 4. Imperfect Match Between Motor Impairments and Required Computer Tasks (Modified from Edwards, 1995).

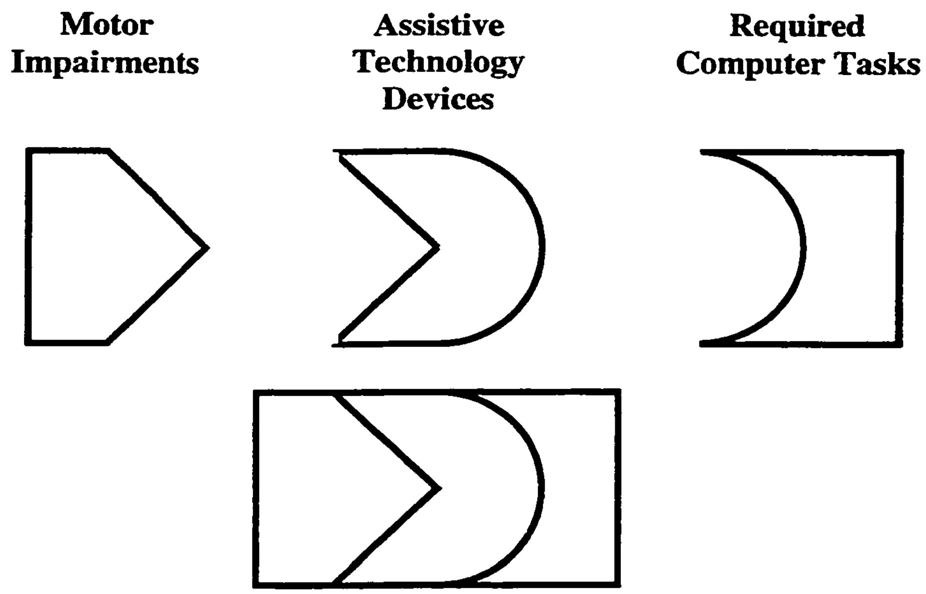


Figure 5. Ideal Match Between Motor Impairments and Required Computer Tasks (Modified from Edwards, 1995).

2.4 Computer Input Devices

According to Mayhew (1992), the primary human input devices are the eyes, ears, and the sensory organs of touch, while the conventional computer input devices are keyboards and mice. People with motor impairments, however, may be unable to use traditional input devices such as keyboards and mice (Edwards, 1995). This section reviews current typical computer input devices. Improving computer input devices to be more accessible should be much easier than improving human input devices.

2.4.1 Text Entry Devices

The most traditional and common computer input device is the keyboard (Mayhew, 1992). To date, numerous types of keyboards have been developed, including the QWERTY keyboard, alphabetic keyboard, DVORAK keyboard, and chord keyboard (Dix, Finlay, Abowd, & Beale, 1998). In addition, various on-screen keyboards have been developed for people who cannot adequately use their hands or do not have hands.

According to Shneiderman (1998), the QWERTY keyboard was developed by Christopher Latham Sholes in the 1870s. A century later, the keyboard had become the most widely used standard keyboard. The name QWERTY comes from the first six letters of the top row of alphabetical keys (Dix et al., 1998). It has been reported that the QWERTY layout was designed to reduce typing errors on mechanical type writers by locating the most frequently used letters far apart (Dix et al., 1998; Mayhew, 1992; Shneiderman, 1998), a concept that now results in potentially slower keyboarding speed. For people with only one hand, the "Half-QWERTY" one-handed keyboard was developed, which uses only half of the QWERTY keyboard. Matias, MacKenzie, and Buxton (1994) conducted a performance test and found that participants using the Half-QWERTY typed between 41% and 73% of their respective two-handed speed.

The alphabetic keyboard, in which the letters are ordered alphabetically across the keyboard, was developed for untrained typists. Many researchers, however, have found no difference in typing speed when compared with the QWERTY keyboard (Dix et al., 1998). Many commercial products exist, such as hand-held calculators, remote-control devices, and children's computer toys and games that use the alphabetic layout (Mayhew, 1992).

The DVORAK keyboard layout is based on the frequency of use of the letters in the English language. Since this keyboard was designed primarily for right-handed people, 56% of the keystrokes are made with the right hand (Dix et al., 1998). Researchers have documented a 10 to 15% speed improvement for the ergonomically rearranged layout of the DVORAK keyboard (Dix et al., 1998). Even though the keyboard was designed to improve comfort and reduce repetitive strain injury (RSI), the factors could not be significantly incorporated because the QWERTY keyboard has dominated the computer keyboard market (Dix et al., 1998).

For people with missing fingers or the use of only one hand, the chord keyboard was developed to minimize finger travel between keys (Sanders & McCormick, 1993). Gopher, Hilsernath, and Raij (1985) found that the chord keyboard is much easier and faster to learn. Gopher et al. (1985), however, were not able to compare the chord keyboard to the QWERTY keyboard on ease of use and overall speed due to a lack of available data for determining the maximum typing speed afforded by the chord keyboard for both experts and novices. The most popular chord keyboard is the BAT Chord Keyboard that is the ultimate typing solution for people with physical or visual impairments.

Another important alternative text input device for people with motor impairments is a speech recognition system. This device is especially designed to help people in "hands-occupied" situations or people who cannot use their hands or arms (Dix et al., 1998). A speech recognition system, therefore, can serve as a supplement or replacement for data entry on a physical keyboard. Many problems, however, are associated with using a speech recognition system. Current technology has not completely solved the problems of inherent vagueness, imprecision and pauses in understanding natural language, different speaking behaviors, strong accents, emotion-related differences in speech, and background noise (Amalberti, Carbonell, & Falzon, 1993; Dix et al., 1998). Numerous efforts to address these issues have met with considerable success.

Keates and Robinson (1999) proposed a gestural input system for users with motion impairments. By increasing the degrees-of-freedom of input devices, interaction rates may be improved. Multimodal input using gestures can feasibly help interaction between computer systems and people with motor impairments. Several problems were identified by Keates and Robinson (1999), including low computer recognition rates for gestures and the physical and cognitive loads placed on the user. When these problems are solved, the gestural input device may become a very efficient tool for people with motor impairments.

The on-screen keyboard can be used by people with limited hand function (Anson, 1997). People with limited hand function may be able to use the mouse system on a desk but not have sufficient finger control to use a keyboard. The on-screen keyboard is a displayed keyboard on the computer screen, which the user can operate by hand, foot, sip-and-puff control, voice recognition, eye movement, head movement, or body position (Lazzaro, 1996). As summarized in Appendix B, many such products are currently on the market, such as the SPT Mouse Keyboard, SofType, WiVik2 REP, OnScreen, and ScreenDoors.

2.4.2 Positioning and Pointing Devices

According to Dix et al. (1998), pointing devices allow the user to point, position and select items, either directly or by manipulating a pointer on the screen. Shneiderman (1998) listed six types of interaction tasks that are addressed by pointing devices: (1) selecting from a set of items, (2) positioning in a higher-dimensional space, (3) direction in a higher-dimensional space, (4) multiple interaction in both positioning and direction, (5) quantifying, that is, one-dimensional selection of integer or real values to set parameters, and (6) editing text in a two-dimensional space. Some examples of advanced 2D pointing devices are the trackball, trackpoint, joystick, touch-sensitive screen, light pen, digitizing tablet, touchpad, and eyegaze (Dix et al., 1998; Sanders & McCormick, 1993). Several keyboard-based positioning device modifications also exist, including cursor keys, mousekeys, and thumb-wheels for computer-aided design (CAD) systems.

Advanced computer technology currently allows three-dimensional (3D) virtual worlds and high-fidelity sampling of the physical world (Fitzmaurice, Balakrishnan, & Kurtenbach, 1999). Input positioning in 3D space is required for these 3D virtual systems. The 3D mouse, dataglove, virtual reality helmet, and whole-body tracking device are potentially useful for people with motor impairments (Dix et al., 1998; Fitzmaurice et al., 1999).

2.4.3 Keyboard Modification Software

Since people with motor impairments have difficulties in the manipulation of ordinary keyboards and mice, keyboard modification software can provide effective assistance for them (Lazzaro, 1996; Trewin & Pain, 1998, 1999). Various forms of keyboard enhancements are available including StickyKeys, MouseKeys, RepeatKeys, SlowKeys, and BounceKeys (Bergman & Johnson, 1995).

StickyKeys provides key locking or latching (e.g., Alt, Shift, or Control key) to allow "simultaneous" pressing of keys by users with disabilities. People who find it difficult to hold down one key while pressing another may benefit by using the StickyKeys (Anson, 1997; Lazzaro, 1996; Trewin & Pain, 1998, 1999). *RepeatKeys* allows users with limited coordination time to release keys by delaying the onset of key repeat (Bergman & Johnson, 1995; Trewin & Pain, 1998, 1999). *MouseKeys* allows users to control the on-screen cursor movement using the keyboard (Anson, 1997; Bergman & Johnson, 1995). *SlowKeys* requires a key to be held down for a set period before keypress acceptance. The function prevents accidental pressing of keys by users with limited coordination (Bergman & Johnson, 1995). *BounceKeys* requires a delay between keystrokes before accepting the next keypress. Therefore, users with tremor can properly perform their computer input task without inadvertent keypresses (Anson, 1997; Bergman & Johnson, 1995).

2.5 Computer Task Requirements

In order to determine which assistive technology tools may be more effective for certain types of motor impairments, the tasks that are to be accomplished must also be defined (Casali & Williges, 1990). Currently, most computer tasks operate in a graphical "windows" environment. Computer task requirements should thus be defined within the graphical environment. In this section, basic computer tasks using computer input devices are summarized.

2.5.1 Computer Task Analysis

Understanding users' needs in human-computer interaction designs may be promoted by applying user-centered design (Fath & Bias, 1992). One good tool for user-centered design is task analysis. Shepherd (1989, p. 15) defined task analysis as "trying to make sense of what people should do or what they actually do." To understand the needs of people prior to design, and to provide highly accessible input devices for people with mobility impairments, the use of task analysis might be beneficial (Fath & Bias, 1992).

Dix et al. (1998) stated that the output of a task analysis is totally dependent on the use of the task analysis. In the scope of this dissertation, therefore, the task analysis for computer input devices is constrained to uses by people with motor impairments. Major handling difficulties and circumstances of computer input devices by people with motor impairments are addressed by Francik (1996). These are difficulties in moving, reaching, pressing, grasping, or lifting, as might be due to aging, arthritis, or injury. People with motor impairments, therefore, will have controlling difficulties in dragging, selecting, holding, and typing.

Czaja, Hammond, Blascovich, and Swede (1986) and Shepherd (1989) applied task analysis to hierarchically decompose a word-processing task. The word-processing task was divided into entering text, editing, formatting, printing, and saving (Shepherd, 1989). Each categorized task can be further decomposed into subtasks (Bailey, 1996; Dix et al., 1998). For example, the editing task may be decomposed into selecting, cutting, copying, and pasting blocks that are supposed to be edited.

2.5.2 Computer Task Taxonomy

According to Casali and Williges (1990), despite several approaches to develop a taxonomy of computer input device movements, no completed taxonomy exists. Casali (1995) developed a standardized taxonomy of computer input actions associated with various pointing devices. The action categories were reaching (or pointing), sliding, moving (grasping and lifting), placing (putting), repetitive tapping, and reaction time. The associated attributes for reaching were target size and distance. For sliding, resistance and target size were the attributes. For moving, the attributes were object size, object shape, and object weight. For placing, object size and shape were the associated attributes.

Table 10 summarizes the Dix et al. classification of various input devices with respect to mapping, selection, and dragging. Simple mappings are straightforward transformations of user motion to screen motion. Complex mappings are those where the action taken to move in a particular direction is not related to movement in that direction. Direct mappings are those where the motion on the screen is directed by user indication on the screen itself. Additionally, selection refers to the process of actually selecting an object, while dragging refers to the method for moving an object from location A to location B.

Table 10. Classification of Computer Input Devices (Modified from Dix et al., 1998).

Device	Mapping	Selection	Dragging
Keyboard/cursor keys	Complex	Button press	Button hold
Mouse	Simple	Button press	Button hold
Trackball	Simple	Button press	Button hold
Joystick	Simple	Button press	Button hold
Touch screen	Direct	Direct	Screen contact
Light pen	Direct	Direct	Screen contact
Digitizing tablet	Simple	Button press	Button hold
Touch pad	Simple	Button press	Button hold
Thumbwheel	Complex	Button press	Button hold
Keymouse	Simple	Button press	Button hold
Footmouse	Simple	Foot button press	Foot button hold
Isopoint	Simple/Complex	Button press	Button hold
Sip-and-Puff	Simple	Sip	Puff
Head/mouth stick	Simple	Button press	Button hold

2.6 Designing Computer Input Devices for People with Disabilities

Despite growing interest in user-centered design, there are still serious gaps between various assistive technologies for people with disabilities and the people's accessibility to information technologies (Bergman & Johnson, 1995). In this section, user-centered design issues that may promote valuable accessibility to people with disabilities are discussed.

2.6.1 Design Guidelines for People with Disabilities

Newell and Gregor (2000) pointed out that "extra-ordinary (disabled) people operating in ordinary environments pose similar problems to able-bodied (ordinary) people operating in extra-ordinary (high workload, environmentally unfriendly) situations" (p. 12). Therefore, designing assistive technology products is not only beneficial for people with disabilities, but for "ordinary" people. In order to design more efficient computer assistive tools for people with functional limitations, many aspects must be considered. Edwards and Hancock (1995) suggested the following design guidelines:

- ***Know the user***: Potential users should be considered in the design process because every user has a different range of ordinary and extra-ordinary abilities. Also, many people have multiple impairments. As a result, the designers should use their valuable experience and knowledge to enumerate the limitations of users.
- ***Use appropriate technology***: High level technology does not always provide the best answer. Appropriate technology should be matched to the type of impairment.
- ***Know the technology***: Since assistive technology is rapidly changing, designers should always review the latest product developments. This approach will possibly allow the designer to make the appropriate assistive tools with the best currently available technology.
- ***Media independence***: Since different people perform differently, computer interfaces should take the form of universal design.
- ***Redundancy***: Multimodal interfaces should be used to provide alternative options to users.
- ***Adapt where possible***: In order to develop more appropriate tools, adaptations of existing technology should be provided.
- ***Cultivate integration***: Computer assistive tools should be universally accessible and designers should incorporate as many factors as possible.
- ***Control must remain with the user***: Control should remain with the user to provide independence.

Vanderheiden and Vanderheiden (1992) suggested other guidelines to make computer input devices more accessible. The four guidelines were: (1) direct accessibility, (2) accessibility via standard options or accessories, (3) compatibility with third-party assistive devices, and (4) facilitation of custom modifications. From the initial design phase of an input device, more directly accessible adaptation should be considered. Often times, simple and low cost adaptation may significantly increase user accessibility. If the adaptation cost is not too great, standard options or accessories should be incorporated to improve accessibility. The use of standard options will make it easier for third-party input device manufacturers to develop new compatible assistive devices. For people with severe impairments, custom modifications of the device may be the best solution because people with severe disabilities need more complex features of the device.

2.6.2 Usability Testing and Universal Design

Designers of a consumer product want to ensure that it is appealing to customers (Stanton, 1998). One aspect of appeal is usability, that is, the ease with which people can learn about and routinely, yet enjoyably, use the product. During product development, the following processes should be followed: (1) set usability goals, (2) test designs with customers, and (3) continue redesigning and testing until the designers meet the usability goals. This can be done with a particular set of customers in mind, or perhaps using multiple sets of customers.

In general, usability testing should be an iterative process including initial design of the computer-based tools, formative evaluation of the various computer interface alternatives, and a summative evaluation of the selected tools (Williges, Williges, & Elkerton, 1987). Through the iterative process, designers can suggest the best assistive tools for people with mobility impairments. In addition, the results of usability testing can be a source for improving the task analysis and the functional assessment of impairment degree (Casali, 1991). In order to propose more appropriate assistive computer input devices for people with mobility impairments, usability testing must play a vital role in the entire selection process.

Universal design means designing and producing products that are robust and accommodating (Francik, 1996). The typical problems with the use of computer input devices relate directly to the type of impairment of the computer user (Mann, 1997). Universal designs take into account differences in vision, hearing, mobility, speech, and cognition (Francik, 1996; Mann, 1997; Orlin, 1995). Universal designs, therefore, may solve this problem and maximize accessibility. Universal design helps people with disabilities and others who do not want a special product, but do want a product that is easy to use (Francik, 1996).

2.6.3 Human-Computer Interaction (HCI) for People with Disabilities

The term human-computer interaction (HCI) was defined by the Association for Computing Machinery (ACM) Special Interest Group on Computer-Human Interaction (SIGCHI) as "a discipline concerned with the design, evaluation and implementation of interactive computing systems for human use and with the study of major phenomena surrounding them" (ACM SIGCHI, 1992, p. 6). Human-computer interaction (HCI) is a thriving area in computer graphics, human factors, cognitive psychology, and artificial intelligence. Until recently, however, there was not sufficient effort to improve accessibility through the development of assistive hardware and software for people with disabilities (Shaw et al., 1995). In many cases, users with disabilities were overlooked during the HCI design process due to a lack of awareness, increased production costs, or insufficient market volumes (Bergman & Johnson, 1995).

There are individual differences among humans as the users of various computer input devices (Dix et al., 1998). The individual differences may be more pronounced within disabled populations. To enhance accessibility, HCI designers should consider the needs of people with disabilities throughout all HCI design stages, including requirements gathering, task analyses, usability tests, and developing design guidelines. In addition, more information interchange between HCI organizations and the disabled community should be expected (Bergman & Johnson, 1995).

It is strongly believed that HCI theory and practice might benefit from correct information and a comprehensive understanding of the accessibility issues in the disabled community. According to Shaw et al. (1995), applying existing HCI technology to the design of assistive computer input devices for people with disabilities will significantly improve the comfort and flexibility of currently available assistive technologies. Moreover, it will provide a vital expansion in the range of activities that are currently possible for people with motor impairments.

2.7 Fitts' Law

A model of human movement time called Fitts' Law may serve as the basis for the development of a methodology for the selection and evaluation of computer input devices. The primary computer input devices depend on hand movement to control a cursor on the display. Fitts' Law can be applied not only to the design of software applications, but also to the design of optimal pointing input devices because the pointing time is a function of the distance and the target width. For pointing, selecting, clicking, and dragging tasks, Fitts' Law has been regarded as a very important tool to test parameters of the tasks, such as designing interfaces of target sizes and movement amplitudes.

In 1954, Paul Fitts developed an effective model of the time it takes to move a given distance, D, to a target of width, W (Shneiderman, 1998). According to Fitts' Law, the average movement time is given by the following Equation (1):

$$\textit{Movement Time}\ (\mathrm{MT}) = a + b \cdot log_2(2D/W), \tag{1}$$

where $log_2(2D/W)$ is called the index of difficulty (ID) and represents the information transmitted in bits. The constants a and b are empirically determined through linear regression. About a decade later, a modified movement time equation was proposed by Welford (Kotani, Horii, & Kitamura, 2000; MacKenzie, Sellen, & Buxton, 1991; Murata, 1996; Soukoreff & MacKenzie, 1995). The modification was made because the original Fitts' Law was designed for one-dimensional movement. Two-dimensional movement is typically required for computer input pointing tasks (Kotani et al., 2000). Welford's modification of Fitts' Law is as follows:

$$\textit{Movement Time}\ (\mathrm{MT}) = a + b \cdot log_2(D/W + 0.5). \tag{2}$$

MacKenzie introduced another formulation of the movement time equation, originally suggested by Shannon (MacKenzie, 1992a; MacKenzie, Sellen, & Buxton, 1991). The formulation was slightly modified from Equation (2) on the basis of information theory, and MacKenzie indicated that the model provides more reasonable results by eliminating the possibility of negative ID values (Murata, 1996). In addition, he insisted that the model yields a better fit to empirical data. Shannon's formulation is as follows:

$$\textit{Movement Time}\ (\mathrm{MT}) = a + b \cdot log_2(D/W + 1). \tag{3}$$

The reciprocal of the regression slope, *b*, is called the *Index of Performance* (IP), or *bandwidth*, and is expressed in units of bits per second (bits/s). According to MacKenzie et al. (1991), IP is the rate of information processing for a given movement task, and is calculated by dividing a change in movement task ID by the corresponding change in movement time (MT) to complete the task. IP is regarded as an important performance metric to compare the performance of different device-task combinations. However, since people with differing degrees of impairment may perform at different skill levels on the speed-accuracy continuum for each device-task condition, the IP performance metric may also be used to determine the most appropriate input device for each person or homogeneous group of people within a given impairment range. Equation (4) shows the IP formulation (Rao, 1998; Soukoreff & MacKenzie, 1995):

$$\textit{Index of Performance}\ (\mathrm{IP}) = (\Delta ID)/(\Delta MT) = 1/b. \qquad (4)$$

To date, numerous studies applying Fitts' Law to the use of computer input devices involving a variety of limb and muscle groups have been conducted. Movement studies include wrist flexion and rotation (Crossman & Goodeve, 1983; Meyer, Kornblum, Abrams, Wright, & Smith, 1988; Kantowitz & Elvers, 1988), finger manipulation (Langolf, Chaffin, & Foulke, 1976), head movements (Jagacinski & Monk, 1985; Radwin, Vanderheiden, & Lin, 1990), and foot positioning movements (Drury, 1975). Several studies have also been conducted using people from special populations, including subjects with amyotrophic lateral sclerosis (ALS) and head injury (Rosen, Goodenough-Trepagnier, Getschow, & Felts, 1986), Parkinson's disease (Flowers, 1975), and cerebral palsy (Bravo, LeGare, Cook, & Hussey, 1990; Radwin et al., 1990; Rao, 1998). These studies utilized various computer input devices including the mouse, trackball, joystick, head-mounted pointing device, touchpad, and keyboard.

According to Radwin et al. (1990), a discrete movement target acquisition task based on Fitts' Law can be useful for evaluating and comparing alternative computer input pointing devices for people with severe motor impairments as well as for people without motor difficulties. Radwin et al. (1990) also found that Fitts' Law is a good tool to reveal delicate performance differences that cannot be observed visually. In addition, Jagacinski and Monk (1985) found that Fitts' Law is a good predictor of the speed-accuracy trade-off for two-dimensional discrete movements of the hand and head. Rao (1998) also confirmed the robustness of Fitts' Law when using a force joystick and a position joystick in a speed-accuracy trade-off model for people with cerebral palsy.

Akamatsu and MacKenzie (1996) investigated the effect of a multi-modal mouse incorporating tactile and force feedback with twelve non-disabled mouse users. They found that adding force feedback to tactile feedback generally reduces error rates for small targets. Their finding provides the potential for people with upper limb disabilities to improve their overall performance for computer input tasks regarding fine adjustments.

Applications for HCI modeling and design using Fitts' Law can be unlimited. Fitts' Law might be a good tool for assessing and comparing computer input tasks to determine characteristics of computer interfaces (MacKenzie, 1992a, 1992b). However, according to Gillan, Holden, Adam, Rudisill, and Magee (1990), Fitts' Law should be considered with individual differences and cognitive processes when various movement control results from the Fitts' Law model are applied to user interface design. In addition, user strategies for pointing and dragging movements are another important factor to be carefully investigated due to each user's unique preferences and characteristics. Also, Fitts' Law tests with various target angles provide a good modeling tool for the layout of graphical interfaces in the Windows environment (Jagacinski & Monk, 1985; Radwin et al., 1990).

CHAPTER 3

PROBLEM STATEMENT

From 1994 until 2000, economic growth in the U.S. achieved almost 4% per year due to the rapid development of information technology (IT). Moreover, with that steady growth, the unemployment rate dropped from 6% to 4% (Mandel, 2000). In spite of this good news, two-thirds of the people with disabilities (approximately 12 million skilled people with disabilities in the U.S.) were unemployed due to a lack of daily task assistance, lack of mobility assistance, or lack of access to assistive technology (Howey, 1995). The current advanced computerized IT society relies on intellectual human performance rather than just physical skills. Unemployed yet intellectually talented people with impairments could join the IT society if appropriate assistive technologies and tools were developed.

Despite the rapidly growing IT domain, there are still significant gaps between various assistive technologies for people with impairments and their accessibility to information technologies. People with disabilities are often overlooked as computer users during the assistive technology design process due to a lack of awareness, increased production cost, or insufficient market volumes. Moreover, the majority of impaired users are not able to freely access the current assistive technology due to budget constraints or a lack of information on assistive technology tools. Therefore, there exists a vital need to facilitate the delivery of assistive technology to people with upper-limb impairments. Figure 6 illustrates current problems in the use of computer input devices by people with functional limitations and the solutions outlined in this research.

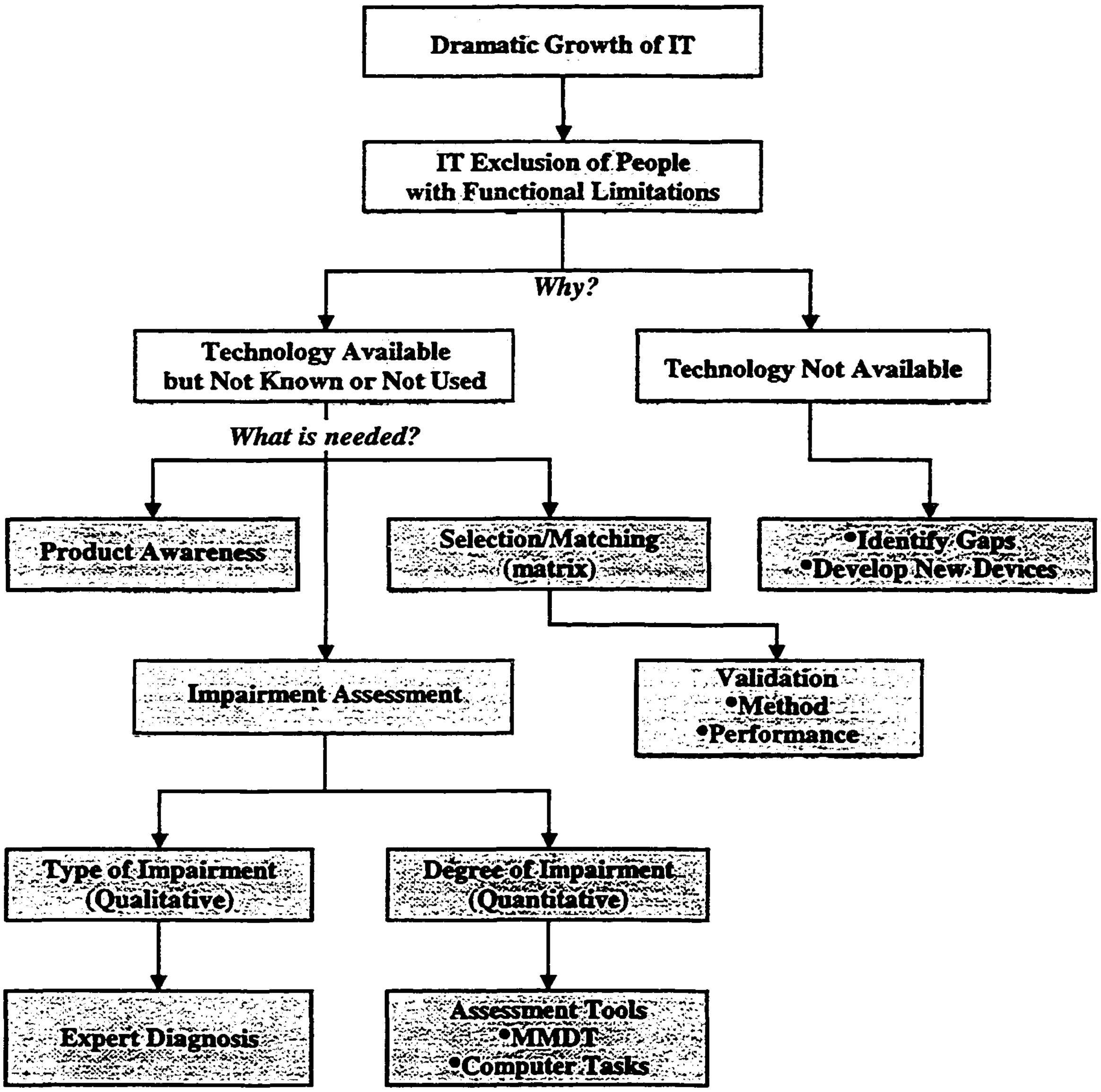


Figure 6. Logic Diagram for Facilitating Access of People with Functional Limitations to Information Technology.

People with motor impairments may be unable to use traditional input devices such as keyboards and mice. Therefore, several alternative input devices have been developed to provide accessibility for people with impairments of computer use. Those input devices are currently available as off-the-shelf products, through special order from assistive technology manufacturers, or as uniquely designed custom-made products. Even though assistive technologies are critically important to allow computer access to people with impairments, many people with impairments are not aware of the availability of those assistive technologies. Therefore, product information on current assistive technologies and sources of funding to acquire those assistive tools must be provided to people with impairments. In addition, clinicians often need assistance determining the appropriate input devices for a patient based on an assessment of that patient's impairment.

Determining the optimal associations between impairment type and assistive technology, and developing specifications for assistive technologies and tools are critical steps for improving access. These steps form the specific objectives of this dissertation. Assistive technology specifications may be met by currently available technology or may take the form of conceptual input devices. Through an extensive investigation of the research literature and the computer markets, currently available input devices and assistive technologies must be identified and delivered to people with impairments. In addition, concepts for improving assistive input devices must be described to provide specification information to designers. Based on this information, functional limitations must be mapped to assistive technology input devices that would facilitate computer use by people with motor impairments.

In order to validate whether a selection matrix can be useful in identifying appropriate input devices for people with motor impairments, the recommended devices must be tested for their usability by impaired people. This study was undertaken to develop and validate a model for assessment of the level of impairment for people with upper-limb motor impairments, and to develop a selection matrix of solutions that allows them to match the assistive technology solutions for input devices with their assessed level of functional limitations.

The primary goal of the research was to develop a matrix for recommending solutions which match assistive technology input devices to the assessed level of functional limitations. Traditional standardized tests for evaluating gross muscle performance and range of motion focus mainly on measuring the force and range of motion of various movements. Few assessment instruments designed for people with impairments or the elderly demonstrate reliability and validity and few exist that are relevant to computer tasks. Therefore, there exists a need to develop an assessment tool for predicting functional performance in computer input tasks.

This study also addressed the development of an appropriate dexterity test for assessing input device usage capabilities. A Fitts' Law task was used as the basis for evaluating the degree of functional limitations in computer pointing tasks. Therefore, a secondary goal of this study was to develop and validate a methodology for assessing the level of impairment for people with upper-limb motor impairments. The secondary research involving the assessment tool addressed the following questions:

- Is Fitts' Law a valid model of performance time for upper-limb motor impaired people?
- How well do the Fitts' Law Movement Time (MT) and Index of Performance (IP) measures associated with a computer-based target pointing task correlate with the results of the Minnesota Manual Dexterity Test (MMDT)?
- Does the IP measure provide a valid comparison of computer input devices for motor impaired people?
- How does the IP value for impaired people compare to that for unimpaired people?
- Are relative device differences consistent across impaired and unimpaired populations?

It is hoped that the results of this work will promote the development of creative solutions for computer access by people with motor impairments.

CHAPTER 4

DEVELOPMENT OF SELECTION MATRIX

This chapter presents the detailed process for developing specifications for assistive technology computer input devices and a selection matrix to match the assistive technology with the assessed level of motor impairment.

4.1 Development of Assistive Input Devices

In order to facilitate the development of assistive technology input devices for people with motor impairments, the following model is proposed (Figure 7). The model is driven by the requirements of people with motor impairments. If products possessing the required features are available, then those assistive devices can be used by the people with motor impairments. On the other hand, if the required features are not available, current technologies should be examined to decide whether the required features could be incorporated into new or existing products.

Once a product with the required features is available, the effectiveness should be assessed by usability testing. If the product does not satisfy the users' needs throughout the usability testing, then alternative products should be examined. If the users are satisfied with the product, the technology should be periodically reviewed to ensure that new alternatives are considered. Then, if the new alternatives are technically or economically feasible, the assistive technology should be updated to provide more enhanced accessibility to people with disabilities.

In Chapter 2, various types of impairments and conditions were reviewed. In order to match the types of motor impairments to appropriate advanced computer technologies, identification of the diseases and other causes of the impairment may be helpful. Table 11 presents the relationship between various impairments and their possible causes. As discussed in Section 2.2.2, the impairment classifications in Table 11 are based on the ability to use computer input devices rather than on clinical classifications. The adjacent bar graph ratings represent the level of disability that is characteristic of each condition.

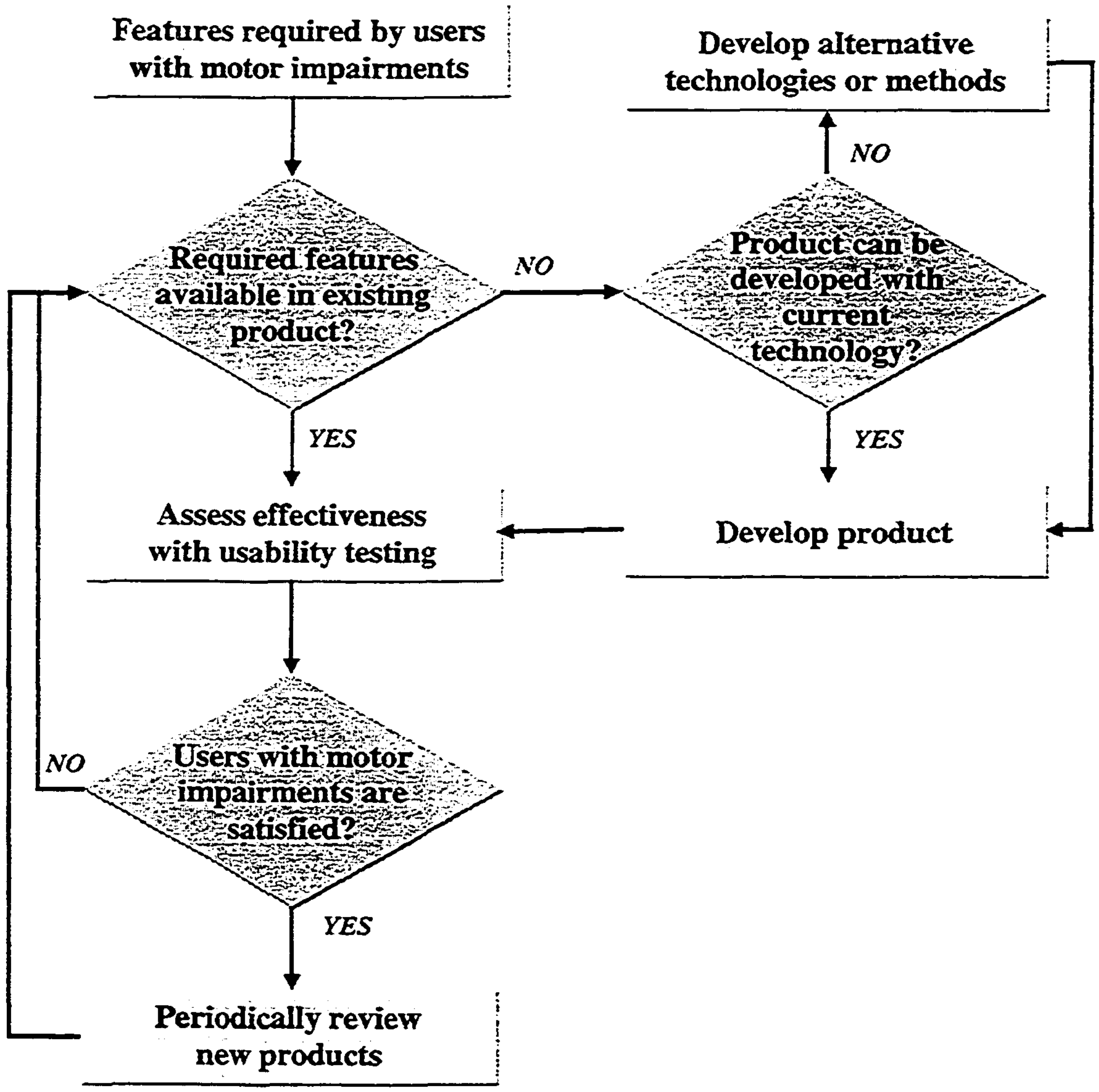


Figure 7. Flow Chart of Assistive Technology Development Model.

Table 11. Relationship Between Diseases and Typical Functional Limitations (Source: Disease, Condition or General Health Topic, 2001).

Disease/Cause	Weakness (Lack of Strength)	Upper Limb Joint Pain	Limited Range of Motion	Dysfunctional Movement (Apraxia)	Jerky Unpredictable Movement (Chorea)	Muscle Spasticity	Uncontrolled Slow Movement (Athetosis)	Muscle Atrophy (Loss of Tissue)	Poor Coordination (Ataxia)	Numbness and Tingling (Loss of Sensation)	Tremor	Muscle Rigidity (Stiffness)	Muscle or Skeletal Deformities	Muscle Function Loss (Paralysis)	Loss of Limbs
Arthritis	X	X		X										X	
Amputation/Congenital Deficiencies															X
Amyotrophic Lateral Sclerosis	X					X		X	X		X	X		X	
Ankylosing Spondylitis		X	X												
Carpal Tunnel Syndrome	X	X		X				X		X	X				
Cerebral Palsy	X		X			X	X		X	X	X		X	X	
Diabetes Mellitus	X							X	X	X	X				
Friedreich's Ataxia	X				X				X	X	X			X	
Guillain-Barre Syndrome	X	X	X	X				X	X	X			X	X	
Huntington Disease					X		X								
Multiple Sclerosis	X	X		X		X		X	X	X	X			X	
Muscular Dystrophy	X			X				X					X		
Myasthenia Gravis	X							X						X	
Osteoarthritis	X	X	X					X					X		
Osteoporosis	X	X	X												
Parkinson's Disease		X	X				X	X			X	X			
Peripheral Neuropathy	X	X		X				X		X				X	
Poliomyelitis	X	X						X				X		X	
Psoriatic Arthritis		X													
Rheumatoid Arthritis	X	X	X					X							
Spinal Cord Injury	X			X	X		X	X		X				X	
Stroke (Cerebrovascular Accident)	X			X	X	X			X	X				X	

For each of the impairments described in Table 11, Table 12 summarizes problems in using input devices and potential solutions that were recommended in the research literature (Anson, 1997; Casali, 1995; Edwards, 1995; Trace Center, 1988). These solutions formed the basis for the author's development of the matrix to match the functional limitation to the appropriate assistive tool. Note that the matching is based on type of impairment and does not incorporate degree of impairment. A detailed discussion of the development of the matrix is presented in the following section.

4.2 Development of Matrix

Precisely matching assistive technology input devices to a certain type of motor impairment would prove helpful in providing people with functional limitations greater accessibility to computer technology. In this section, currently available input device products are surveyed and a matrix that matches assistive input devices to different degrees of motor impairment is proposed.

4.2.1 Available Assistive Input Device Technology

To date, many computer input devices and solutions have been designed to facilitate the interface between people with motor impairments and computer input activities (DeJong & Brannont, 1998). To accommodate the needs of people with impairments, it is critical to incorporate new advanced technology in the design phase of product development. Information describing various organizations which support access to advanced assistive devices and information technologies, and funding sources for assistive technology tools for people with impairments is collected in Appendix C.

Advanced assistive technology products span a range from devices addressing mild disability to devices for severely disabled users. Moreover, the products can be in the form of either hardware or software. The most widely used conventional

Table 12. Assistive Technology Solutions for Functional Limitations.

Functional Limitations	Problems Using Input Devices	Suggested Assistive Input Device Technologies (References)
Weakness (lack of strength)	Difficulty in grasping or dragging	Touch pad/touch screen/light pen (Dix et al., 1998) On-screen keyboard (Anson, 1997; Bergman & Johnson, 1995; Lazzaro, 1996) MouseKeys (Anson, 1997; Bergman & Johnson, 1995)
Upper limb joint pain	Lack of manual dexterity	Ergonomic designed mouse and keyboard (Anson, 1997; Dix et al., 1998)
Limited range of Motion	Difficulty in reaching	Remote controllable keyboard and mouse (Anson, 1997; Lazzaro, 1996; McGregor et al., 1994) Trackball (McGregor, Arango, Fraser, & Kangas, 1994) Touch pad (Dix et al., 1998)
Dysfunctional movement (apraxia)	Problem making timed responses	Adjustable keyboard repeat rate (Trace Center, 1988) RepeatKeys (Trace Center, 1988; Trewin & Pain, 1998, 1999)
	Fine movement problem	Force joystick (McGregor et al., 1994) Keyguard (Anson, 1997; Lazzaro, 1996; Trace Center, 1988)
Jerky unpredictable movement (chorea)	Inadvertently bump extra keys	Keyguard (Anson, 1997; Lazzaro, 1996; Trace Center, 1988) Force joystick (McGregor et al., 1994) Trackball (McGregor et al., 1994) Speech input (Anson, 1997; Bergman & Johnson, 1995)
Muscle spasticity	Lack of manual dexterity	Adjustable keyboard repeat rate (Trace Center, 1988) RepeatKeys (Trace Center, 1988;Trewin & Pain, 1998, 1999)
Uncontrolled slow movement (athetosis)	Problem making timed responses	Adjustable keyboard repeat rate (Trace Center, 1988) RepeatKeys (Trace Center, 1988; Trewin & Pain, 1998, 1999)
Muscle atrophy (loss of tissue)	Problem making timed responses	Adjustable keyboard repeat rate (Trace Center, 1988) RepeatKeys (Trace Center, 1988; Trewin & Pain, 1998, 1999)
Poor coordination (ataxia)	Difficulty in finger coordination	Keyguard (Anson, 1997; Lazzaro, 1996; Trace Center, 1988) SlowKeys (Bergman & Johnson, 1995) RepeatKeys (Bergman & Johnson, 1995) Switch (Anson, 1997; Lazzaro, 1996) Force joystick (McGregor et al., 1994) Trackball (McGregor et al., 1994)/touch pad (Dix et al., 1998) Speech input (Anson, 1997; Bergman & Johnson, 1995)
Numbness and tingling (loss of sensation)	Lack of manual dexterity and fine adjustment	Sip-and-puff (Trace center, 1988) Eyegaze (Anson, 1997; Bergman & Johnson, 1995; Lazzaro, 1996) Speech input (Anson, 1997; Bergman & Johnson, 1995) Expanded keyboard (Anson, 1997; Lazzaro, 1996; McGregor et al, 1994) Head control/mouth control (McGregor et al, 1994)
Tremor	Inadvertently bump extra keys	Keyguard (Anson, 1997; Lazzaro, 1996; Trace Center, 1988) BounceKeys (Anson, 1997; Bergman & Johnson, 1995) Force joystick (McGregor et al., 1994) Trackball (McGregor et al., 1994) Speech input (Anson, 1997; Bergman & Johnson, 1995)
Muscle rigidity (stiffness) / Muscle or skeletal deformities	Lack of manual dexterity and fine adjustment	Sip-and-puff (Trace center, 1988) Eyegaze (Anson, 1997; Bergman & Johnson, 1995; Lazzaro, 1996) Speech input (Anson, 1997; Bergman & Johnson, 1995) Switch (Anson, 1997; Lazzaro, 1996) Head control/mouth control (McGregor et al, 1994)
Paralysis or limb loss - one arm or hand	Unable to activate multiple buttons/keys at the same time	StickyKeys/key latches (Anson, 1997; Lazzaro, 1996; Trewin & Pain, 1998, 1999)
	Limited range of motion	Mini keyboard (Anson, 1997; Lazzaro, 1996)
Paralysis or limb loss - both arms or hands	Unable to use arms and hands	Sip-and-puff (Trace center, 1988) Eyegaze (Anson, 1997; Bergman & Johnson, 1995; Lazzaro, 1996) Speech input (Anson, 1997; Bergman & Johnson, 1995) Footmouse (Bergman & Johnson, 1995) Head control/mouth control (McGregor et al, 1994)

hardware input devices are the keyboard and mouse. Alternatively, a number of software input devices employ programs that are designed to boost the use of computers by people with motor impairments. In this dissertation, both hardware and software solutions are considered to serve as an interface between different types of functional limitations and differing requirements of specific computer input tasks.

In general, alternative input devices are available as off-the-shelf products, through special order from assistive technology manufacturers, or as uniquely designed custom-made products. Table 13 summarizes the alternative input devices that are available in the year 2001. The available products in Table 13 were selected based on the suggested assistive input device technologies in Table 12. More detailed information about these products and their availability is provided in Appendix B.

4.2.2 Matrix for Matching Level of Impairments and Assistive Technology

This section presents the proposed selection matrix that matches assistive technology input devices to specific types of motor impairment. The selection matrix in Table 14 was developed to match each type of impairment and computer user capability requirements to the technology solutions that are summarized in Table 12. The rows of Table 14 present the various types of impairment, while computer task requirements are presented in the columns. The matrix suggests the most appropriate assistive technology for each combination of impairment and desired computer input task.

A form was developed to determine the most available and feasible input devices for individuals with specific upper-limb motor impairments (Figure 8). To identify the most appropriate input devices, the device requirements for performing computer input tasks with each assistive input device were enumerated. After careful assessment of the functional capabilities by a physical therapist/occupational therapist, the feasibility of each input device can be determined by comparing the device requirements to the user capabilities. If the user capability is greater than or equal to

Table 13. Available Alternative Input Device Products.

Device Type	Functional Limitations	Available Products
Keyboard modification	One-hand (limited range of motion, minimum finger travel required)	• Hand-held device (Magic Wand Keyboard) • Keyboard layout modification (Half-QWERTY one-handed keyboard)
	No arms or hands	• Mouth stick (Magic Wand Keyboard)
Mouse modification	No arms, severe shaking of hands (tremor)	• Clicking by other body parts (Switch Adapted Mouse)
	Lack of fine adjustment	• Evolution Mouse-Trak
Eye controlled input system	CP, spinal cord injuries, head injuries, MS (with good vision)	• Eyegaze communication system
Head controlled input system	CP, muscular dystrophy, spinal cord injuries, head injuries, MS (with good vision)	• Headmaster 2000 (with sip-and-puff control) • APT cordless Gyro-head mouse • Tracker 2000 (with sip-and-puff, optical switch, and laser option)
Mouth controlled input system	CP, spinal cord injuries, head injuries, MS (with good vision)	• JOUSE • QuadJoy (especially for Quadriplegia)
Controlled by touching (tactile)	Muscle weakness, low level of manual dexterity, muscle or skeletal deformities or lack of fine movement control	• WiVik on-screen keyboard • ScreenDoors 2000 on-screen keyboard • Cirque Touchpad
Control switch (mouse button replacement)	Low level of manual dexterity or lack of fine movement control	• Totally Active Surface • TASH MouseMovers • WISP and Magic Cursor
Speech recognition	No arms or severe shaking of hands (tremor)	• Apple Speech Recognition • Dragon Naturally Speaking • Via Voice Pro Elite

Table 14. Matrix for Matching Impairment with Assistive Technology.

Impairment	Capability Requirements	Technology Solutions: Cursor Control Task	Technology Solutions: Graphical Object Movement Task	Technology Solutions: Text Entry Task
Weakness (lack of strength)	weak, but with good finger control	F or O	F or O	I with (F or O)
Upper limb joint pain	has joint pain, but with full functionality	R	R	Q
Limited range of motion	with good finger control	F or O	F or O	B
Dysfunction movement (apraxia)	not with fine finger control, but can move stick	P	P	(B or Q) with J
	cannot control timed responses	P	P	Q with (X and Z)
Jerky unpredictable movement (chorea)	with good speech capability	G	K	H with G
	with at least one good finger control	F or O	F or O	(B or Q) with J
	without good finger control, but can move stick	P	P	H with P
Muscle spasticity / Uncontrolled slow movement (athetosis) / Muscle Atrophy (loss of tissue)	lack of finger dexterity, but with somewhat finger control	F or P	F or P	L with (X and Z)
Poor coordination (ataxia)	with poor coordination, but with somewhat finger control	F or P	S	L with (J, X and Y)
	with good speech capability	G	K	H with G
Numbness and tingling (loss of sensation)	with good eye movement control	D	K	H with D
	with good mouth control	C or M	K or M	H with (C or M)
	with good head movement control	E or N	K or N	H with (E or N)
	with good speech capability	G	K	H with G
Tremor	has mild tremor, but with somewhat finger control	F or P	F or P	L with (J and W)
	has severe tremor, but with good speech capability	G	K	H with G
Muscle rigidity (stiffness) / Muscle or skeletal deformities	with good eye movement control	D	K or S	H with D
	with good mouth control	C	K or S	H with C
	with good head movement control	E	K or S	H with E
	with good speech capability	G	K or S	H with G
Paralysis or limb loss - one arm or hand	with at least one good finger control	A or F or O	A or F or O	(A or B) with (U or V)
	mild or moderate difficulty, but not severe	R	R	Q with (U or V)
Paralysis or limb loss - both arms or hands	with good eye movement control	D	K	H with D
	with good mouth control	C or M	K or M	H with (C or M)
	with good head movement control	E or N	K or N	H with (E or N)
	with good speech capability	G	K	H with G
	with good foot control	T	K	H with T

Index of Technology Solutions	
A	Keyboard Layout Modification
B	Hand-Held (Mini) Keyboard
C	Mouth Stick
D	Eyegaze
E	Head Tracker
F	Trackball
G	Speech Recognition
H	Virtual On-Screen Keyboard (operated by remote sensing)
I	Virtual On-Screen Keyboard (operated by touching)
J	Keyguard
K	Sip-and-Puff
L	Expanded Keyboard
M	Mouth Joystick
N	Head Stick
O	Touchpad
P	Force Joystick
Q	Ergonomic Keyboard
R	Ergonomic Mouse
S	Switch
T	Footmouse
U	Keylatches
V	StickyKeys
W	BounceKeys
X	RepeatKeys
Y	SlowKeys
Z	Extend Keyboard Tolerance

Patient ID: D07 Impairment Type: Muscular Dystrophy Date: 06 / 12 / 2001

INSTRUCTION

1. Fill in user capability ratings.
2. Place a check mark in each cell for device requirements when the device requirement exceeds the user capability.
3. Select feasibility based on the most appropriate match between capabilities and requirements.
4. Compare the cost and availability among the selected feasible devices.

USER CAPABILITIES		DEVICE REQUIREMENTS: KEYBOARD MODIFICATION: EXPANDED KEYBOARD	KEYBOARD MODIFICATION: MINI KEYBOARD	KEYBOARD MODIFICATION: ON-SCREEN KEYBOARD	KEYBOARD SUPPORT: KEYGUARD	MOUSE MODIFICATION: HEAD TRACKING	MOUSE MODIFICATION: TRACKBALL	MOUSE MODIFICATION: JOYSTICK	MOUSE MODIFICATION: TOUCH PAD	MOUSE MODIFICATION: TOUCH SCREEN	MOUSE MODIFICATION: FOOT MOUSE	KEYBOARD & MOUSE MODIFICATION: SPEECH RECOGNITION
2	Finger Dexterity	1	2	0	1	0	1	1	2	2	0	0
2	Motor Control	1	2	2	1	0	1	1	1	2	1	0
0	Foot Dexterity	0	0	0	0	0	0	0	0	0	2 ✓	0
2	Eye Control	0	0	0	0	2	0	0	0	0	0	0
1	Breath Control/Support	0	0	0	0	1	0	0	0	0	0	2 ✓
1	Speech	0	0	0	0	0	0	0	0	0	0	2 ✓
2	Vision	1	1	2	1	2	1	1	2	2	1	0
2	Eye-Hand Coordination	1	2	2	1	0	1	1	2	2	0	0
1	Range of Motion (ROM)	2 ✓	2 ✓	0	2 ✓	0	1	1	1	2 ✓	1	0
	Feasibility (circle one)	YES / NO	YES / NO	YES / NO	YES / NO	YES / NO	YES / NO	YES / NO	YES / NO	YES / NO	YES / NO	YES / NO
	Cost ($)	$170-$400	$50-$250	$100-$400	$50-$70	$1600-$1900	$60-$100	$60-$450	$60	$260-$340	$100	$150-$250
	Availability	2	2	3	1 or 2	2	2 or 3	2 or 3	3	2	2	3

INDEX LEGEND

User Capabilities	0	Not Capable
	1	Moderately Capable
	2	Fully Capable
Device Requirements	0	Not Required
	1	Moderately Required
	2	Fully Required
Feasibility	YES	(User capabilities) ≥ (Device Requirements)
	NO	(User capabilities) < (Device Requirements)
Availability	1	Custom-made (unique prototype)
	2	Special order from AT manufacturer
	3	Available in the market (off-the-shelf)

FEASIBLE DEVICE SUGGESTIONS

1. On-Screen Keyboard: available in the market, but it is somewhat expensive.
2. Head Tracking: very expensive.
3. Trackball and Joystick: reasonable costs, and widely available.
4. Touch Pad: available in the market, and cost is reasonable.

➤ Trackball, Joystick, or Touch Pad should be recommended to the patient.

Figure 8. Sample Form for Selecting Appropriate Assistive Input Devices.

the device requirement, the assistive input device is feasible.

The currently available input devices were additionally evaluated in terms of cost and availability. Appendix B provides specific product availability and costs for various assistive input devices. When multiple devices are feasible, decisions might be based on the device availability and cost. Refinement of the matrix was one of the primary objectives of this dissertation, followed by validation of a subset of the matrix cells. In order to validate whether the matrix can be useful in selecting appropriate input devices for people with motor impairments, selected matrix cells were tested using a computer-based target pointing task based on Fitts' Law. The selected input devices and the target pointing task are discussed in detail in the following chapter.

CHAPTER 5

VALIDATION METHODOLOGY

Since numerous computer assistive tools are currently available, validation of the selection matrix that was proposed in Chapter 4 is necessary to confirm the optimal selection of assistive technology as a function of the impairment assessment and the desired computer tasks. The overall framework for the methodology of validation, the constraints and limitations, participant selection, experimental procedures, and statistical design are also addressed.

5.1 Validation Procedure

In order to validate the selection methodology, a series of steps is applied as presented in Figure 9. The first step is to select participants spanning a broad range of impairment types and degrees. Then, a careful assessment of the type and degree of impairment must be made for the selected participants. To date, even though various physical dexterity tests have been developed and used for evaluating manual dexterity, computer-based tests of functional dexterity for evaluating computer input devices have been neither fully explored nor applied by physical therapy/occupational therapy experts or assistive technology developers. General types of functional limitation were identified in the previous chapter (Table 11).

In the third step, the form in Figure 8 should be completed to determine the matrix recommendation. As presented in Chapter 4, the matrix for selecting assistive computer input devices for people with upper-limb motor impairments was developed based on an extensive literature review. The most appropriate computer input devices for people with upper-limb motor impairments can be chosen with consideration of the cost-performance tradeoffs, feasibility, and availability. Cost information and availability information can be acquired using a thorough market survey (as provided in Appendix B).

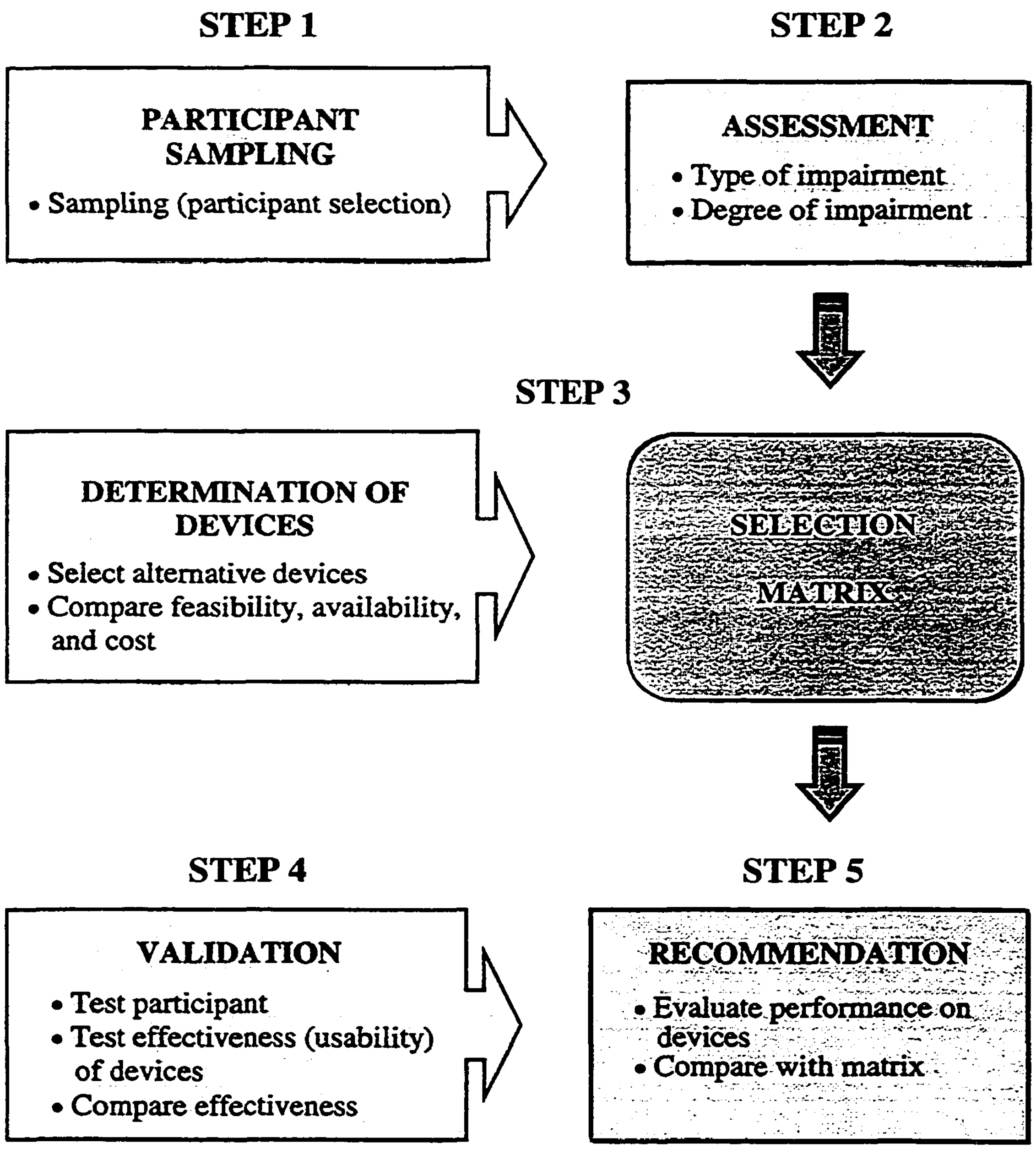


Figure 9. Procedure for Validating the Proposed Matrix for Selecting Assistive Computer Input Devices.

In the fourth step, each participant should be tested using the recommended device and other devices for comparison. The fifth step is to evaluate performance using the devices and compare the results with the matrix recommendation. The entire procedure should be continued until the impairment structure has been fully tested.

In this study, physical therapy/occupational therapy (PT/OT) experts were consulted to identify existing tools currently being used by clinicians to assess the degree of functional limitation. Various resources were reviewed and many professionals were contacted. However, no standard assessment tools were identified that specifically assess the degree of impairment relevant to the use of computer input devices by people with upper-limb motor impairments. Since the Minnesota Manual Dexterity Test (MMDT) reviewed in Section 2.2.3 uses relatively large objects manipulated with the hands and fingers, the MMDT was used to assess degree of impairment and to examine the relationship between manual dexterity test scores and input device performance. Therefore, in the second step, the type and degree of impairment for each participant were assessed by using the MMDT and expert opinions.

This study also proposed a more precise computer-based dexterity test based on Fitts' Law. The test measures the time required to move a displayed cursor to targets of various sizes and at differing distances. This same computer-based test was also used to evaluate the performance of various input devices. In this research, the proposed matrix was partially validated with three pre-selected input devices (Joystick, Trackball, and Mouse). The detailed experimental methodologies for the steps accomplished in this research are presented in the following sections.

5.2 Participant Selection

Participants were sampled from two populations: people with and without impairments. A control group of 23 participants without impairments was recruited from the student population of the University of Oklahoma (OU). An additional 11 participants with upper-limb motor impairments formed the main study group, recruited through the Oklahoma Assistive Technology Center (OATC) and the Assistive Technology Work Project at the University of Oklahoma Health Sciences Center.

The participant characteristics are summarized in Table 15. The overall number of participants was 34 (18 males and 16 females). The ages of the 23 participants (14 males and 9 females) in the unimpaired group ranged from 18 to 41 years, with a mean of 28.2 years and a standard deviation of 5.7 years. The ages of the 11 participants (4 males and 7 females) in the impaired group ranged from 15 to 41 years, with a mean of 25.8 years and a standard deviation of 10.0 years. The overall age range was 15 to 41 years, with a mean age of 27.4 years (28.5 for males and 26.2 for females) and a standard deviation of 7.3 years. All participants were unpaid volunteers, but an appreciation gift was provided to the impaired group participants upon completion of the testing.

Table 15. Participant Characteristics Summary.

Group	**Unimpaired (23 Participants)**		**Impaired (11 Participants)**	
Gender	**Male**	**Female**	**Male**	**Female**
Number	14	9	4	7
Mean Age	28.6	27.6	28.3	24.4
SD* Age	5.0	6.8	9.0	10.9
Min Age	21	18	16	15
Max Age	37	41	36	41
Group Mean Age	28.2		25.8	
Group SD* Age	5.7		10.0	
Total Mean Age	27.4 (Male: 28.5, Female: 26.2)			
Total SD* Age	7.3 (Male: 5.8, Female: 8.6)			

Note: SD = Standard Deviation.

People in the impaired group were identified and recruited with the help of trained physical therapists at OATC. Only persons who were expected to have limitations that may affect input device operation were selected as candidate participants. In addition, participants were screened for known cognitive impairments by the physical therapists at OATC. Those participants with potential cognitive impairments were excluded from the study.

For each of the impaired participants, Table 16 provides information on the type of impairment, time since onset of the impairment, and input device interaction technique commonly used. A short narrative describing each of the impaired participants follows.

Table 16. Participant Sample of the Impaired Group.

ID	Type of Impairment	Years Since Onset	Input Device Interaction Technique
D01	Cerebral Palsy	36 (from birth)	performed as the unimpaired group participants
D02	Cerebral Palsy	27 (from birth)	performed as the unimpaired group participants
D03	Cerebral Palsy	36 (from birth)	put the joystick controller between index finger and middle finger; used index finger for the trackball; used index finger to push the mouse
D04	Cerebral Palsy	29 (from birth)	performed as the unimpaired group participants
D05	Spina Bifida	15 (from birth)	used palm to move the joystick; used thumb for the trackball
D06	Multiple Disabilities	11 (from age 5 years)	used outside of thumb for rolling the trackball; only slid the mouse to move
D07	Muscular Dystrophy	15 (from birth)	used outside of index finger for rolling the trackball; used index finger to push the mouse
D08	Head Injury	15 (from age 9 months)	used palm for rolling the trackball
D09	Quadriplegia (C3)	27 (from October 1974)	used thumb and palm for rolling the trackball
D10	Quadriplegia (C5)	10 (from May 1991)	performed as the unimpaired group participants
D11	Multiple Disabilities	17 (from age 2½ years)	used palm to push the joystick; used thumb and index finger for rolling the trackball; used palm to move the mouse

- Participant D01 was a 36-year old man with cerebral palsy who had moderate difficulty controlling his upper limbs. He also had a moderate speech impairment. Since he usually used computers at his work, he had moderate experience in the use of computers.

- Participant D02 was a 27-year old man with cerebral palsy who experienced mild difficulty using input devices. This participant had more severe difficulty controlling his lower limbs. He had a successful computer experience with a PC at home.

- Participant D03 was a 36-year old woman with cerebral palsy who had very severe difficulty in controlling motions involving both her upper limbs and lower limbs. She also had a severe communication disorder. She had a minimal level of computer experience at her local care center. She had particular difficulties adjusting the pointer to the small target during the test. She also had difficulties in grasping and lifting the mouse to move it around. She was only able to use her index finger to operate the devices.

- Participant D04 was a 29-year old woman with cerebral palsy who had very mild impairment in her upper body. She had mildly impaired eyesight and had the most difficulty in controlling her lower limbs. She had moderate computer experience.

- Participant D05 was a 15-year old high school girl with spina bifida who had severe difficulty grabbing input devices due to a deformity in her hand. Her left hand was slightly more severe than her right hand. She was moderately experienced in computer use at school and at home. She typically used a mouse with her right hand as an input device.

- Participant D06 was a 16-year old high school boy with multiple orthopedic spine disabilities. He had moderate computer experience at home and at school. He manipulated the input devices predominantly with the palm and thumb of his left hand.

- Participant D07 was a 15-year old high school girl with muscular dystrophy. Since she had very low body strength, she was not able to perform the MMDT. In addition, she faced great difficulties interacting with the joystick and trackball due to the weakness of her hand and fingers. She used a mouse at home set to a very high sensitivity to avoid a wide range of finger or hand movement.

- Participant D08 was a 16-year old high school girl whose impairment was caused by a head injury when she was 9 months old. She was dropped by her baby sitter and the damage affected the right side of her body. She is blind in her right eye, and the right side of her body is partially paralyzed. She had difficulty with coordination, especially for small targets. Although her left hand was not severely affected, she performed all the tests in this study with her right hand to demonstrate the difficulties she experienced.

- Participant D09 was a 41-year old woman with a spinal cord injury (C3 quadriplegia) due to a gun shot accident as a teenager. She has lost all sensation in her arms and hands. She had never used a computer before the test. However, since she has experienced 27 years of using a wheel chair joystick controller, she performed very well with the joystick during the test sessions.

- Participant D10 was a 34-year old man with a spinal cord injury (C5 quadriplegia) due to a diving accident in a lake. His impairments mostly affected his lower-body. He had moderate experience in the use of computers. Thus, he performed the task with minor difficulties compared to the other impaired participants.

- Participant D11 was a 19-year old high school girl with multiple disabilities. Her symptoms began at the age of two and a half years. She had a moderate speech impairment. She was moderately experienced in computer use at school.

5.3. Assessment of Impairment Level

To assess the level of impairment for each participant, the completion times for the MMDT test were compared and the relative performance was then grouped into three categories reflecting mild, moderate, and severe levels of impairment. The results of the assessment procedures are presented in Section 6.3.

Individual differences in the performance of the impaired participants on the computer-based target pointing task may also provide a valid assessment tool. The movement time (MT) and index of performance (IP) scores for each impaired participant based on the Fitts' Law model were grouped into the same three categories used for the MMDT test. Sections 6.8.2 and 6.8.4 provide the results from the experiment. In addition, the categorization results based on both the MMDT and the IP measures are summarized in Section 7.1.

5.4 Determination of Feasible Input Devices

The form proposed in Section 4.2.2 (Figure 8) was used to determine which device(s) would be appropriate for each impaired participant based on his/her ability to use input devices. After careful completion of the form for each of the impaired participants, Table 17 was developed to suggest feasible input devices. These suggestions were then cross-checked with the proposed devices in Table 14. Among all feasible input devices, a joystick and a trackball were selected to partially validate the selection matrix to examine how accurately the matrix recommends appropriate input devices for people with impairments. In addition, a standard mouse was selected for comparison.

5.5 Experimental Tasks

Two experimental tasks were employed in this study to assess the dexterity level of the participants as input to the proposed matrix to determine the most appropriate input device. The Minnesota Manual Dexterity Test (MMDT) was used to assess participant dexterity, and a discrete movement computer-based target pointing task was incorporated to measure computer input task performance. The computer task also provided a more precise measure of dexterity in an operationally relevant setting.

5.5.1 Minnesota Manual Dexterity Test (MMDT)

To assess each participant's degree of impairment, the Minnesota Manual Dexterity Test (MMDT) was employed. The test evaluates the eye-hand coordination necessary for many computer input tasks using various input devices. This test uses a board that has spaces to hold 58 round blocks. Detailed procedures for the MMDT are presented in Section 5.8.1.

Table 17. Feasible Input Devices for the Impaired Group Participants.

ID	Type of Impairment	User Capability	Feasible Input Devices
D01	Cerebral Palsy	• Some finger control • Good head movement	• Expanded Keyboard with Keyguard • Head Tracking • Trackball or Joystick
D02	Cerebral Palsy	• Some finger control • Lack of range of motion, but at least one good finger control • Good head movement	• Expanded Keyboard or Mini Keyboard with Keyguard, or On-Screen Keyboard • Head Tracking • Trackball or Joystick • Touch Pad or Touch Screen
D03	Cerebral Palsy	• Some finger control	• Trackball or Joystick
D04	Cerebral Palsy	• Some finger control • Lack of eye movement • Clear voice	• Expanded Keyboard or Mini Keyboard with Keyguard • Trackball or Joystick • Speech Recognition
D05	Spina Bifida	• Good head movement • At least one good finger control • Clear voice	• Head Tracking • Trackball or Joystick • Speech Recognition
D06	Multiple Disabilities	• Some finger control • At least one good finger control • Good head movement • Clear voice	• Expanded Keyboard or On-Screen Keyboard with Keyguard • Head Tracking • Trackball or Joystick • Speech Recognition
D07	Muscular Dystrophy	• Lack of finger control • Weak strength • Good head movement • Lack of range of motion	• On-Screen Keyboard • Head Tracking • Trackball or Joystick • Touch Pad
D08	Head Injury	• Some finger control • Good foot control • Clear voice	• Expanded Keyboard with Keyguard • Trackball or Joystick • Foot Mouse • Speech Recognition
D09	Quadriplegia (C3)	• Some finger control • Good head movement • Clear voice	• Head Tracking • Trackball or Joystick • Speech Recognition
D10	Quadriplegia (C5)	• Some finger control • Lack of range of motion, but at least one good finger control • Good head movement	• Expanded Keyboard, Mini Keyboard, or On-Screen Keyboard with Keyguard • Head Tracking • Trackball or Joystick • Touch Pad or Touch Screen • Speech Recognition
D11	Multiple Disabilities	• Some finger control • Good head movement • Clear voice	• Head Tracking • Trackball or Joystick • Speech Recognition

5.5.2 Computer-Based Target Pointing Task

A discrete movement target pointing task based on Fitts' Law was developed by Soukoreff and MacKenzie (1995). The task was used to examine the effectiveness of various input devices when used by people with motor impairments. Based on the performance and accuracy results of the test, the most appropriate assistive tool for each type of impairment was determined. These results were compared to the device recommended by the selection matrix.

5.5.2.1 Fitts' Law Software

Soukoreff and MacKenzie (1995) developed the Generalized Fitts' Law Model Builder (GFLMB), a software tool that allows the experimenter to design experiments, capture data, and build models based on applying Fitts' Law. For research purposes, this software is available to the public. Since the GFLMB software runs very accurately and effectively for various computer input pointing devices (Soukoreff & MacKenzie, 1995), the software has been widely used by many researchers. Figure 10 shows the basic task presented by the GFLMB software.

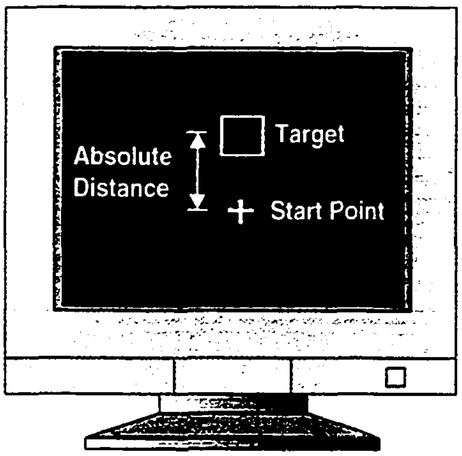


Figure 10. Display of Computer-Based Target Pointing Task.

Before the test started, the aspect ratio of the display screen was calibrated to present accurate target sizes and movement amplitudes. When the aspect ratio option was selected, one white box was displayed. Using the arrow keys on the keyboard, this box was then adjusted to measure 8 cm on each side. The GFLMB software configuration file was modified to specify the desired input elements. Figure 11 shows a configuration of the GFLMB software for a run using the mouse as the input device.

```
#
#  Config file for GFLMB version 1.1c
#
Device: Mouse
TaskType: Discrete Pointing
TaskBeginning: Immediate
TaskEnding: Dwell Time
Target: Square
ErrorBeep: Yes
PracticeSession: No
AmplitudeConditions: 40,80,160
WidthConditions: 5,15,25
HeightConditions:
AngleConditions: 0,90,225
TrialsPerCondition: 1
CDGainConditions: 1
DwellTime: 500
TargetTextFile: textfile
ExtraFactors:
AspectRatioX: 2.1
AspectRatioY: 2.1125
```

Figure 11. Contents of a Configuration File.

At the start of the runs, the participants were instructed to move the cursor over the target area and remain inside the box for a brief period. The "DwellTime" function was provided to aid target selection by disabled participants. The target was considered successfully acquired when the cursor entered the target area and remained inside the box for more than 500 milliseconds (ms). If the cursor overshot the target or otherwise stayed inside the target area for less than 500 ms, the monitoring continued until the 500 ms criterion was satisfied. The program automatically stored the task results in computer data storage.

5.5.2.2 Selected Testing Elements

In this section, the selected testing parameters for the software are presented. The main configuration elements, target size, movement amplitude, movement direction, and control-display gain, are discussed in detail.

Target Size

The choices of target size and movement amplitude were limited by the 20-inch screen size, and were related to the actual size of icons available in the current Microsoft® Windows environment. That is, these target sizes and distances are representative of the range typically encountered in graphics and word processing task environments (Casali, 1991; Epps, 1986; Rao, 1998).

Murata (1996) empirically demonstrated that the performance of target pointing tasks was best when the square target was used. Hence, for this research, each target was square in shape. Target size had three levels of width: 5, 15, and 25 mm (Figure 12).

Movement Amplitude

Target distance from the start point to the center of the target had three levels: 40, 80, and 160 mm (Figure 12). These distances are representative of the range typically encountered in various graphical user interfaces in current computer input tasks (Epps, 1986).

Movement Direction

The movement directions used in this study were 0 (East), 90 (North), and 225 (Southwest) degrees. Movement to the East involved a lateral movement in the transverse plane with the left or right hand moving away from the sagittal plane, while movement to the North involved a horizontal movement in the transverse plane with the left or right hand moving anterior to the frontal plane. In addition, movement in the Southwest direction involved a diagonal posterior movement in the transverse plane from a lateral to a medial position.

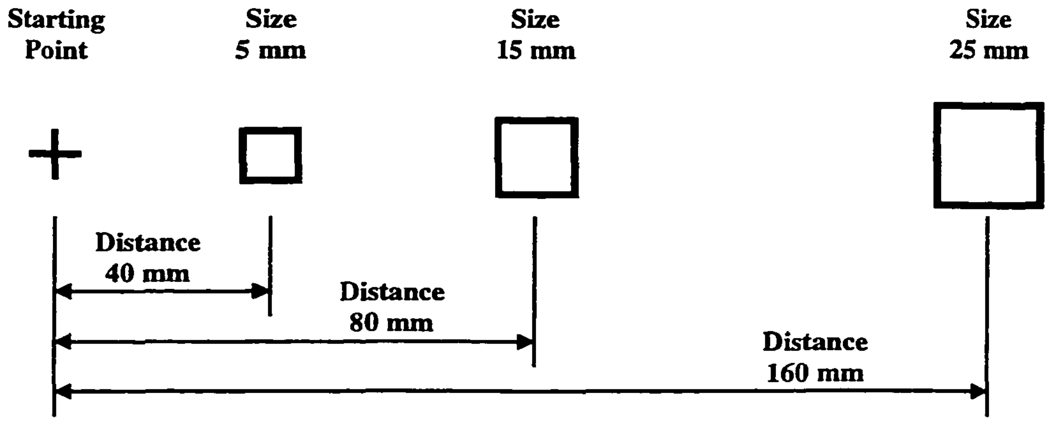


Figure 12. Target Sizes and Movement Amplitudes.

Within each run, the three movement directions were intermixed in a randomized sequence. Based on a lack of significant differences between the North and Southwest directions for the unimpaired participant group, only the East and North directions were tested for the impaired group. In general, the impaired participant group took much longer to complete the experiment. Therefore, this reduction in the number of directions helped reduce fatigue for the impaired group. As shown in Table 18, the movement rate of the GFLMB Fitts' Law software was designed to be different for each direction. The movement rate for the East direction was exactly two times faster than the North direction.

Table 18. **Required Movement Rate for Each Direction with Movement Amplitude of 40 mm in the GFLMB Software.**

CD Gain	Required Number of Clicks	
	East	North
0.5	160	320
1.0	80	160
2.0	40	80

The joystick is operated by pushing and pulling a vertical stick using a finger or palm of the hand to move the computer cursor. A spring-loaded force returns the stick to the center position when the stick is released. This force requirement may prove difficult for people with an impairment. People with muscle weakness may lack the strength needed to operate the joystick. Therefore, the force required to operate the joystick should be adjustable for use by people with an impairment. The cursor will move in accordance with the direction of stick movement. The trackball is operated by rolling a large ball in the transverse plane using a finger or palm of the hand. The cursor remains at the position where the ball is stopped. The trackball requires minimal force to operate. The mouse is operated by moving the device in the desired direction. Difficulty is encountered by people with impairments because the mouse must be occasionally repositioned by grasping, lifting, and moving.

Control-Display Gain

The control-display (CD) gain refers to the relationship between displacement of the input device and displacement of the cursor. The CD gains used in this study were 0.5 and 1.0. Although the CD gain may be fixed to the specified level in software, the devices can respond at different actual gains. Among the selected input devices, the allowable movement speed of the mouse was the fastest, the movement speed of the trackball was slightly slower, and the speed of the joystick was the slowest. Two different CD gains were tested for each input device to help determine appropriate CD gain parameters (and device movement speeds) to be used by people with various impairments.

Test Session

There were three sessions: Practice, Main 1, and Main 2. Each session consisted of six runs made up of combinations of the three devices and the two CD gains. In each run, each combination of target size, movement amplitude, and movement direction appeared four times in random order (Figure 10). Each unimpaired participant responded to 108 targets (3 target sizes, 3 movement amplitudes, 3 movement directions, and 4 replications) in each run using each input device. Participants were insrtructed to equally weight speed and accuracy in completing the tasks.

Participants were allowed to rest between runs for approximately two minutes. During this resting period, participants were encouraged to stretch their arms and hands, and to relax their fingers. Since the impaired participants performed only two movement directions, each impaired participant pointed to 72 targets in each run (3 target sizes, 3 movement amplitudes, 2 movement directions, and 4 replications).

5.6 Equipment

This section describes in detail the experimental tasks for this research. The equipment used in this research is presented in two categories: equipment for the MMDT and equipment for the computer-based target pointing task containing computer requirements and input devices.

5.6.1 Minnesota Manual Dexterity Test (MMDT)

An MMDT (Model 32023) from Lafayette Instrument Company was used (Figure 13). The equipment was borrowed from the Department of Health and Sport Sciences (HSS) at the University of Oklahoma for this study. To measure the completion time of each run, a stop watch (Micronta LCD electronic stopwatch: Model No. 63-5012) was used. Detailed procedures for this test are presented in Section 5.8.1.

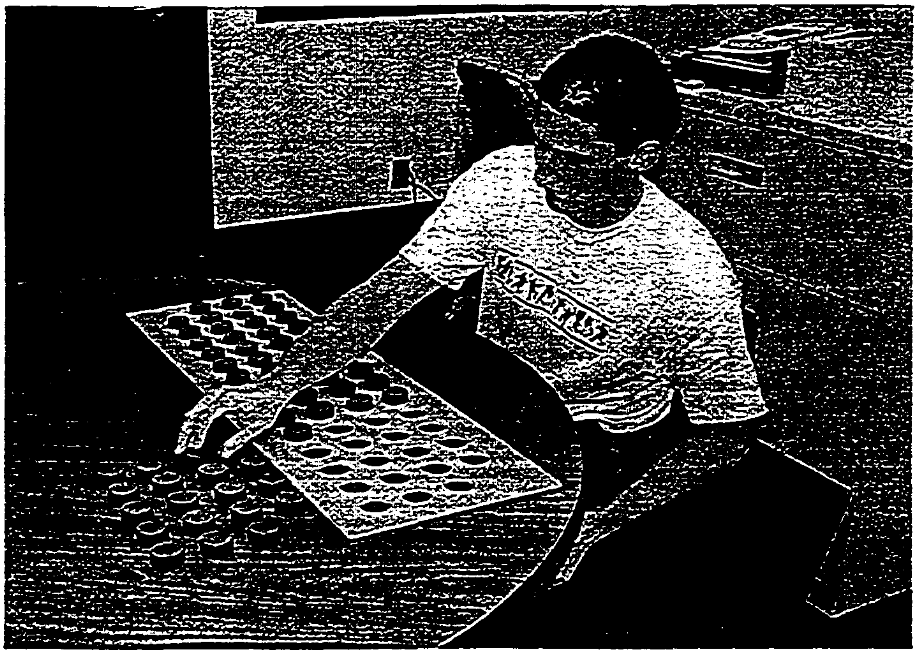


Figure 13. Minnesota Manual Dexterity Test: Model 32023.

5.6.2 Computer-Based Target Pointing Task

The computer and input devices used in the computer-based target pointing task are presented in this section. Specifications of the computer system and selection criteria for the tested input devices are also summarized.

5.6.2.1 Computer

The main control computer was a Dell® Inspiron 7500 laptop computer with an Intel® Pentium III Processor running at 700 MHz. The laptop computer provided full mobile access to participants that could not easily travel to the testing site. The computer had 192 MB Synchronous Dynamic Random Access Memory (SDRAM).

The output display was a Dell® UltraScan 20-inch (19.0 inches viewable image size) Trinitron D2026T-HS color monitor with a resolution of 1280 pixels (horizontal) by 1024 lines (vertical) and 0.26 mm per pixel dot pitch. For consistency, the same computer was used throughout all testing. Figure 14 shows the computer and input devices used in this study. The operating system used was Microsoft® Windows 98 Second Edition. The cursor motion speed setting, which is controlled under the "Mouse" option in the "Control Panel", was set at the fastest option for all of the devices.

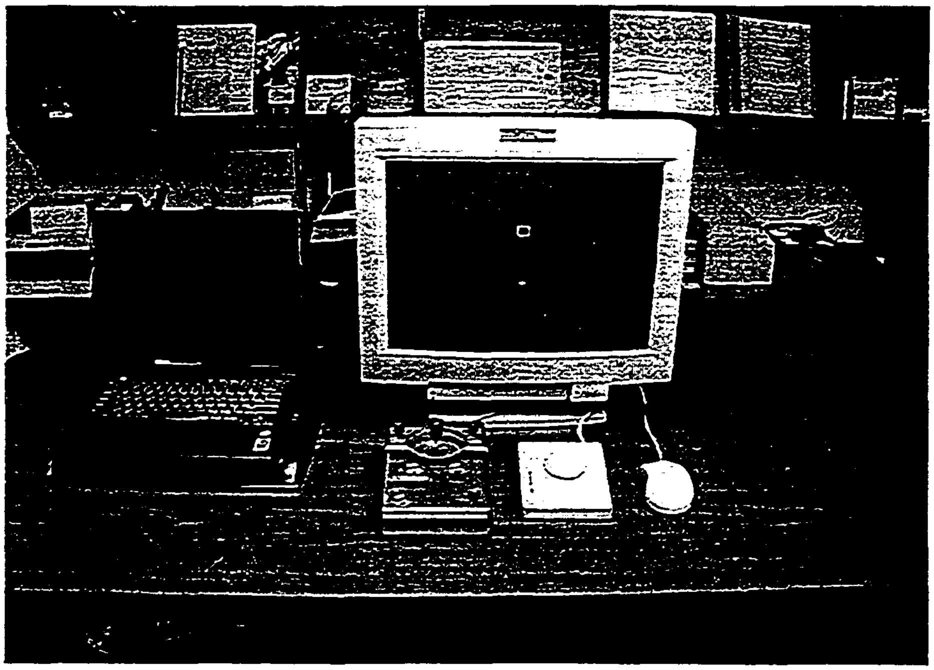
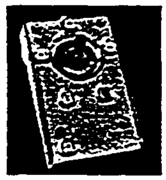
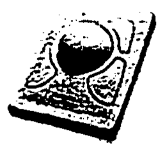


Figure 14. Main Control Computer and Input Device Set-Up.

5.6.2.2 Input Devices

As presented in Tables 12 and 13, numerous assistive input devices are currently available. Three devices that are most widely used by people with motor impairments were evaluated (Table 19). The selection criteria for the input devices

Table 19. Tested Input Devices and Specifications.

Input Device	Feature and Model	Specifications
Joystick	 Penny & Giles® Joystick Plus	▸ Rate-controlled, nonlinear force joystick ▸ Dimensions: 134 x 215 x 100 mm (W x L x H) Mouse cursor stays in position when joystick is released. Red light indicates drag button is active. Button presses require 2.25 oz. pressure. Removable handguard helps to locate and target buttons.
Trackball	 Kensington® Expert Mouse Trackball	▸ Rate-controlled, nonlinear displacement trackball ▸ Dimensions: 114 x 146 x 65 mm (W x L x H) Four extra-large buttons are easy to click, comfortable to use. Free high-powered software saves time by reducing repetitive tasks. Large ball offers more control and precision, less hand and arm movement. Symmetrical design fits left- and-right-handed users and all hand sizes.
Standard Mouse	 Microsoft® Mouse	▸ Rate-controlled, nonlinear displacement mouse ▸ Dimensions: 65 x 115 x 40 mm (W x L x H) This mouse is a standard, basic mouse with two buttons that fits a range of hand sizes and is comfortable for either left- or right-handed users.

were based on the relationship between people's level of upper-limb dexterity for using input devices and the device manipulation requirements.

As shown in Figure 15, the three input devices were selected to test a range of performance for various levels of upper-limb dexterity and device manipulation requirements. Based on previous research (MacKenzie, 1992a), a standard mouse requires a high level of upper-limb dexterity and a high level of device manipulation requirements, while a trackball requires a low level of upper limb dexterity and a low level of device manipulation requirements. The requirements of a joystick fall between these levels. Although higher technology assistive tools (e.g., eyegaze, speech recognition, sip-and-puff, head tracking systems) may be recommended for some individuals, the devices tested in this study were limited to those requiring manual contact with the device.

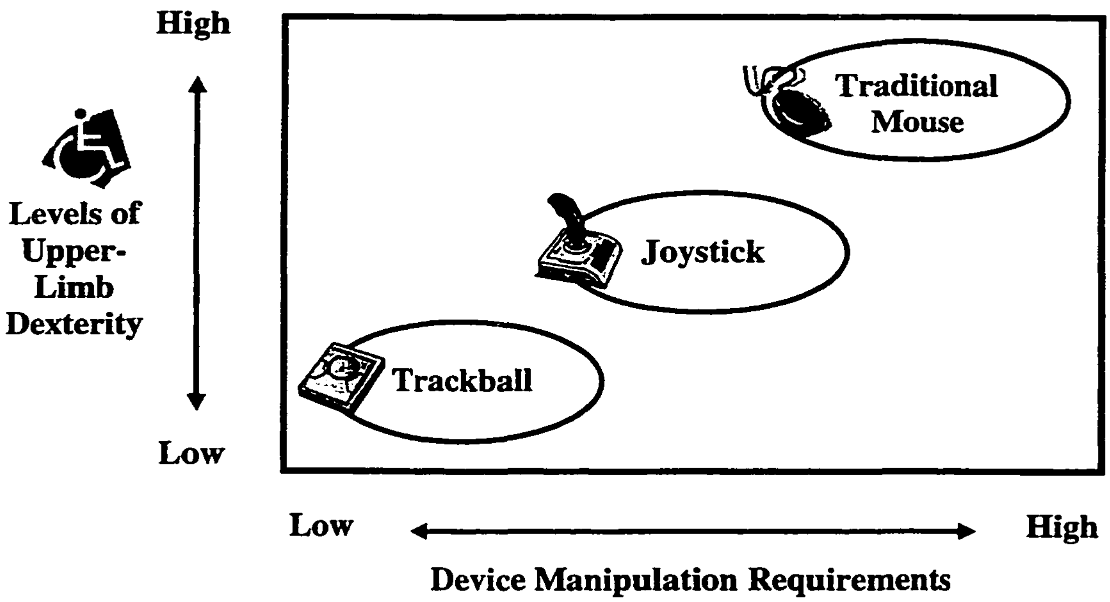


Figure 15. Relationship of the Selected Devices Between Levels of Upper-Limb Dexterity and Device Manipulation Requirements.

5.7 Test Facilities

For the convenience of each participant, the experiment was conducted in several different places: the University of Oklahoma (OU) Norman Campus for the unimpaired participants (participants S01 to S23), the Oklahoma Assistive Technology Center (OATC) Computer Lab at the University of Oklahoma Health Sciences Center (participants D01 to D04), Putnam City North High School in Oklahoma City, Oklahoma (participants D05 to D08), Midwest City High School in Midwest City, Oklahoma (participant D11), and at private residences (participant D09 in Norman, Oklahoma and participant D10 in Del City, Oklahoma).

For the group of people without upper-limb impairments, all testing was conducted in a laboratory space located on the second floor of Carson Engineering Center (CEC) at the University of Oklahoma. Two testing workstations (Bevis CTI Walnut Folding Table) approximately 152 cm wide and 76 cm deep were located in CEC Room 217. The MMDT was conducted on a table at a height of 77 cm. Computers and testing devices for the computer-based target pointing task were also placed at the same height. The testing room was equipped with centrally controlled heating and air conditioning systems.

For the participants with upper-limb impairments, the test environment was similarly controlled. In order to maintain consistent testing conditions, all equipment, including the computer hardware, the MMDT, input devices, and tables were brought to the remote testing sites.

5.8 Experimental Procedure

Once participants confirmed participation in this study, a testing schedule was arranged to suit their convenience. Before starting the main task, participants were asked to carefully read and sign an informed consent form (Appendix D). For each high school student in the impaired group, a parental informed consent form was completed as well as an informed assent form (Appendix E). For the group with impairments, a video recorder was used with permission to record their informed consent, and for observing the participants' behavior during data collection. The participants were asked to spend a sufficient time reading both the MMDT and computer-based target pointing task instructions (Appendix F). Figure 16 is a schematic representation of the experimental procedures for both tasks.

The experiment consisted of two tests: an MMDT dexterity test and a computer-based target pointing test. The time required to complete the testing was estimated at approximately two hours. All tests were completed in one day to minimize travel to the testing site. After completing the tests, the participant was asked to fill out a participant survey form (Appendix G). The form asked personal information, including gender, age, and handedness, and solicited the participant's preference for different input devices.

5.8.1 Procedures for MMDT

The primary objective of the MMDT is to see how quickly an individual can place the 58 blocks one at a time in order into the holes. Participants were provided one run to practice performing the test. They were asked not to strive for speed during the practice run since it did not count in their score. The test was begun from either the right or left side, depending on handedness. In the case of a right-handed participant, the task started by placing the bottom right block into the top hole at the right edge. Then, the block second from the bottom on the right was to be placed into the second hole from the top at the right. The participant repeated this procedure for the rest of the columns, working from right to left, until finished putting in the rest of the blocks. The participant was allowed to use only one hand, either right or left and was encouraged to rest the free hand on the board if desired. The experimenter demonstrated the procedure before the test was started.

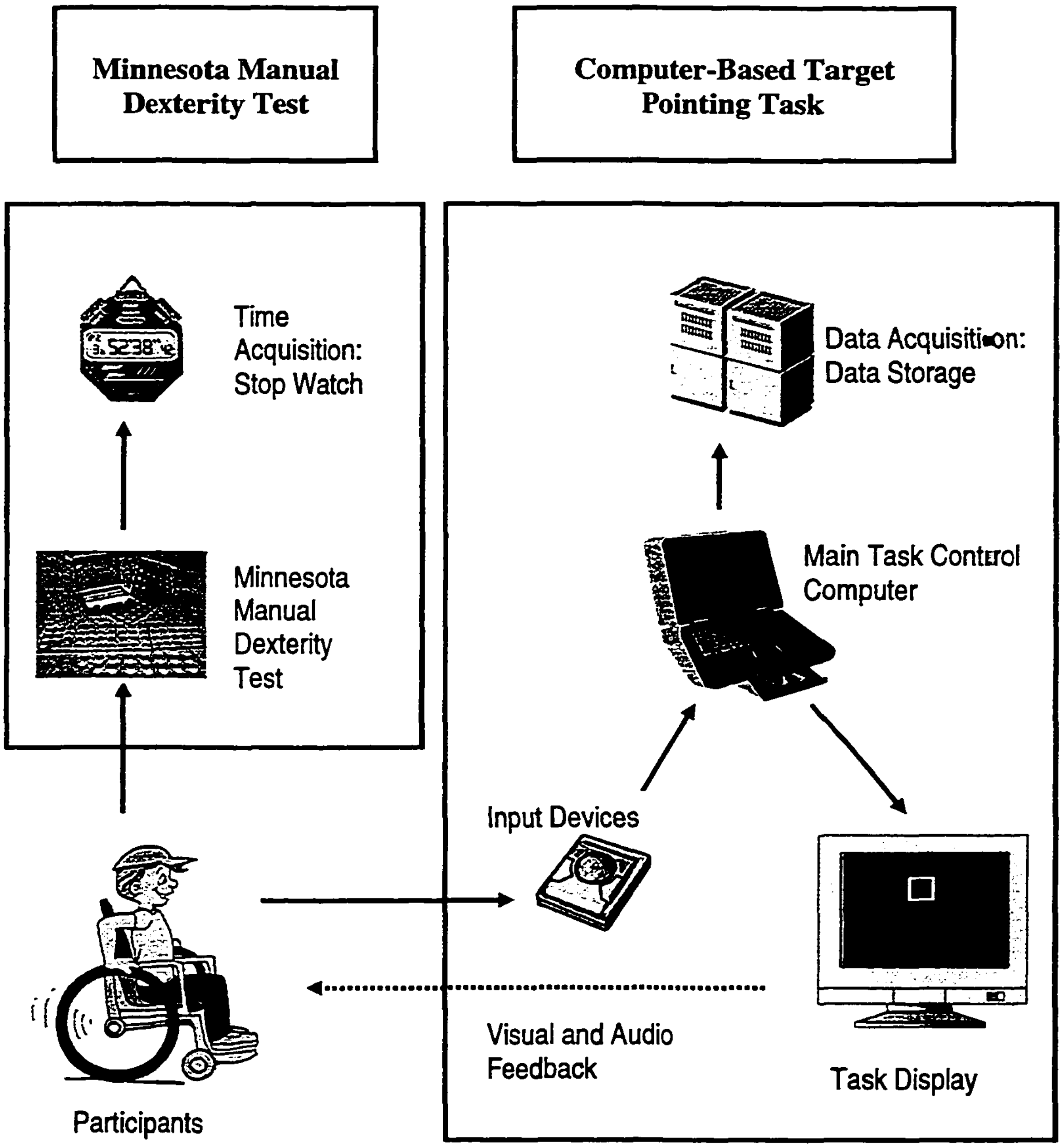


Figure 16. Schematic Diagram of the Experimental Procedures.

After finishing the practice run, each participant performed the task four more times. Completion time was recorded for each run. After each run, the participant was asked to stop and wait for instructions to start the next run. The experimenter gave the verbal signals "READY" and "GO". At the word "GO", the participant began to work as fast as possible. A short break was provided between runs in order to reduce tension and fatigue. The participant was instructed to relax between runs, and was reminded that speed was very important when performing the test.

5.8.2 Procedures for Computer-Based Target Pointing Task

Following the manual dexterity test, a standardized Fitts' Law program was used to test the effects of different target sizes, movement amplitudes, and movement directions on movement speed. OATC provided two assistive input devices (a joystick and a trackball) that are widely used by people with motor impairments. In addition, a standard mouse was tested for comparison.

Each participant was instructed to sit in an upright position at a distance of approximately 80 cm from the monitor. Then, each participant was provided with adequate training and instructions before the testing began. Participants were allowed to take sufficient time to familiarize themselves with the experimental setup during a practice run. Each test run included three target sizes, three amplitudes, and three target directions (two target directions for the impaired group) for each input device. Each participant had at least a two-minute rest period between runs. Each run was expected to take approximately ten minutes to complete for the unimpaired participants, while the impaired participants were expected to require a longer time. After completion of the task for each input device, the participant had a five-minute rest period. During this time, the experimenter replaced the input device with the next scheduled device. The order of devices and CD gains was counterbalanced.

5.9 Experimental Design

The experiment was designed to compare the three pointing devices on a target pointing task by varying target size, movement amplitude, and direction of cursor movement. In this section, the experimental design for the test is discussed.

5.9.1 Independent Variables

The six independent variables were: (1) input device (joystick, trackball, and mouse), (2) movement direction (East, North, and Southwest), (3) control-display gain (0.5 and 1.0), (4) session (Practice, Main 1, and Main 2), (5) test group (unimpaired and impaired), and (6) subjects (23 unimpaired participants and 11 impaired participants, which are nested in the test group). However, the Southwest level of the movement direction factor and the Practice level of the session factor were removed from the SAS database to form a balanced statistical analysis. Table 20 shows each level of the independent variables.

Table 20. Independent Variables and Levels.

Independent Variables	Levels
Input Device	Joystick
	Trackball
	Mouse
Movement Direction	East (0 degrees)
	North (90 degrees)
	Southwest (225 degrees)†‡
CD Gain	0.5
	1.0
Session	Practice†
	Main 1
	Main 2
Group	Unimpaired (23 Participants)
	Impaired (11 Participants)
Subject (nested in Group)	34 Participants

Note: † = Southwest direction and Practice session were not included in the SAS GLM analysis.
‡ = Unimpaired participants only.

5.9.2 Dependent Variables

Since Fitts' Law tests are generally accepted as good predictors of movement speed (Jagacinski & Monk, 1985; Radwin et al., 1990; Rao, 1998), the GFLMB test developed by Soukoreff and MacKenzie (1995) was used in this study to validate the specifications of assistive computer input devices.

Movement time in milliseconds was the primary dependent measure for the testing of cursor movements. The movement time in this study is defined as the time taken to move the cursor from the starting position until the target was successfully acquired. To minimize the variability associated with the Fitts' Law slope and intercept, the derived measure of predicted movement time at the mid-point (MidMT) of the tested index of difficulty range (ID = 3.21) was used for analysis. The index of difficulty for each combination of target size and movement amplitude is shown in Table 21.

Table 21. ID Generated by Target Sizes and Movement Amplitudes.

Target Size (mm)	Movement Amplitude (mm)	Index of Difficulty (bits)
25	40	1.38
15	40	1.87
25	80	2.07
15	80	2.66
25	160	2.89
5	40	3.17
15	160	3.54
5	80	4.09
5	160	5.04

According to MacKenzie (1992b), the Index of Performance, which is the reciprocal of the slope (IP=1/b), is widely used for assessing task performance because IP measures permit performance comparisons across factors such as device, limb, or task. In order to assess whether IP provides a valid comparison of computer input devices for motor impaired people, IP was analyzed as the second dependent variable. In addition to the objective measures of task performance, subjective evaluations of each input device were obtained. User preferences and the usability of each device were carefully assessed to compare the subjective evaluation with the performance data from the test.

5.9.3 Control Variables

The testing workstation was adjustable to provide the participants the most comfortable work environment. Since participants may use various mobility devices, including wheel chairs, an adjustable workstation was necessary. In addition, the same workstation was used throughout the testing.

Environmental conditions were maintained at approximately the same levels for the duration of the experiment at each test site. Temperature in the testing rooms was maintained at approximately 20°C, and humidity was between 30% and 40% throughout the test sessions. Lighting in the testing rooms was maintained at approximately 300 lux, which is recommended by the U.S. Illuminating Engineering Society (IES) for computer work to avoid glare and reflectance problems (Bridger, 1995).

5.9.4 Statistical Model

The experimental design used for this research was a mixed-effects *nested factorial design*. As discussed in the previous section, the six independent variables were (1) the selected input device with three levels, (2) the movement direction with two levels, (3) the CD gain with two levels, (4) the session with two levels, (5) the population group with two levels, and (6) the subjects nested in the group effect. Within each session block, the presentation order of the target selections was randomized. In addition, the testing order of input devices was counterbalanced (Table 22).

Table 22. Counterbalancing Schedule for the Experiment.

Device Testing Order	Unimpaired Group	Impaired Group
Mouse → Trackball → Joystick	S01, S10, S21	D04, D02
Mouse → Joystick → Trackball	S02, S09, S16, S23	D09, D07
Trackball → Mouse → Joystick	S12, S17, S19, S22	D03, D11
Trackball → Joystick → Mouse	S05, S06, S08, S15	D08
Joystick → Trackball → Mouse	S04, S11, S14, S18	D10, D01
Joystick → Mouse → Trackball	S03, S07, S13, S20	D05, D06

Data from the experiment were exported to Microsoft Excel (Version 2000). Statistical analysis was completed using SAS (Version 8.01). The SAS General Linear Model (GLM) procedure was used to test for significant main and interaction effects of the six independent variables on both MidMT and index of performance (IP) at a significance level (α) of .05. Since there is no replicate for each condition, the highest interaction [I×D×C×T×S(G)] was pooled with the error term. The statistical model used for analysis of each response measure is presented in Equation (5).

$$\begin{aligned} y_{ijklmn} = {} & \mu + \mathrm{I}_i + \mathrm{D}_j + \mathrm{C}_k + \mathrm{T}_l + \mathrm{G}_m + \mathrm{ID}_{ij} + \mathrm{IC}_{ik} + \mathrm{DC}_{jk} + \mathrm{IT}_{il} + \mathrm{DT}_{jl} + \mathrm{CT}_{kl} + \\ & \mathrm{IG}_{im} + \mathrm{DG}_{jm} + \mathrm{CG}_{km} + \mathrm{TG}_{lm} + \mathrm{IDC}_{ijk} + \mathrm{IDT}_{ijl} + \mathrm{ICT}_{ikl} + \mathrm{DCT}_{jkl} + \\ & \mathrm{IDG}_{ijm} + \mathrm{ICG}_{ikm} + \mathrm{DCG}_{jkm} + \mathrm{ITG}_{ilm} + \mathrm{DTG}_{jlm} + \mathrm{CTG}_{klm} + \mathrm{IDCT}_{ijkl} + \\ & \mathrm{IDCG}_{ijkm} + \mathrm{IDTG}_{ijlm} + \mathrm{ICTG}_{iklm} + \mathrm{DCTG}_{jklm} + \mathrm{IDCTG}_{ijklm} + \\ & \mathrm{S(G)}_{n(m)} + \mathrm{IS(G)}_{in(m)} + \mathrm{DS(G)}_{jn(m)} + \mathrm{IDS(G)}_{ijn(m)} + \mathrm{CS(G)}_{kn(m)} + \\ & \mathrm{ICS(G)}_{ikn(m)} + \mathrm{DCS(G)}_{jkn(m)} + \mathrm{IDCS(G)}_{ijkn(m)} + \mathrm{TS(G)}_{ln(m)} + \\ & \mathrm{ITS(G)}_{iln(m)} + \mathrm{DTS(G)}_{jln(m)} + \mathrm{IDTS(G)}_{ijln(m)} + \mathrm{CTS(G)}_{kln(m)} + \\ & \mathrm{ICTS(G)}_{ikln(m)} + \mathrm{DCTS(G)}_{jkln(m)} + \varepsilon_{ijklmn} \end{aligned} \tag{5}$$

where y_{ijklmn} is a response measure,

μ is overall mean,

I_i is input device effect (i=1 to 3 for joystick, trackball, and mouse),

D_j is movement direction effect (j=1 to 2 for East [0°] and North [90°]),

C_k is control-display gain effect (k=1 to 2 for 0.5 and 1.0 CD Gain),

T_l is session effect (l=1 to 2 for Main 1 and Main 2),

G_m is group effect (m=1 to 2 for unimpaired and impaired),

$S(G)_{n(m)}$ is subject effect nested in group (n=1 to 32), and

ε_{ijklmn} is random error term with NID $(0, \sigma^2)$.

The expected mean squares (EMS) for the statistical model and the appropriate F-ratios are presented in Table 23.

Table 23. Expected Mean Squares for a Six-Factor Mixed-Effects Model.

Source	SS	DF	EMS	F-ratio
Input Device [I]	SS_I	(a-1)	$\sigma^2 + I + IS(G)$	$MS_I / MS_{IS(G)}$
Direction [D]	SS_D	(b-1)	$\sigma^2 + D + DS(G)$	$MS_D / MS_{DS(G)}$
CD Gain [C]	SS_C	(c-1)	$\sigma^2 + C + CS(G)$	$MS_C / MS_{CS(G)}$
Session [T]	SS_T	(d-1)	$\sigma^2 + T + TS(G)$	$MS_T / MS_{TS(G)}$
Group [G]	SS_G	(e-1)	$\sigma^2 + G + S(G)$	$MS_G / MS_{S(G)}$
IxD	SS_{ID}	(a-1)(b-1)	$\sigma^2 + ID + IDS(G)$	$MS_{ID} / MS_{IDS(G)}$
IxC	SS_{IC}	(a-1)(c-1)	$\sigma^2 + IC + ICS(G)$	$MS_{IC} / MS_{ICS(G)}$
DxC	SS_{DC}	(b-1)(c-1)	$\sigma^2 + DC + DCS(G)$	$MS_{DC} / MS_{DCS(G)}$
IxDxC	SS_{IDC}	(a-1)(b-1)(c-1)	$\sigma^2 + IDC + IDCS(G)$	$MS_{IDC} / MS_{IDCS(G)}$
IxT	SS_{IT}	(a-1)(d-1)	$\sigma^2 + IT + ITS(G)$	$MS_{IT} / MS_{ITS(G)}$
DxT	SS_{DT}	(b-1)(d-1)	$\sigma^2 + DT + DTS(G)$	$MS_{DT} / MS_{DTS(G)}$
IxDxT	SS_{IDT}	(a-1)(b-1)(d-1)	$\sigma^2 + IDT + IDTS(G)$	$MS_{IDT} / MS_{IDTS(G)}$
CxT	SS_{CT}	(c-1)(d-1)	$\sigma^2 + CT + CTS(G)$	$MS_{CT} / MS_{CTS(G)}$
IxCxT	SS_{ICT}	(a-1)(c-1)(d-1)	$\sigma^2 + ICT + ICTS(G)$	$MS_{ICT} / MS_{ICTS(G)}$
DxCxT	SS_{DCT}	(b-1)(c-1)(d-1)	$\sigma^2 + DCT + DCTS(G)$	$MS_{DCT} / MS_{DCTS(G)}$
IxDxCxT	SS_{IDCT}	(a-1)(b-1)(c-1)(d-1)	$\sigma^2 + IDCT$	MS_{IDCT} / MS_E
IxG	SS_{IG}	(a-1)(e-1)	$\sigma^2 + IG + IS(G)$	$MS_{IG} / MS_{IS(G)}$
DxG	SS_{DG}	(b-1)(e-1)	$\sigma^2 + DG + DS(G)$	$MS_{DG} / MS_{DS(G)}$
CxG	SS_{CG}	(c-1)(e-1)	$\sigma^2 + CG + CS(G)$	$MS_{CG} / MS_{CS(G)}$
TxG	SS_{TG}	(d-1)(e-1)	$\sigma^2 + TG + TS(G)$	$MS_{TG} / MS_{TS(G)}$
IxDxG	SS_{IDG}	(a-1)(b-1)(e-1)	$\sigma^2 + IDG + IDS(G)$	$MS_{IDG} / MS_{IDS(G)}$
IxCxG	SS_{ICG}	(a-1)(c-1)(e-1)	$\sigma^2 + ICG + ICS(G)$	$MS_{ICG} / MS_{ICS(G)}$
DxCxG	SS_{DCG}	(b-1)(c-1)(e-1)	$\sigma^2 + DCG + DCS(G)$	$MS_{DCG} / MS_{DCS(G)}$
IxTxG	SS_{ITG}	(a-1)(d-1)(e-1)	$\sigma^2 + ITG + ITS(G)$	$MS_{ITG} / MS_{ITS(G)}$
DxTxG	SS_{DTG}	(b-1)(d-1)(e-1)	$\sigma^2 + DTG + DTS(G)$	$MS_{DTG} / MS_{DTS(G)}$
CxTxG	SS_{CTG}	(c-1)(d-1)(e-1)	$\sigma^2 + CTG + CTS(G)$	$MS_{CTG} / MS_{CTS(G)}$
IxDxCxG	SS_{IDCG}	(a-1)(b-1)(c-1)(e-1)	$\sigma^2 + IDCG + IDCS(G)$	$MS_{IDCG} / MS_{IDCS(G)}$
IxCxTxG	SS_{ICTG}	(a-1)(c-1)(d-1)(e-1)	$\sigma^2 + ICTG + ICTS(G)$	$MS_{ICTG} / MS_{ICTS(G)}$
IxDxTxG	SS_{IDTG}	(a-1)(b-1)(d-1)(e-1)	$\sigma^2 + IDTG + IDTS(G)$	$MS_{IDTG} / MS_{IDTS(G)}$
DxCxTxG	SS_{DCTG}	(b-1)(c-1)(d-1)(e-1)	$\sigma^2 + DCTG + DCTS(G)$	$MS_{DCTG} / MS_{DCTS(G)}$
IxDxCxTxG	SS_{IDCTG}	(a-1)(b-1)(c-1)(d-1)(e-1)	$\sigma^2 + IDCTG$	MS_{IDCTG} / MS_E
Subject [S(G)]	$SS_{S(G)}$	$(f_\bullet - e)$, where $f_\bullet = f_1 + f_2$	$\sigma^2 + S(G)$	$MS_{S(G)} / MS_E$
IxS(G)	$SS_{IS(G)}$	$(f_\bullet - e)$(a-1)	$\sigma^2 + IS(G)$	$MS_{IS(G)} / MS_E$
DxS(G)	$SS_{DS(G)}$	$(f_\bullet - e)$(b-1)	$\sigma^2 + DS(G)$	$MS_{DS(G)} / MS_E$
IxDxS(G)	$SS_{IDS(G)}$	$(f_\bullet - e)$(a-1)(b-1)	$\sigma^2 + IDS(G)$	$MS_{IDS(G)} / MS_E$
CxS(G)	$SS_{CS(G)}$	$(f_\bullet - e)$(c-1)	$\sigma^2 + CS(G)$	$MS_{CS(G)} / MS_E$
IxCxS(G)	$SS_{ICS(G)}$	$(f_\bullet - e)$(a-1)(c-1)	$\sigma^2 + ICS(G)$	$MS_{ICS(G)} / MS_E$
DxCxS(G)	$SS_{DCS(G)}$	$(f_\bullet - e)$(b-1)(c-1)	$\sigma^2 + DCS(G)$	$MS_{DCS(G)} / MS_E$
IxDxCxS(G)	$SS_{IDCS(G)}$	$(f_\bullet - e)$(a-1)(b-1)(c-1)	$\sigma^2 + IDCS(G)$	$MS_{IDCS(G)} / MS_E$
TxS(G)	$SS_{TS(G)}$	$(f_\bullet - e)$(d-1)	$\sigma^2 + TS(G)$	$MS_{TS(G)} / MS_E$
IxTxS(G)	$SS_{ITS(G)}$	$(f_\bullet - e)$(a-1)(d-1)	$\sigma^2 + ITS(G)$	$MS_{ITS(G)} / MS_E$
DxTxS(G)	$SS_{DTS(G)}$	$(f_\bullet - e)$(b-1)(d-1)	$\sigma^2 + DTS(G)$	$MS_{DTS(G)} / MS_E$
IxDxTxS(G)	$SS_{IDTS(G)}$	$(f_\bullet - e)$(a-1)(b-1)(d-1)	$\sigma^2 + IDTS(G)$	$MS_{IDTS(G)} / MS_E$
CxTxS(G)	$SS_{CTS(G)}$	$(f_\bullet - e)$(c-1)(d-1)	$\sigma^2 + CTS(G)$	$MS_{CTS(G)} / MS_E$
IxCxTxS(G)	$SS_{ICTS(G)}$	$(f_\bullet - e)$(a-1)(c-1)(d-1)	$\sigma^2 + ICTS(G)$	$MS_{ICTS(G)} / MS_E$
DxCxTxS(G)	$SS_{DCTS(G)}$	$(f_\bullet - e)$(b-1)(c-1)(d-1)	$\sigma^2 + DCTS(G)$	$MS_{DCTS(G)} / MS_E$
IxDxCxTxS(G)=Error	SS_E	$(f_\bullet - e)$(a-1)(b-1)(c-1)(d-1)	$\sigma^2 = MS_E$	

Note: ***a*** refers to the number of input devices, ***b*** refers to the number of movement direction, ***c*** refers to the number of CD gains, ***d*** refers to the number of sessions, ***e*** refers to the number of groups, and $f_\bullet$ ($= f_1 + f_2$) refers to the total number of nested subjects in the groups.

CHAPTER 6

RESULTS AND ANALYSES

This chapter presents the results of the experiment and analyses of the data collected for this study. The participant survey was summarized to provide information on device preference and usability. In addition, the results from the MMDT and the computer-based target pointing task were analyzed.

6.1 Overview

A survey form was used to document the participant's previous computer interaction experience with various input devices, opinions on the usability of the tested input devices, and preference among the tested devices.

For assessing the degree of impairment and for examining the relationship between a traditional manual dexterity measure and input device performance, this study employed the Minnesota Manual Dexterity Test (MMDT). The test completion times for the unimpaired group and the impaired group were compared. To validate the MMDT as a predictor of input device performance, correlation analysis was conducted for both the MidMT and IP measurements versus the MMDT scores. Test reliability can be concisely defined as obtaining the same value of a measurement when tests are repeated under identical conditions. To evaluate the reliability of the two input device measures (MidMT and IP), test-retest correlation coefficients were examined for all devices.

Without sacrificing the information content of the data, various data reduction processes were applied to generate manageable statistics that were representative of each testing period. MMDT test data for participants D05 and D07 were excluded from the data set because the participants were unable to complete the test. Since the

Southwest movement direction was not included in testing the impaired group, only the North and East movement directions were included in the final SAS GLM statistical analysis to achieve a balanced dataset. In addition, the practice session was not included in the SAS GLM procedure. Only the two main sessions were of interest in examining test-retest reliability. However, the practice session data were included in graphical presentations.

The SAS GLM results have been summarized by the Fitts' Law components. To examine whether proposed alternative input devices are appropriate for upper-limb motor impaired people, two different tasks were employed. The MMDT was used as a potential assessment tool to predict performance based on the level of impairment, while the Fitts' Law pointing task measured performance as a function of movement time and task difficulty. Then, correlation analysis and test-retest reliability analysis were performed to evaluate the effectiveness of these tests in assessing human performance with various input devices.

6.2 Survey Data Analyses

The mouse was reported to be the most widely used input device for both the impaired and unimpaired groups. The participants of the unimpaired group generally had greater experience with input devices (Figure 17). However, the impaired group had relatively more experience with the trackball than did the unimpaired group.

The joystick selected for use in this research was specifically designed for people with disabilities. Unfortunately, the Penny & Giles® Joystick Plus, at approximately $450, is very expensive and is available through only a few assistive technology suppliers. Information on the joystick was not widely available, and many of the impaired participants had never heard about this device.

The mouse was rated as easy or very easy to use by 87% of the unimpaired group, while approximately half of the group indicated that the joystick and trackball

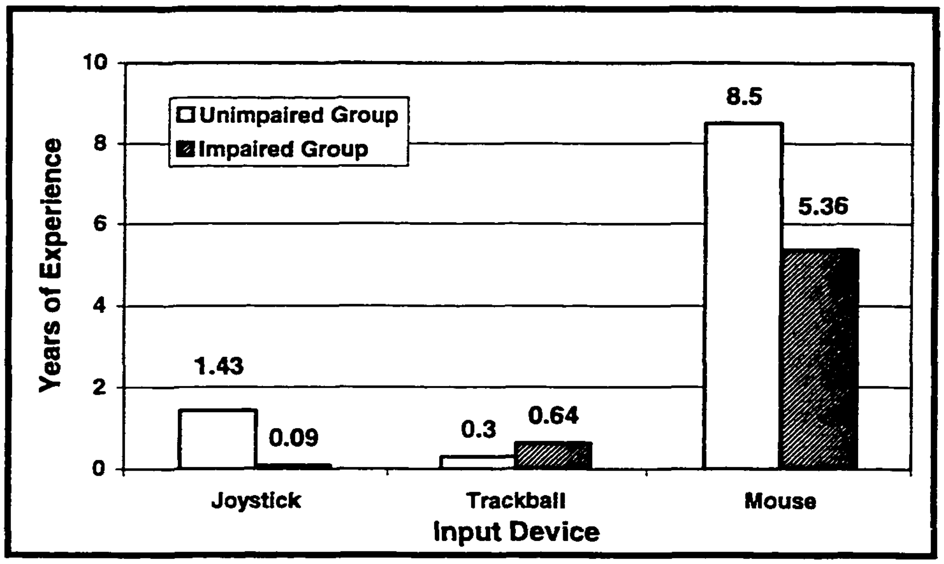


Figure 17. Participant Experience with Selected Input Devices.

were easy or very easy to use (Figure 18). Similarly, approximately half of the impaired participants indicated that the joystick and trackball were easy or very easy to use (Figure 19). The mouse was also a very usable device for the impaired group. As shown in Figure 19, approximately 82% of the impaired group indicated that the mouse was easy or very easy to use. People with more severe impairments preferred using the joystick and trackball. However, this was not the case for participant D07 with weak muscle strength. This fact would encourage a redesign of these devices with reduced resistance force for the joystick and a more appropriate ball (smaller) size for the trackball.

As shown in Figure 20, the majority of the unimpaired group (87%) identified the mouse as their first or second preference, compared to the trackball (61%) and the joystick (52%), while the impaired group favored the trackball. Figure 21 shows that approximately 91% of the impaired group preferred the trackball over the mouse (73%) or the joystick (36%). The results of this survey suggest that people with motor impairments may gain some advantage from the trackball. Many people in the impaired group who have been using a wheelchair joystick control for a long time

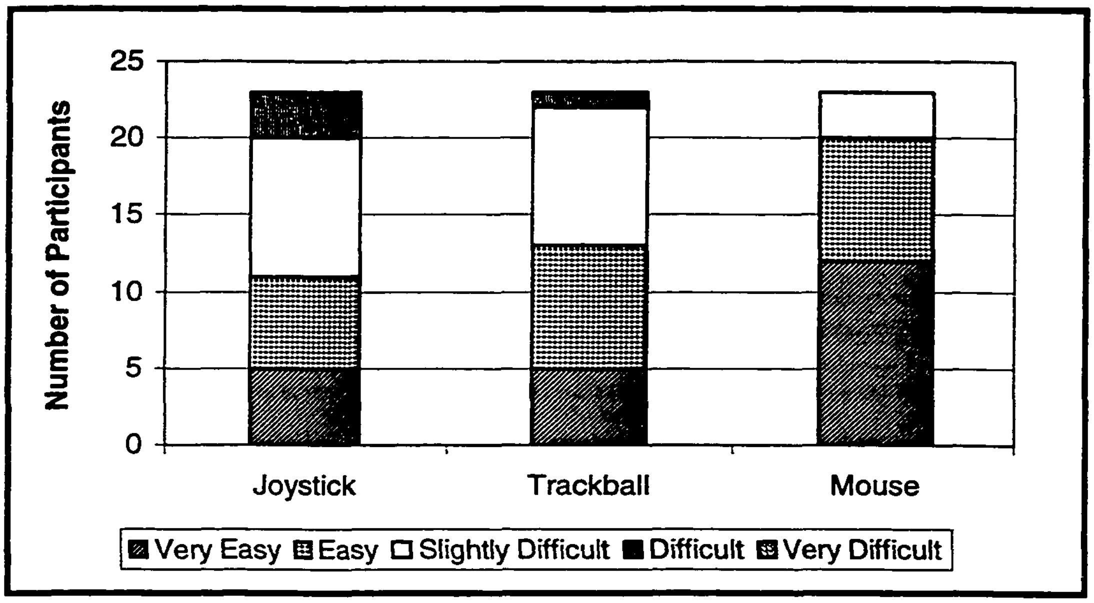


Figure 18. Reported Device Usability for the Unimpaired Group.

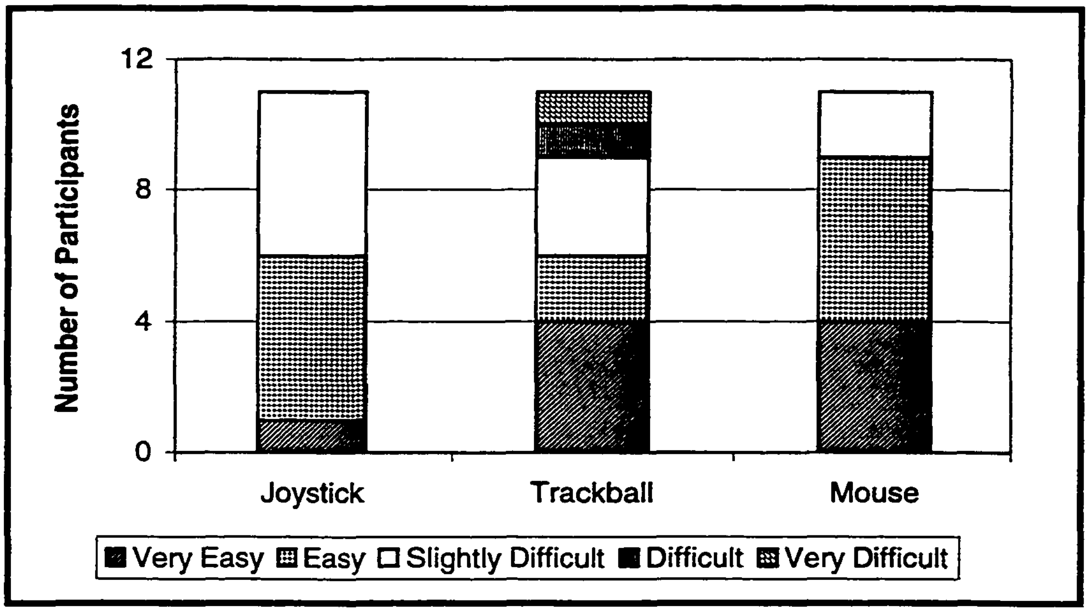


Figure 19. Reported Device Usability for the Impaired Group.

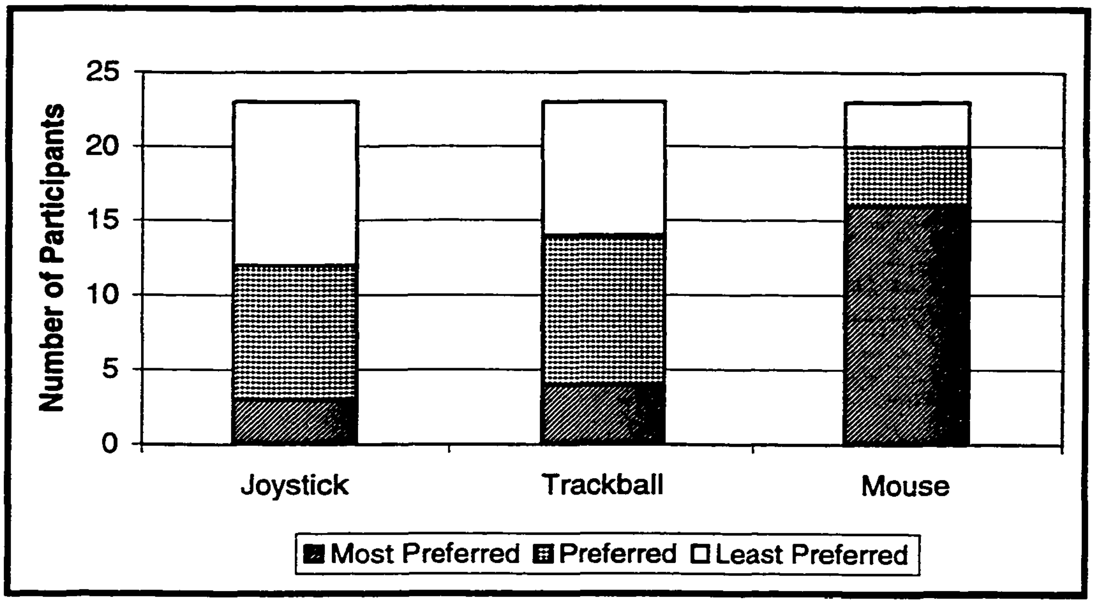


Figure 20. Reported Device Preference for the Unimpaired Group.

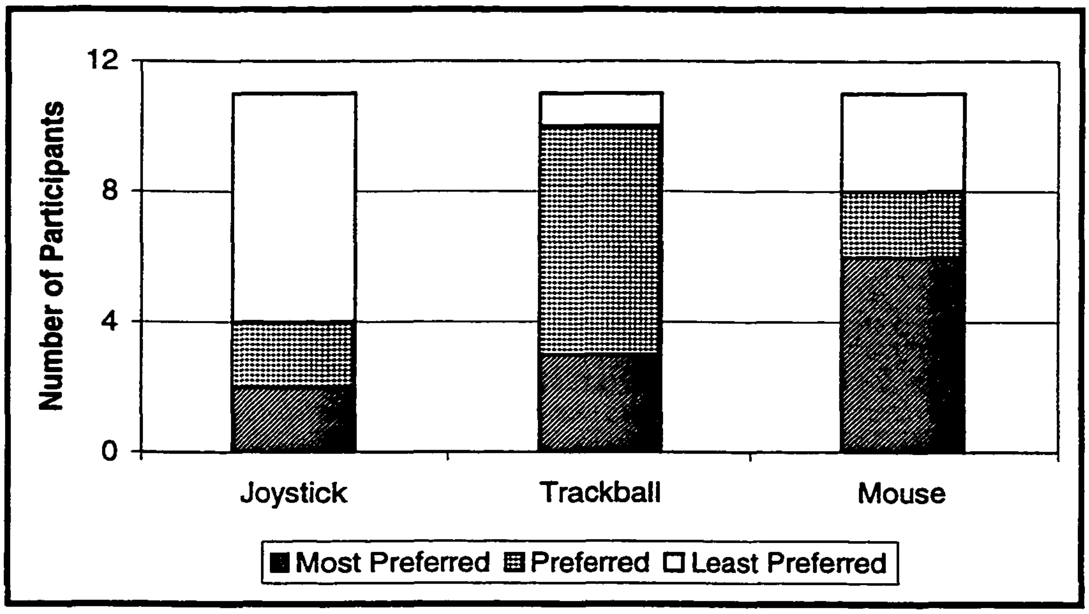


Figure 21. Reported Device Preference for the Impaired Group.

indicated that the joystick used in this study was not appropriate. The primary reason given was that joysticks for use by impaired people generally provide more sensitive control than the device used in this study.

6.3 Minnesota Manual Dexterity Test

MMDT test data for participants D05 and D07 were excluded from the data set because the participants were unable to complete the test. Participant D05 completed two runs and then requested to stop the MMDT test. The other participant (D07) was completely unable to conduct the test due to a severe range of motion limitation. Participant D07 could not extend her arm to the test equipment.

The average completion time for the MMDT for the unimpaired group showed a minimal learning effect during the four test runs (from 56.91 sec to 55.43 sec), while the impaired group improved by 8.3% from 164.11 sec to 150.44 sec (Tables 24 and 25). As presented in Figure 22, the standard deviation across the impaired participants was significantly higher (average standard deviation of 80.11 sec for the four test runs) than for the unimpaired group (4.29 sec), whose standard deviation across participants was low for all runs (3.63 sec to 4.70 sec).

For the unimpaired group, mean completion time appeared stable from the beginning. However, the impaired group showed a steady learning effect throughout the main runs, decreasing their completion time by approximately 3 seconds per run. As shown in Figure 23, approximately 78% of the unimpaired group completed the test with a speed rating of "Very Fast" or "Upper Average." However, all of the impaired participants performed at a speed slower than the lowest named rating category (338 sec to 1135 sec).

For analysis purposes, the degree of upper-limb motor impairment for each participant was categorized based on the general interpretation of test completion speed, which is provided by the Lafayette Instrument Company (Table 26). The table

Table 24. Minnesota Manual Dexterity Test Completion Time (sec) Data for the Unimpaired Group.

ID	Practice	Run						Percentile
		1	2	3	4	Total	SD	
S01	56	54	56	58	53	**221**	**2.22**	**57.5**
S02	60	54	56	53	54	**217**	**1.26**	**60.0**
S03	56	53	56	53	51	**213**	**2.06**	**62.5**
S04	65	62	67	63	61	**253**	**2.63**	**37.5**
S05	54	57	53	57	55	**222**	**1.91**	**57.0**
S06	55	55	55	52	51	**213**	**2.06**	**62.5**
S07	54	55	54	51	50	**210**	**2.38**	**64.5**
S08	58	61	64	60	63	**248**	**1.83**	**40.5**
S09	62	55	57	55	55	**222**	**1.00**	**57.0**
S10	59	52	53	48	46	**199**	**3.30**	**71.0**
S11	56	56	54	53	53	**216**	**1.41**	**60.5**
S12	54	53	56	50	53	**212**	**2.45**	**63.0**
S13	59	54	54	53	52	**213**	**0.96**	**62.5**
S14	61	53	55	55	55	**218**	**1.00**	**59.5**
S15	58	59	59	56	59	**233**	**1.50**	**50.0**
S16	60	56	58	56	54	**224**	**1.63**	**55.5**
S17	60	54	59	57	60	**230**	**2.65**	**52.0**
S18	65	58	58	54	53	**223**	**2.63**	**56.0**
S19	61	59	59	57	53	**228**	**2.83**	**53.0**
S20	66	63	71	64	64	**262**	**3.70**	**32.0**
S21	65	63	56	56	58	**233**	**3.30**	**50.0**
S22	63	63	62	63	64	**252**	**0.82**	**38.0**
S23	65	60	61	62	58	**241**	**1.71**	**45.0**
Mean	59.65	56.91	57.96	55.91	55.43			
SD	3.93	3.63	4.53	4.28	4.70			

Table 25. Minnesota Manual Dexterity Test Completion Time (sec) Data for the Impaired Group.

ID	Practice	Run					
		1	2	3	4	Total	SD
D01	132	121	130	118	118	**487**	**5.68**
D02	103	88	92	93	87	**360**	**2.94**
D03	371	296	284	267	274	**1121**	**12.61**
D04	108	99	98	95	105	**397**	**4.19**
D06	154	124	125	111	121	**481**	**6.40**
D08	246	242	202	190	188	**822**	**25.11**
D09	127	129	121	114	110	**474**	**8.35**
D10	103	92	82	85	79	**338**	**5.57**
D11	340	286	272	305	272	**1135**	**15.63**
Mean	187.11	164.11	156.22	153.11	150.44		
SD	105.36	85.33	77.26	81.83	76.00		

Note: Two participants (D05 and D07) in the impaired group were not able to complete the MMDT due to their level of upper-limb impairment.

Table 26. Cumulative Percentage of Unimpaired Populations in MMDT Speed Categories (Modified from Lafayette Instrument Co., 1971).

Speed Category	Completion Time Range (sec)	% Population in Speed Category	Cumulative % of Population
Extremely slow	275 to 313	25	25
Very slow	251 to 273	15	40
Lower average	233 to 249	10	50
Upper average	219 to 231	10	60
Very fast	193 to 217	15	75
Extremely fast	153 to 191	25	100

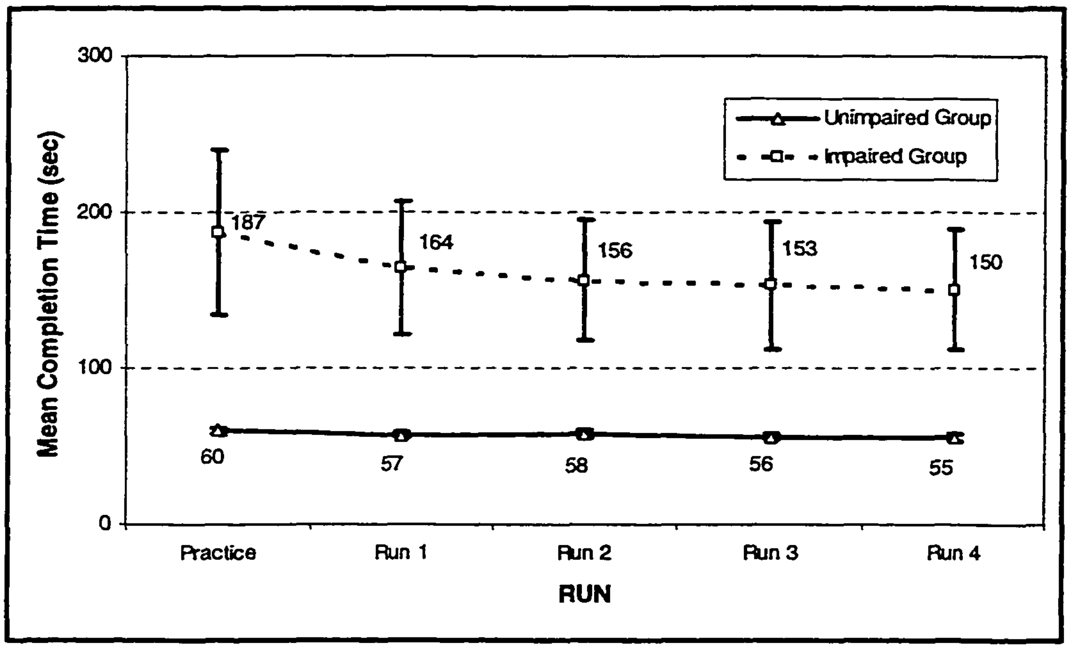


Figure 22. Minnesota Manual Dexterity Test Completion Times with Standard Deviations.

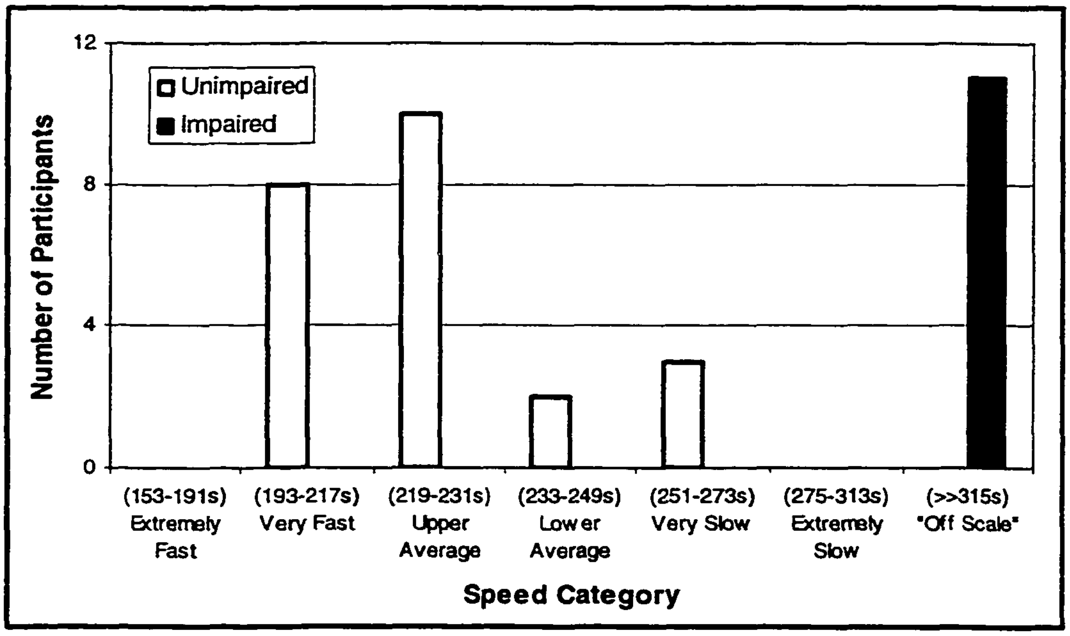


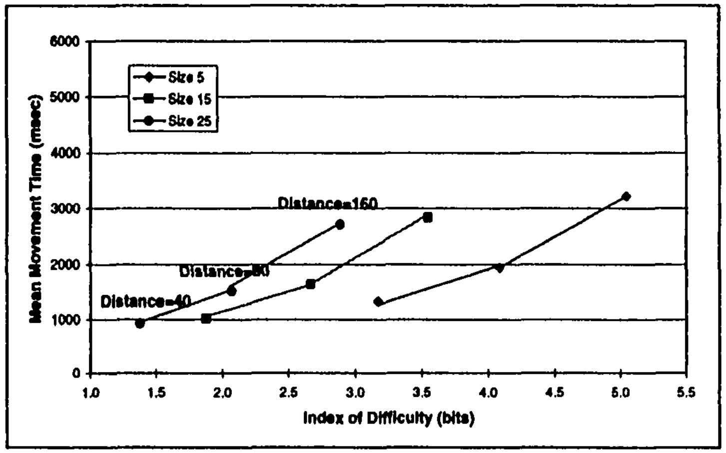
Figure 23. Completion Time Categories for the MMDT Data.

was developed by the Employment Stabilization Research Institute at the University of Minnesota from 3,000 participants randomly sampled from the general population.

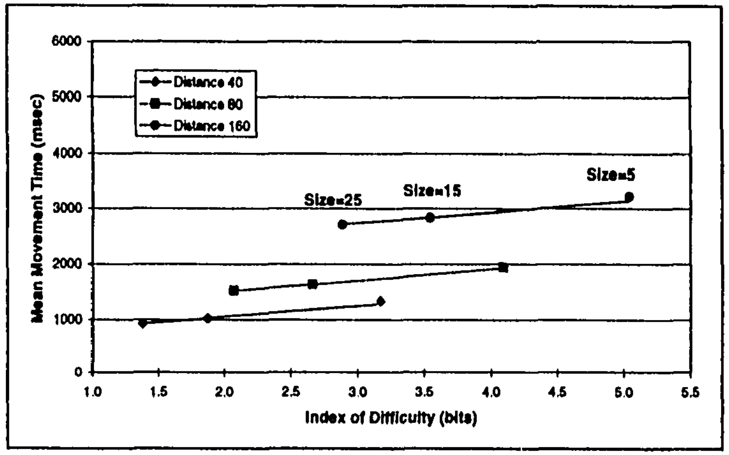
6.4 Validation of Fitts' Law

Fitts' Law indicates that the human hand movement time to control a cursor to a target position is a function of two parameters: target size and movement amplitude. In order to assess whether Fitts' Law is applicable for determining appropriate devices for people with upper-limb impairments, various target sizes and movement amplitudes were analyzed using the Index of Difficulty (ID). Using regression analyses involving movement time and ID, the slope, intercept, and R-square values were analyzed.

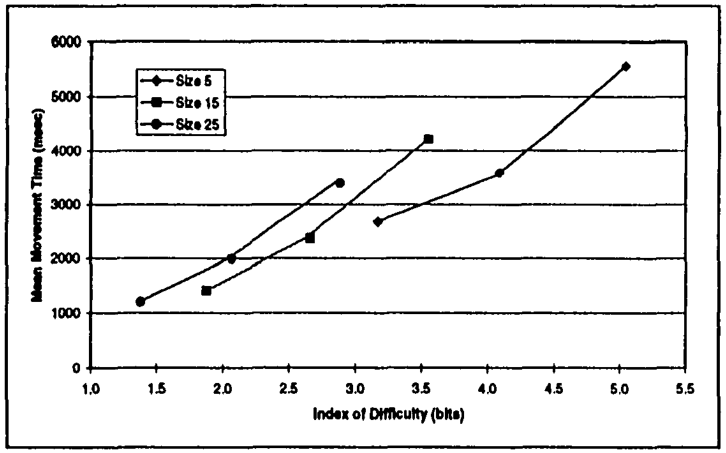
The following novel approach was used to evaluate the applicability of Fitts' Law. For each input device, the target sizes and movement amplitudes were graphed separately to determine their relative contributions to movement time. For the joystick, the impaired group followed the Fitts' Law model better for both target size and movement amplitude than did the unimpaired group. On the other hand, there was not much performance change within the same movement amplitude group for different target sizes for the unimpaired participants as shown in Figure 24 (a) and (b). At a movement amplitude of 160 mm, target size 25 mm was expected to result in a faster movement time than target size 5 mm. Performance did not significantly differ between the two sizes. This suggested that the target pointing performance in the joystick was more dependent on travel time than adjustment time. This was likely due to the design characteristics of the joystick. Moreover, for both groups, within the same target size, the time for the largest movement amplitude (160 mm) was longer than that predicted by the model based on the other two amplitudes (40 mm and 80 mm). This fact is observable from the slope change between the sizes (Figure 24).



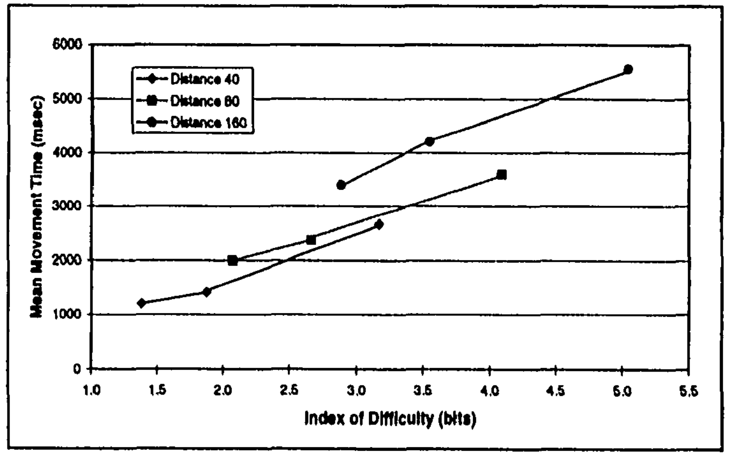
(a) Target Size for Unimpaired Group



(b) Movement Amplitude for Unimpaired Group



(c) Target Size for Impaired Group



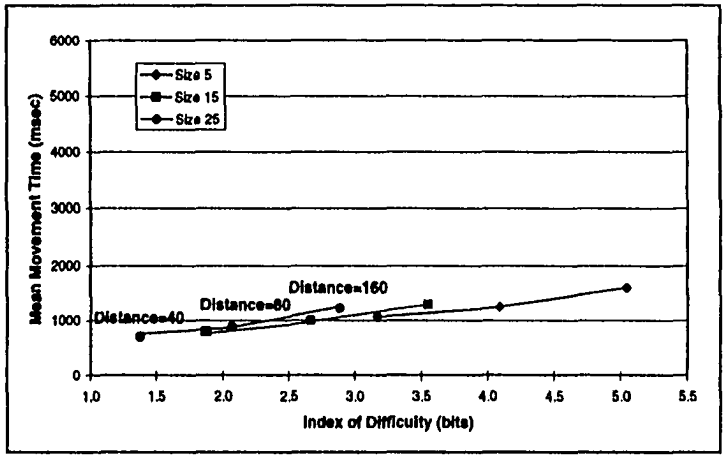
(d) Movement Amplitude for Impaired Group

Figure 24. Joystick Mean Movement Time by ID
(in Main 2 Session with East Direction and 0.5 CD Gain).

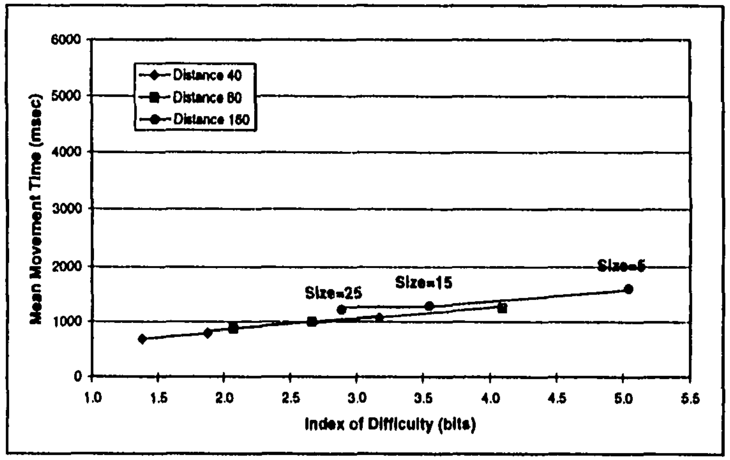
Target size and movement amplitude analyses for the trackball yielded different results for the two groups (Figure 25). The impaired group had relatively greater difficulty with the longest movement amplitude (160 mm) within each target size group. Especially in the 25 mm size group, the longest movement amplitude (160 mm) resulted in a disproportionately larger increase in movement time. This implied that larger movement amplitude caused a disproportional performance deterioration for people with impairments. As shown in Figure 25 (d), the changes due to movement amplitudes for the 25 mm and 15 mm sizes were not as significant as for the 5 mm size. This implied that amplitude and size both contributed to differences in trackball movement time for the impaired group. On the other hand, the performance change for the unimpaired group was minimal.

In order to determine how much of the variation in the data is explained by the Fitts' model, the proportion of variance in the movement time that is predicted from the coefficients of the regression equation (R^2) is typically used as an indicator. In this study, Fitts' Law was a valid predictor of the speed-accuracy tradeoff for the unimpaired group using both the mouse and trackball (mean R^2 = .75 to .86 for CD gain of 0.5; mean R^2 = .76 to .86 for CD gain of 1.0). However, joystick performance of the Fitts' task appeared to depend primarily on movement time (distance) rather than adjustment time (target size) with mean R^2 = .48 to .66 for CD gain of 0.5, and mean R^2 = .59 to .83 for CD gain of 1.0. For the unimpaired group, Fitts' Law held very well with the mouse for both target size and movement amplitude, while the impaired group had slightly more difficulty (Figure 26).

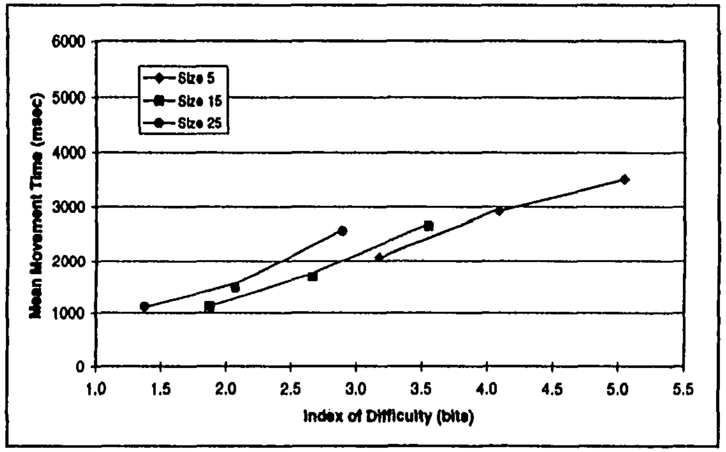
Fitts' Law model held better for the group of impaired participants with the joystick and trackball (R^2 = .58 to .80 for CD gain of 0.5; R^2 = .68 to .80 for CD gain of 1.0). The poorer fit of the linear regression line for the mouse indicated that the Fitts' Law model for the impaired group was not as valid (R^2 = .56 to .70 for CD gain of 0.5; R^2 = .59 to .70 for CD gain of 1.0). This finding supported the observed problems the impaired participants had in acquiring the target when using the



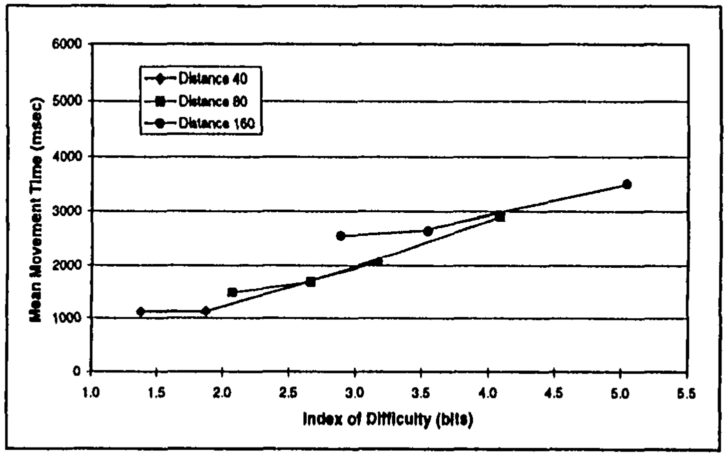
(a) Target Size for Unimpaired Group



(b) Movement Amplitude for Unimpaired Group

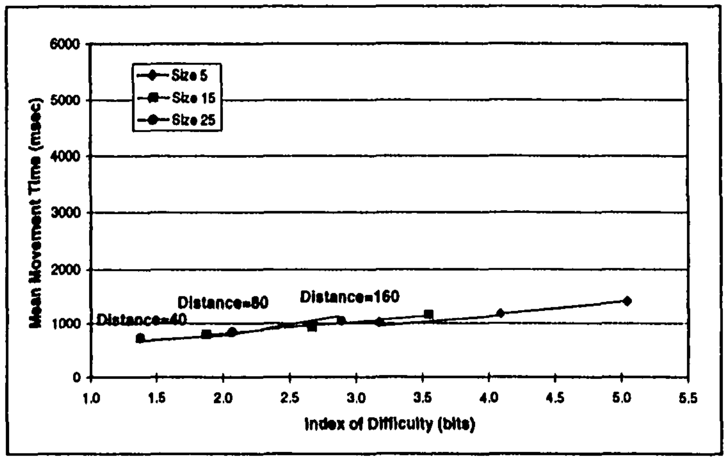


(c) Target Size for Impaired Group

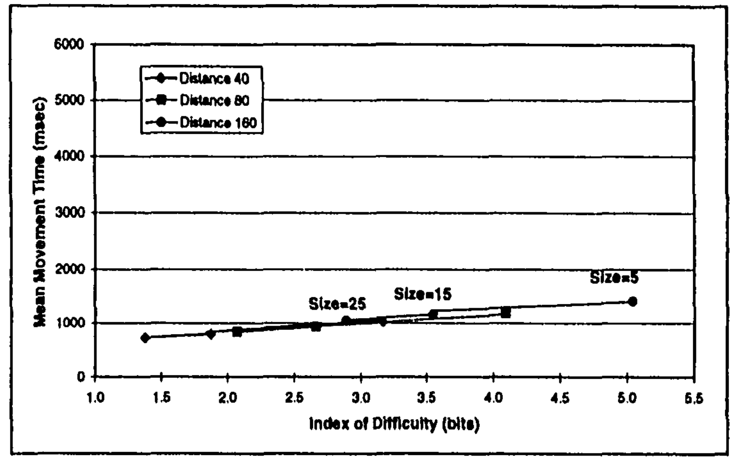


(d) Movement Amplitude for Impaired Group

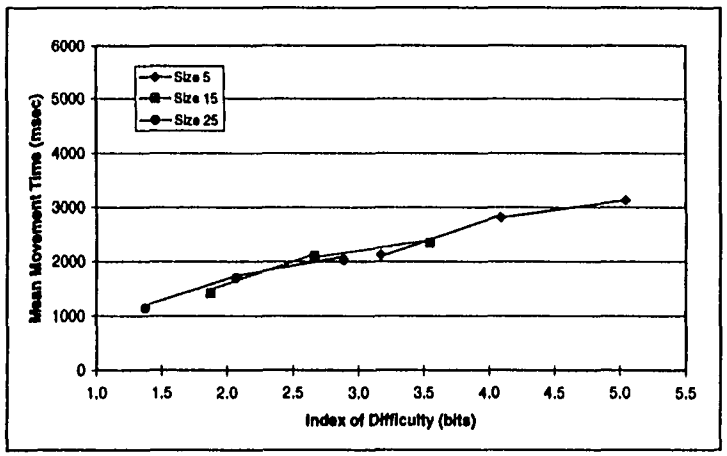
Figure 25. Trackball Mean Movement Time by ID (in Main 2 Session with East Direction and 0.5 CD Gain).



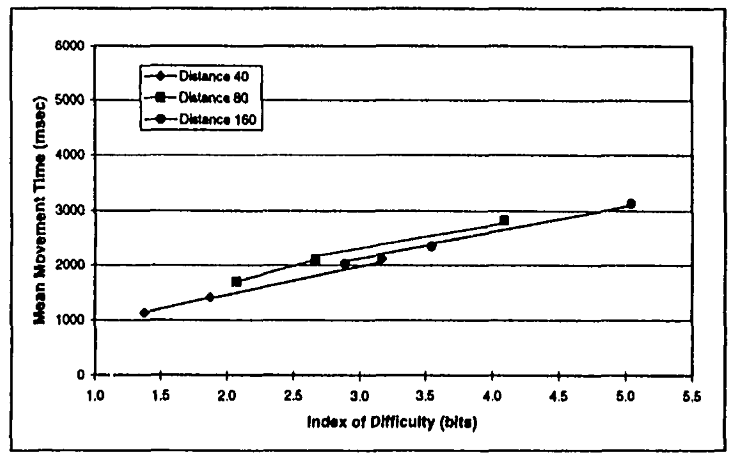
(a) Target Size for Unimpaired Group



(b) Movement Amplitude for Unimpaired Group



(c) Target Size for Impaired Group



(d) Movement Amplitude for Impaired Group

Figure 26. Mouse Mean Movement Time by ID
(in Main 2 Session with East Direction and 0.5 CD Gain).

joystick. Moreover, the impaired participants were unable to utilize the device with higher CD gain due to an excessive loss of control. Appendix H presents the linear regression graphs for all of the devices. Appendix I contains summary tables of the mean slopes, intercepts, R^2 values, indexes of performance (IP), and mid-point movement times (MidMT) for each device and CD gain.

6.5 Correlation Analysis

In order to validate the MMDT as a predictor of input device performance, correlation analysis was performed using the MidMT and IP measures. MidMT is a good measure of average movement time. IP is a measure of relative difficulty for small targets. For the impaired participants, MMDT data were highly correlated with the predicted movement time at the middle of the ID range (MidMT) for all three input devices. The correlations of MMDT scores with the predicted MidMT scores for the impaired group were $r = .74$ for the joystick, $r = .84$ for the trackball, and $r = .70$ for the mouse. However, the correlation of the MMDT scores with the Fitts' index of performance (IP) for the impaired group was somewhat weaker (joystick, $r = .76$; trackball, $r = .70$; mouse, $r = .57$).

On the other hand, the correlations for the unimpaired group were low and ranged from -.05 to .42 (Table 27). Due to the minimal variation both in MMDT and Fitts' scores, there was little opportunity to establish a high correlation. Overall correlation analysis showed that there were high correlations between the MMDT measures and the MidMT measures (joystick, $r = .81$; trackball, $r = .92$; mouse, $r = .86$) due to the vast differences between groups. For the same reason, even though the correlation of the MMDT with the Fitts' IP for overall data showed a weaker correlation than with the MidMT, the correlations were highly significant (joystick, $r = .78$; trackball, $r = .70$; mouse, $r = .64$).

Correlations involving IP for the North direction were higher for the impaired group with the joystick and for the unimpaired group with the mouse. This was

Table 27. Correlation Analysis Results for MMDT Test.

Device	CD Gain	Direction	Unimpaired Group		Impaired Group		Overall	
			MidMT	IP	MidMT	IP	MidMT	IP
Joystick	0.5	East	.3346 (.0230)	.3626 (.0133)	.7204 (.0007)	.7122 (.0009)	.7917 (<.0001)	.7555 (<.0001)
		North	.3548 (.0156)	.2447 (.1013)	.8246 (<.0001)	.8874 (<.0001)	.8873 (<.0001)	.9099 (<.0001)
	1.0	East	.3266 (.0268)	.4176 (.0039)	.7467 (.0004)	.6568 (.0031)	.8163 (<.0001)	.6465 (<.0001)
		North	.3105 (.0357)	.3321 (.0241)	.6881 (.0016)	.7846 (.0001)	.7334 (<.0001)	.7938 (<.0001)
Trackball	0.5	East	.4177 (.0039)	.2587 (.0826)	.8865 (<.0001)	.7417 (.0004)	.9417 (<.0001)	.7112 (<.0001)
		North	.2821 (.0575)	.3415 (.0202)	.8852 (<.0001)	.7287 (.0006)	.9375 (<.0001)	.7117 (<.0001)
	1.0	East	.3526 (.0162)	.2756 (.0638)	.8043 (<.0001)	.7477 (.0004)	.9047 (<.0001)	.6804 (<.0001)
		North	.3412 (.0203)	.2103 (.1607)	.7968 (<.0001)	.6004 (.0084)	.9044 (<.0001)	.6945 (<.0001)
Mouse	0.5	East	.1711 (.2556)	-.0539 (.7223)	.7788 (.0001)	.6239 (.0057)	.8971 (<.0001)	.6417 (<.0001)
		North	.2640 (.0762)	.3557 (.0153)	.7295 (.0006)	.5327 (.0228)	.8728 (<.0001)	.5873 (<.0001)
	1.0	East	.2680 (.0718)	.0074 (.9611)	.7204 (.0007)	.5733 (.0129)	.8576 (<.0001)	.6637 (<.0001)
		North	.3799 (.0092)	.4290 (.0029)	.5906 (.0099)	.5383 (.0212)	.8053 (<.0001)	.6621 (<.0001)

Note: The values in parentheses show *p*-values for the correlations.

anticipated since the movement direction was the same for the MMDT and the North direction. This finding suggests that it may be beneficial to test MMDT movements in an East-West direction with each device.

6.6 Test-Retest Reliability Analysis

For the impaired group, test-retest reliability analysis revealed that the MidMT data for each device were highly correlated between the Main 1 and Main 2 sessions (joystick, r = .97; trackball, r = .96; mouse, r = .92). However, the correlation analysis for the IP data showed that the test measure for the North direction with both CD Gains of the mouse was not reliable for the impaired group (North direction and 0.5 CD Gain, r = .32; North direction and 1.0 CD Gain, r = .45). The joystick and trackball demonstrated higher reliability under these conditions than the mouse (joystick, r = .93; trackball, r = .87).

Test-retest reliability for the unimpaired group was weaker. The MidMT measure was highly reliable for all input devices (joystick, r = .79; trackball, r = .77; mouse, r = .69). However, IP was not a reliable measure for the unimpaired group (Table 28). Overall test-retest reliability for the groups combined was very strong for both measures, due to the variability differences mentioned in Section 6.5. The test-retest reliability of the MidMT measure was high (joystick, r = .97; trackball, r = .98; mouse, r = .96). In addition, even though the overall IP reliability (joystick, r = .86; trackball, r = .71; mouse, r = .62) was somewhat weaker than for MidMT, the reliability was significant.

6.7 Graphical Analysis of the Fitts' Law Task

In this section, two response measures, movement time and index of performance, are graphically presented. Mean predicted movement time at the middle ID value and mean index of performance were plotted along with the range and standard deviation (SD) for each input device for each group. Based on the graphs, visual interpretations of the two measures are discussed for each group.

6.7.1 Movement Time (MT) Analysis

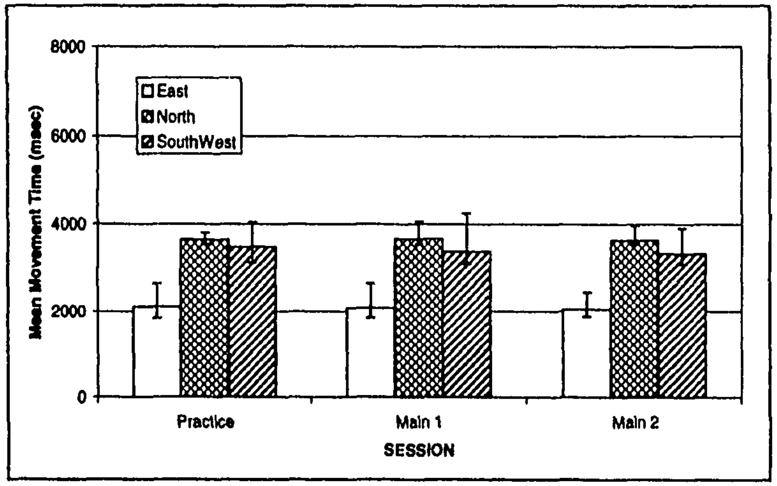
Unimpaired Group

For the joystick, the higher CD gain (1.0) resulted in high variability across participants (Figure 27), particularly for the Southwest direction. The variability across participants for the trackball and mouse was notably small for all combinations of Session, CD Gain, and Direction (Figures 28 and 29). In addition, the average movement time (mean MidMT) for the joystick was slowest among the three devices, while the average movement times for the trackball and mouse were not significantly different. For all three devices, there were no noticeable performance changes across sessions.

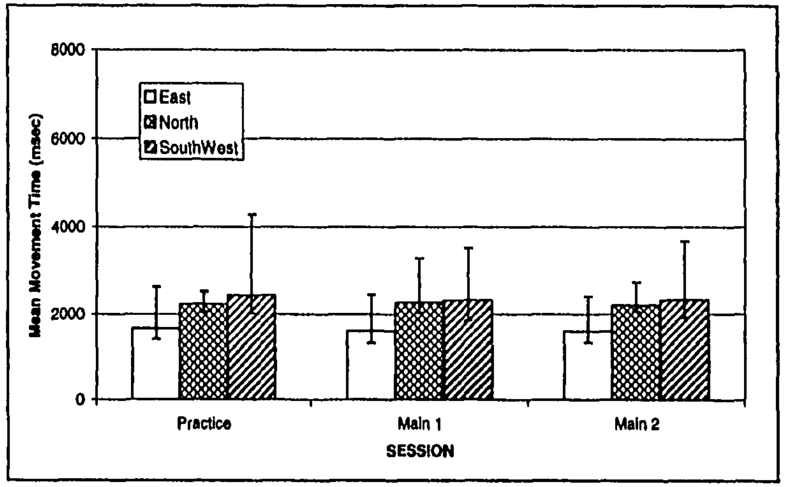
Table 28. Test-Retest Reliability for Each Input Device.

Device	CD Gain	Direction	Unimpaired Group		Impaired Group		Overall	
			MidMT	IP	MidMT	IP	MidMT	IP
Joystick	0.5	East	.8153 (<.0001)	.5825 (.0035)	.9550 (<.0001)	.9219 (.0004)	.9419 (<.0001)	.8553 (<.0001)
		North	.6186 (.0017)	.2235 (.3052)	.9626 (<.0001)	.9293 (.0003)	.9688 (<.0001)	.9023 (<.0001)
	1.0	East	.8834 (<.0001)	.6108 (.0020)	.9610 (<.0001)	.8968 (.0010)	.9632 (<.0001)	.7984 (<.0001)
		North	.8259 (<.0001)	.6813 (.0003)	.9987 (<.0001)	.9722 (<.0001)	.9968 (<.0001)	.8949 (<.0001)
Trackball	0.5	East	.7349 (<.0001)	.2013 (.3570)	.9326 (.0002)	.8807 (.0017)	.9643 (<.0001)	.6777 (<.0001)
		North	.8766 (<.0001)	.4470 (.0325)	.9961 (<.0001)	.9508 (<.0001)	.9948 (<.0001)	.7966 (<.0001)
	1.0	East	.6586 (.0006)	.0690 (.7547)	.9530 (<.0001)	.8747 (.0020)	.9733 (<.0001)	.5850 (.0004)
		North	.8028 (<.0001)	.3473 (.1044)	.9704 (<.0001)	.7855 (.0121)	.9840 (<.0001)	.7635 (<.0001)
Mouse	0.5	East	.5505 (.0065)	.3790 (.0745)	.9290 (.0003)	.8354 (.0050)	.9637 (<.0001)	.6437 (<.0001)
		North	.8350 (<.0001)	.3760 (.0771)	.9742 (<.0001)	.3190 (.4027)	.9856 (<.0001)	.4634 (.0076)
	1.0	East	.6334 (.0012)	.3656 (.0863)	.9117 (.0006)	.8719 (.0022)	.9509 (<.0001)	.7373 (<.0001)
		North	.7384 (<.0001)	.4864 (.0186)	.8804 (.0017)	.4512 (.2229)	.9360 (<.0001)	.6177 (.0002)

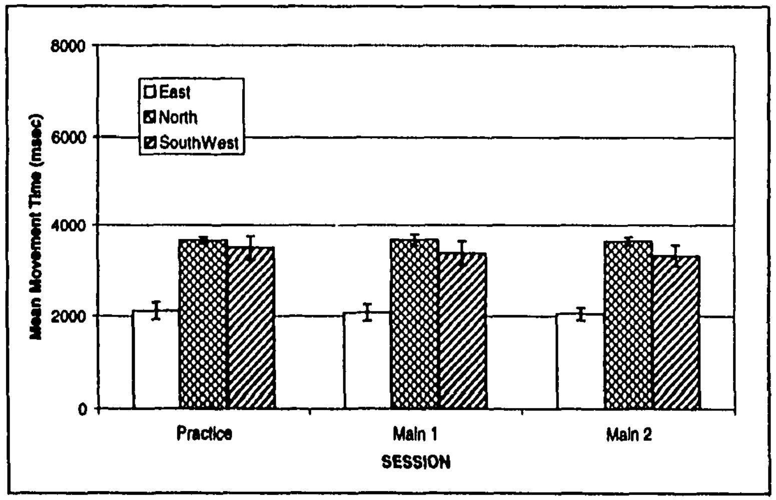
Note: The values in parentheses show *p*-values for the correlations.



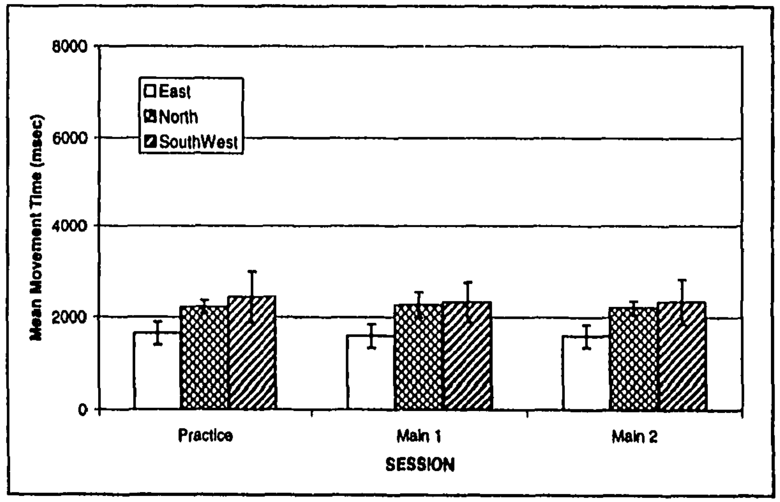
(a) Mean MidMT with Range for 0.5 CD Gain



(b) Mean MidMT with Range for 1.0 CD Gain

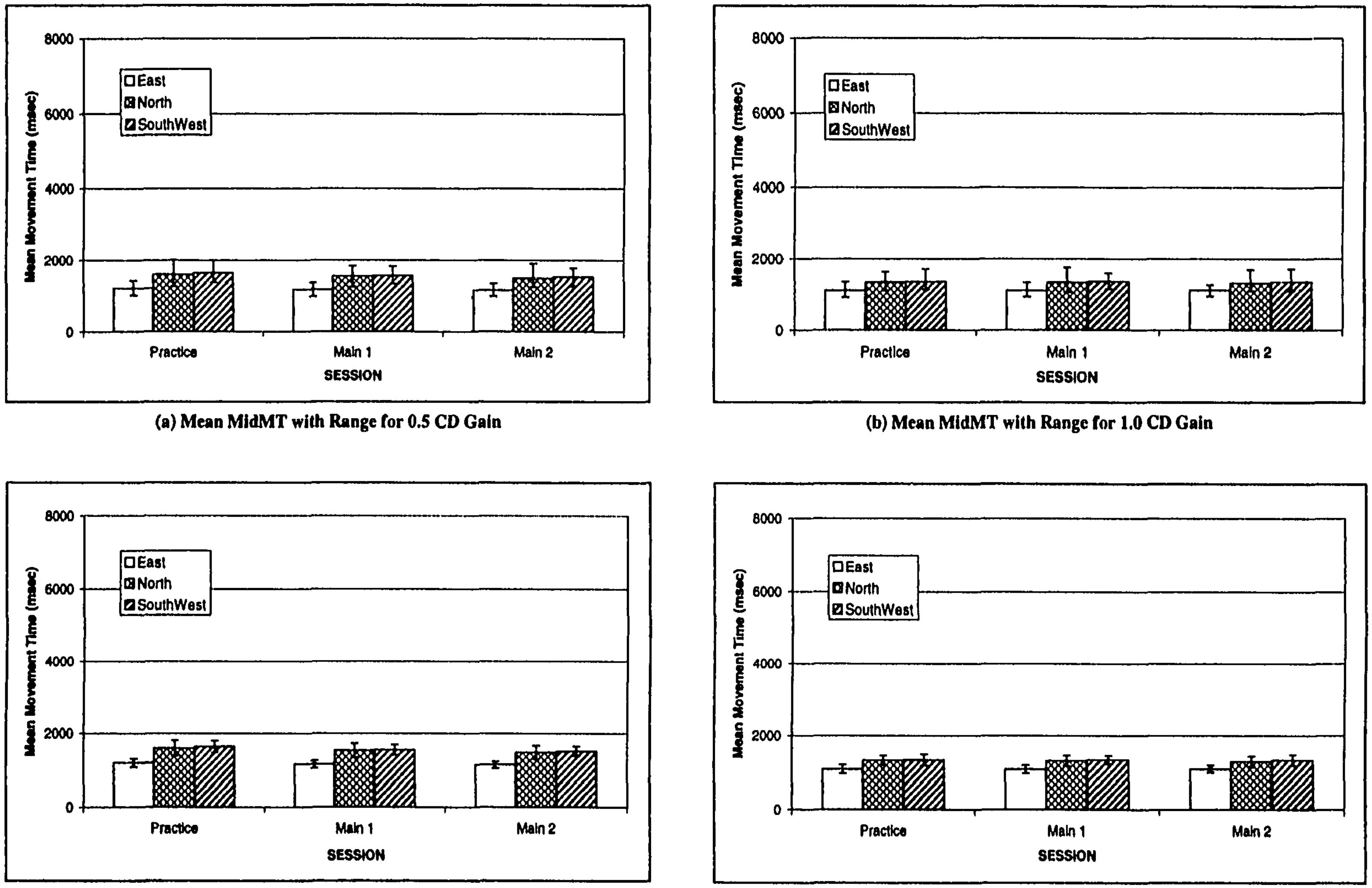


(c) Mean MidMT with Standard Deviation for 0.5 CD Gain



(d) Mean MidMT with Standard Deviation for 1.0 CD Gain

Figure 27. Joystick Movement Time Mean and Standard Deviation by Session for the Unimpaired Group.



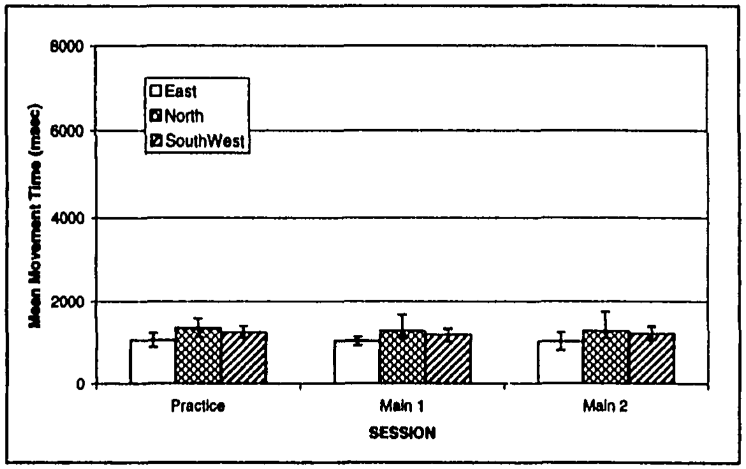
(a) Mean MidMT with Range for 0.5 CD Gain

(b) Mean MidMT with Range for 1.0 CD Gain

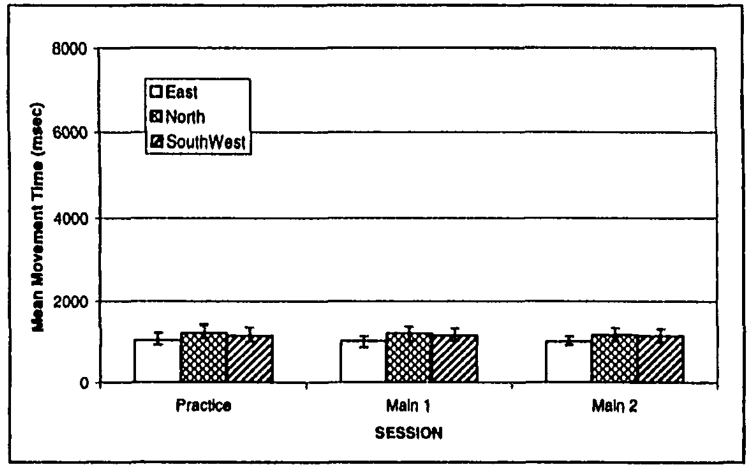
(c) Mean MidMT with Standard Deviation for 0.5 CD Gain

(d) Mean MidMT with Standard Deviation for 1.0 CD Gain

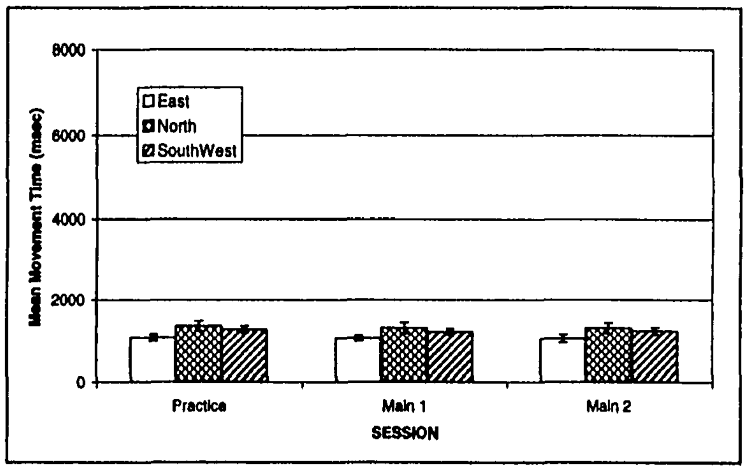
Figure 28. Trackball Movement Time Mean and Standard Deviation by Session for the Unimpaired Group.



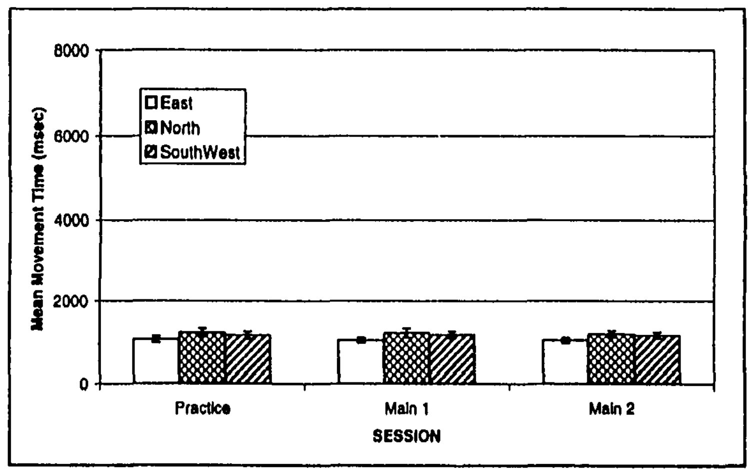
(a) Mean MidMT with Range for 0.5 CD Gain



(b) Mean MidMT with Range for 1.0 CD Gain



(c) Mean MidMT with Standard Deviation for 0.5 CD Gain



(d) Mean MidMT with Standard Deviation for 1.0 CD Gain

Figure 29. Mouse Movement Time Mean and Standard Deviation by Session for the Unimpaired Group.

Impaired Group

The impaired group performed the tests in a similar pattern to the unimpaired group. However, the variability was much greater for the impaired group than for the unimpaired group. The performance by the impaired participants was significantly worse with the joystick (Figure 30). The performance ranges and standard deviations as well as the mean movement times were very similar for the trackball and mouse (Figures 31 and 32). The performance changes between sessions were not remarkable, while the performance change between CD gains was notable, particularly for the joystick. A higher CD gain resulted in faster movement by decreasing travel time without adversely affecting adjustable time.

6.7.2 Index of Performance (IP) Analysis

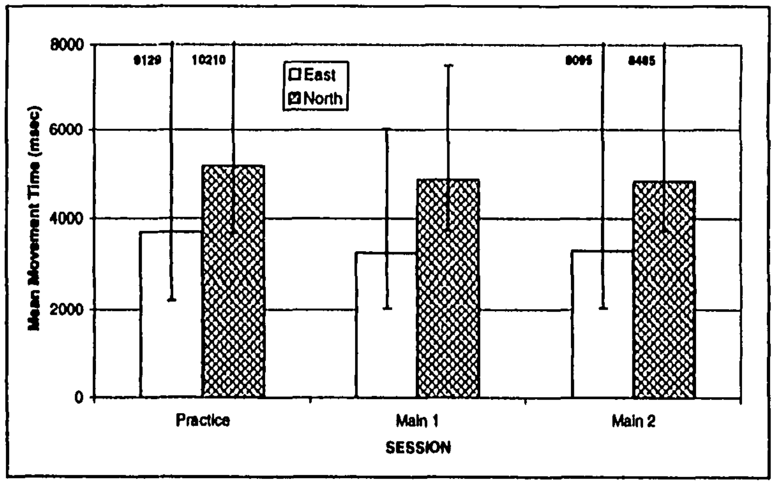
Unimpaired Group

In contrast with the MidMT measure, the IP measure for the joystick displayed the least variability, suggesting that joystick performance was more dependent on the characteristics of the device and less dependent on human control differences (Figure 33). As the CD gain increased, the joystick variability increased slightly. The variability for the trackball and mouse was higher than the variability for the joystick (Figures 34 and 35). Performance differences between input devices were clearly detectable, while the changes across sessions were minimal.

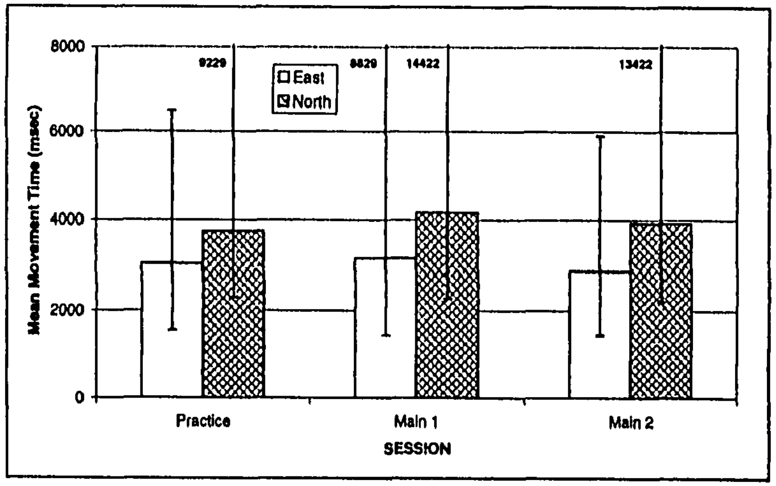
Impaired Group

The impaired group produced similar results to the unimpaired group. However, overall variability of the IP measure for the impaired group was higher than for the unimpaired group. For the joystick, range differences between CD gains were more noticeable than standard deviation differences (Figure 36). The trackball and mouse, however, showed less of a change as CD gain increased (Figures 37 and 38).

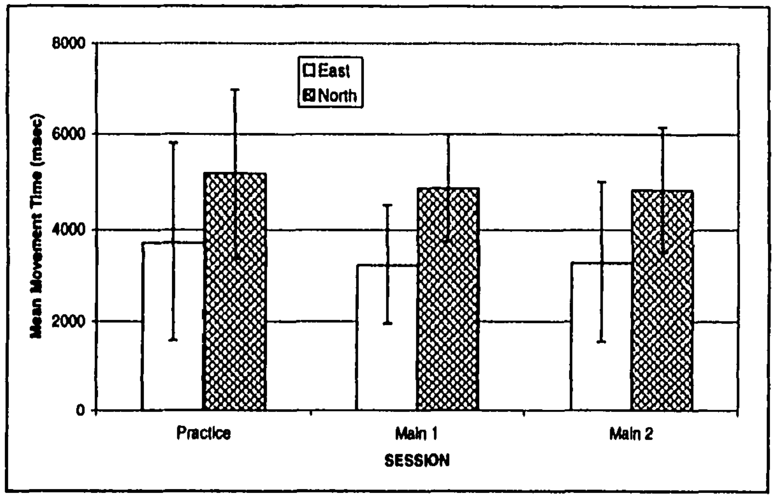
For all three devices, variability in the East direction was much higher than in the North direction. The variability differences between directions were particularly



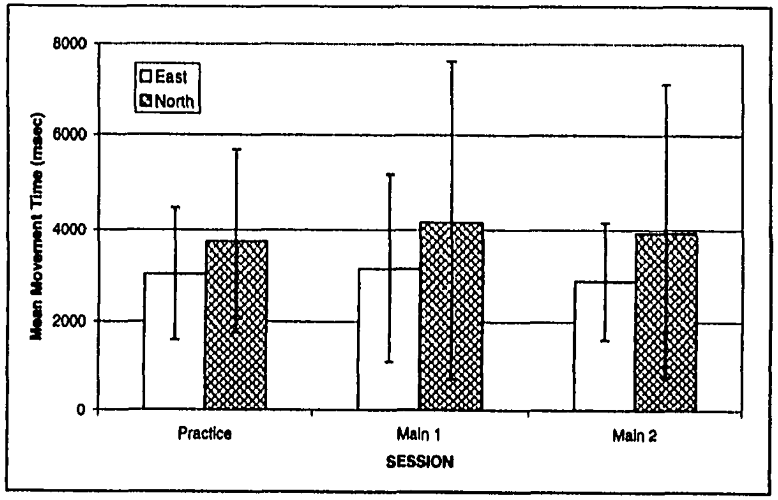
(a) Mean MidMT with Range for 0.5 CD Gain



(b) Mean MidMT with Range for 1.0 CD Gain

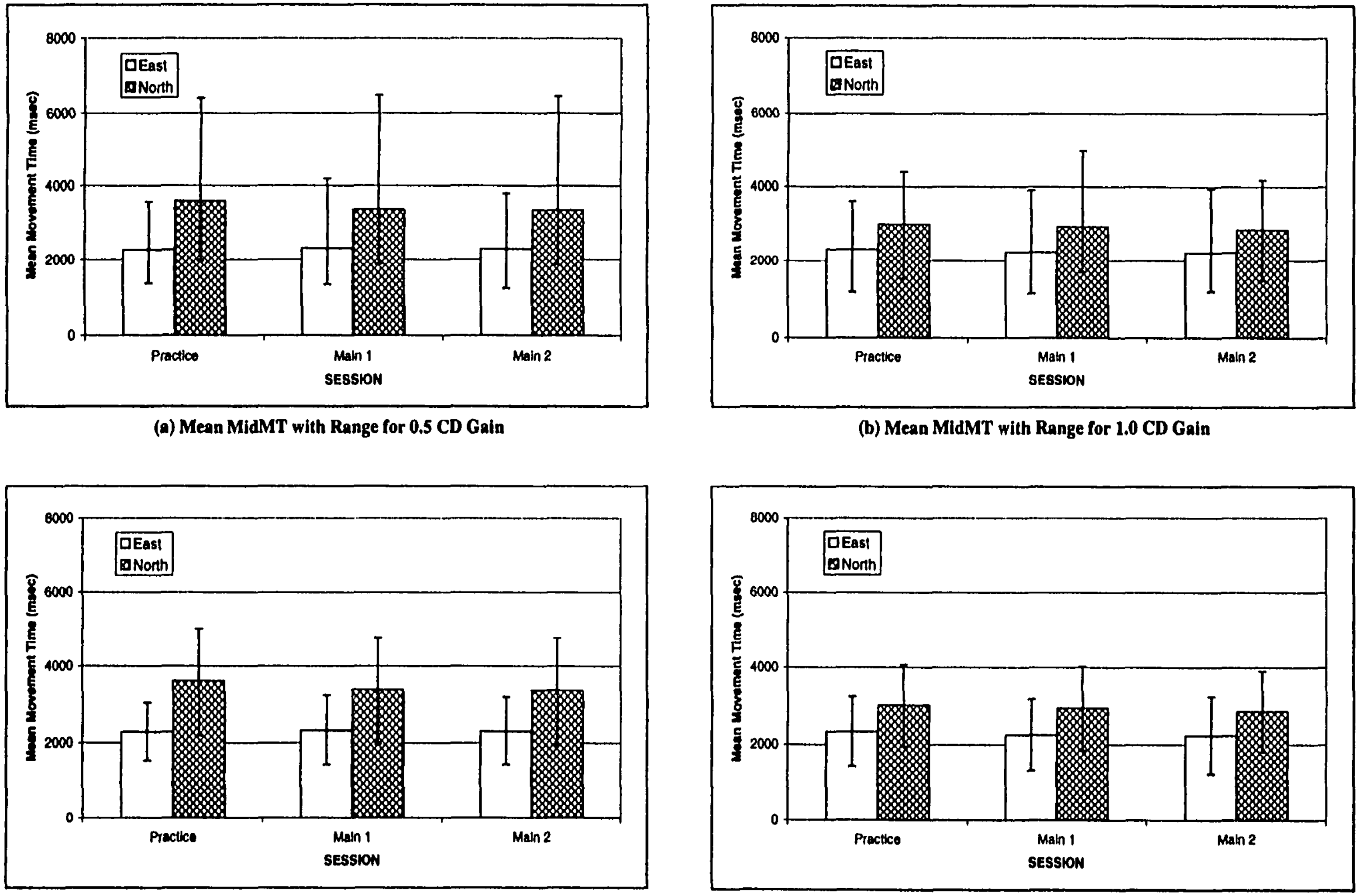


(c) Mean MidMT with Standard Deviation for 0.5 CD Gain



(d) Mean MidMT with Standard Deviation for 1.0 CD Gain

Figure 30. Joystick Movement Time Mean and Standard Deviation by Session for the Impaired Group.



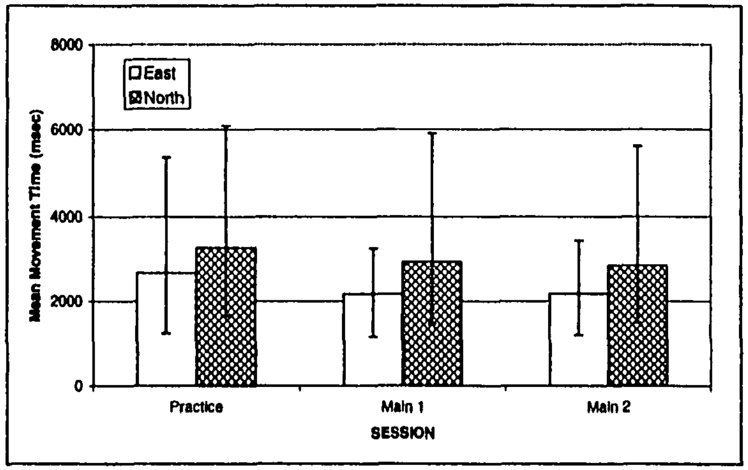
(a) Mean MidMT with Range for 0.5 CD Gain

(b) Mean MidMT with Range for 1.0 CD Gain

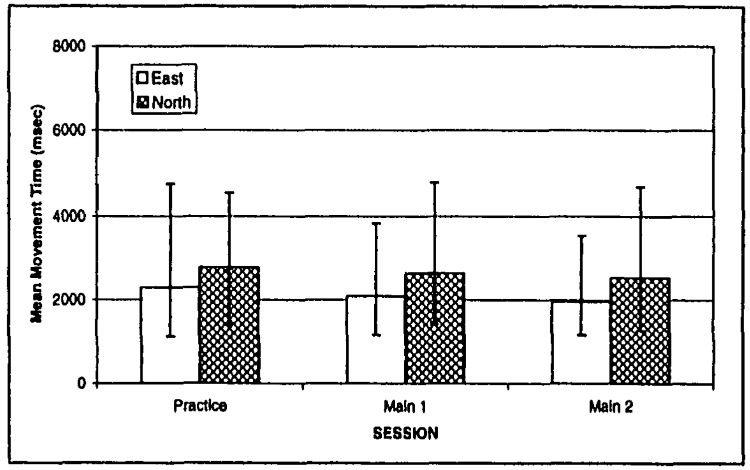
(c) Mean MidMT with Standard Deviation for 0.5 CD Gain

(d) Mean MidMT with Standard Deviation for 1.0 CD Gain

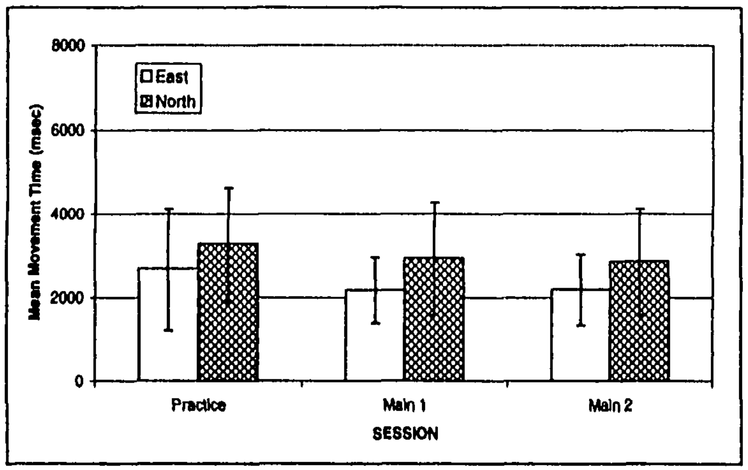
Figure 31. Trackball Movement Time Mean and Standard Deviation by Session for the Impaired Group.



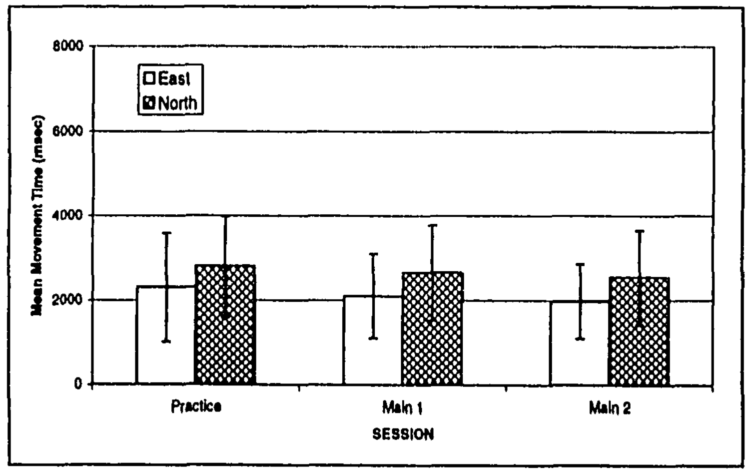
(a) Mean MidMT with Range for 0.5 CD Gain



(b) Mean MidMT with Range for 1.0 CD Gain

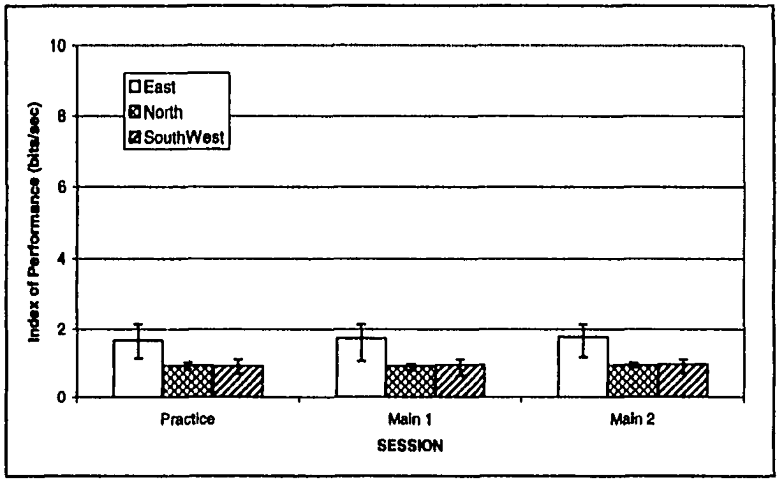


(c) Mean MidMT with Standard Deviation for 0.5 CD Gain

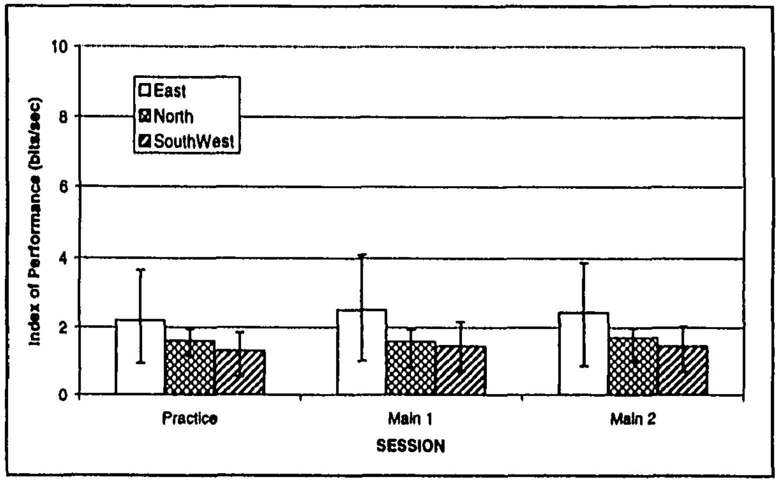


(d) Mean MidMT with Standard Deviation for 1.0 CD Gain

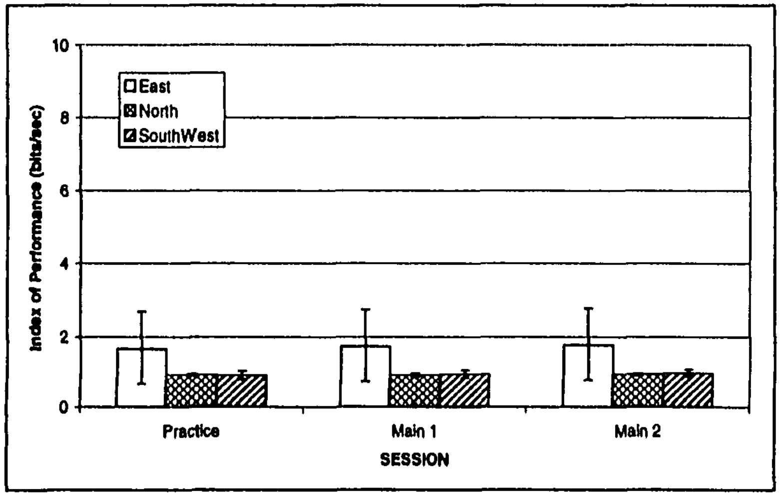
Figure 32. Mouse Movement Time Mean and Standard Deviation by Session for the Impaired Group.



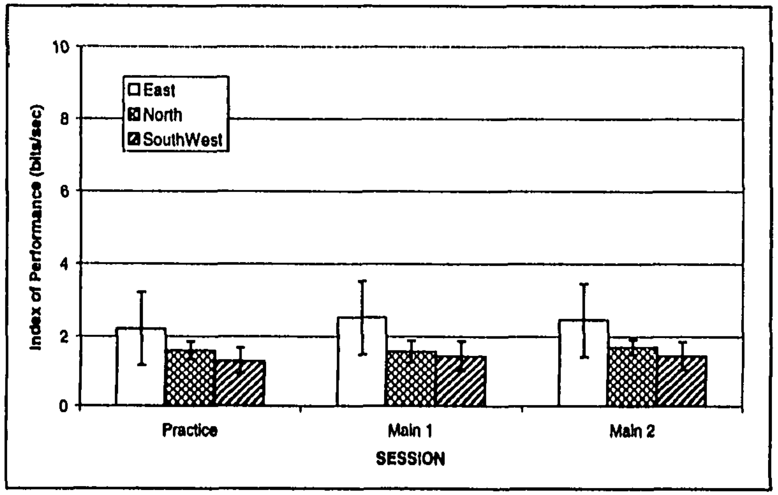
(a) Mean IP with Range for 0.5 CD Gain



(b) Mean IP with Range for 1.0 CD Gain

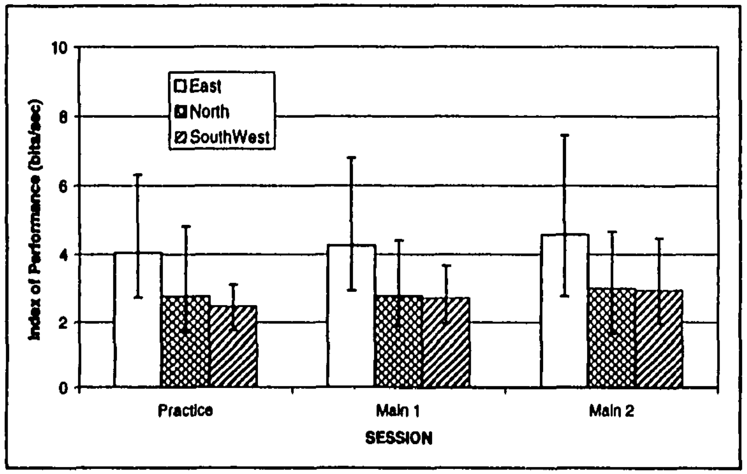


(c) Mean IP with Standard Deviation for 0.5 CD Gain

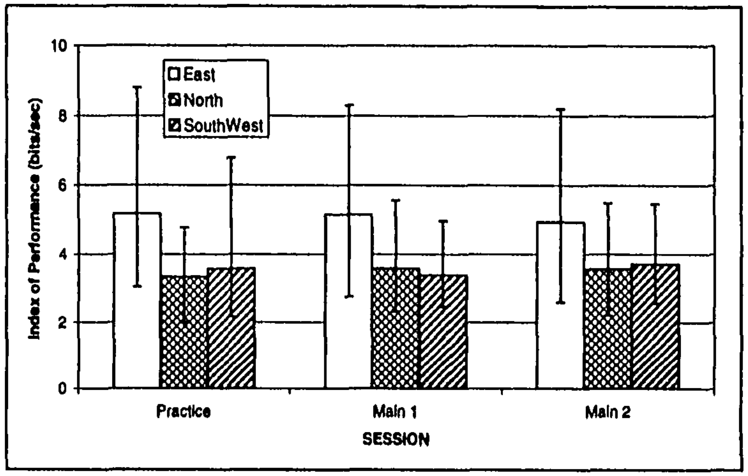


(d) Mean IP with Standard Deviation for 1.0 CD Gain

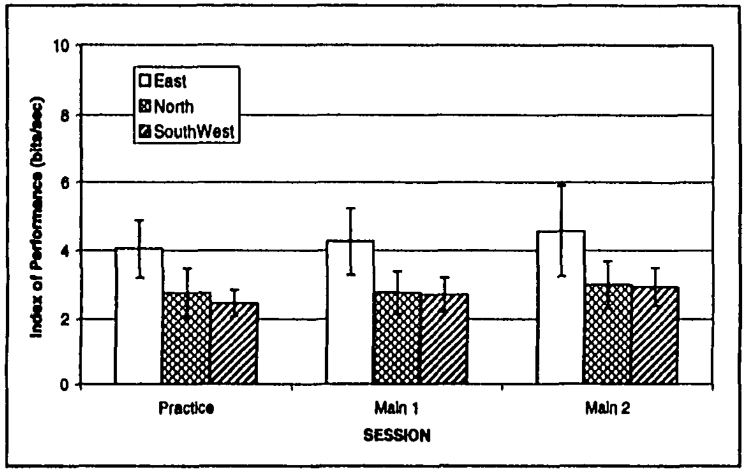
Figure 33. Joystick IP Mean and Standard Deviation by Session for the Unimpaired Group.



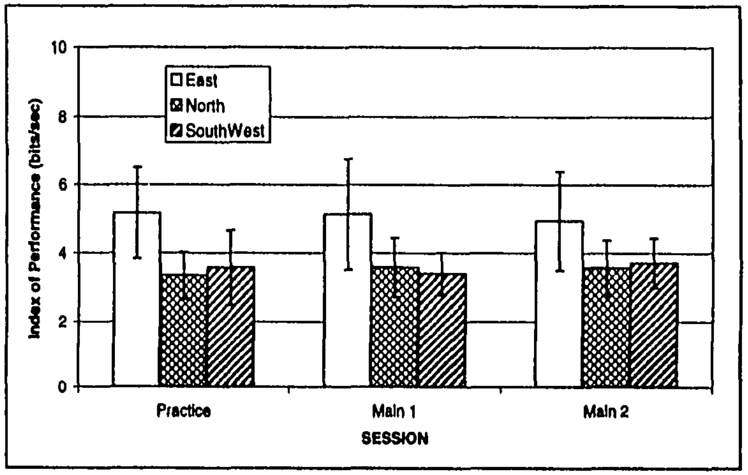
(a) Mean IP with Range for 0.5 CD Gain



(b) Mean IP with Range for 1.0 CD Gain

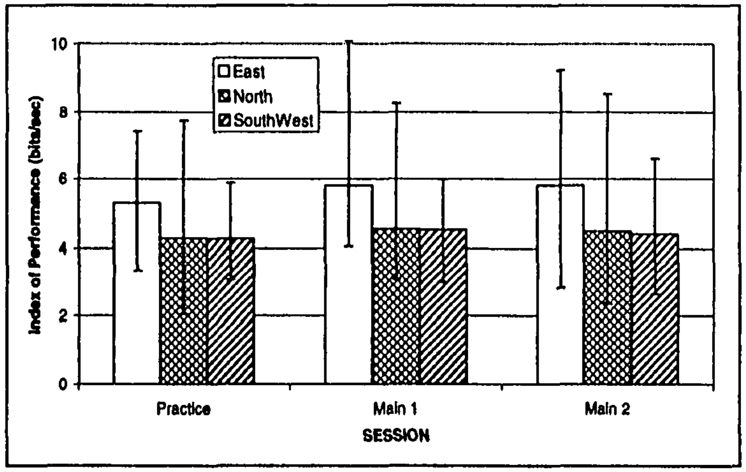


(c) Mean IP with Standard Deviation for 0.5 CD Gain

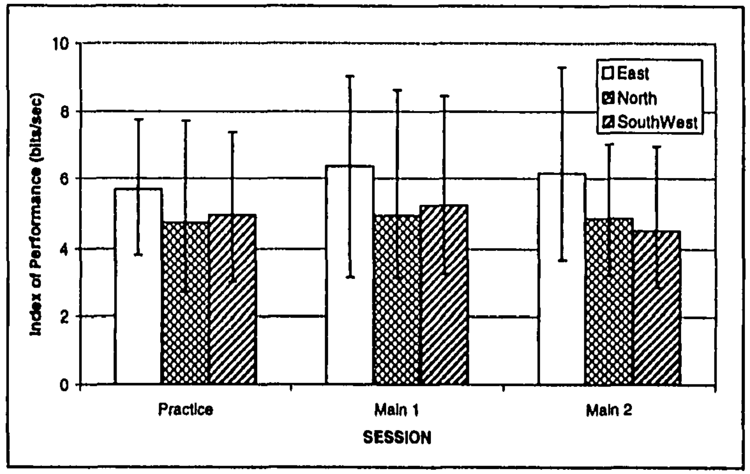


(d) Mean IP with Standard Deviation for 1.0 CD Gain

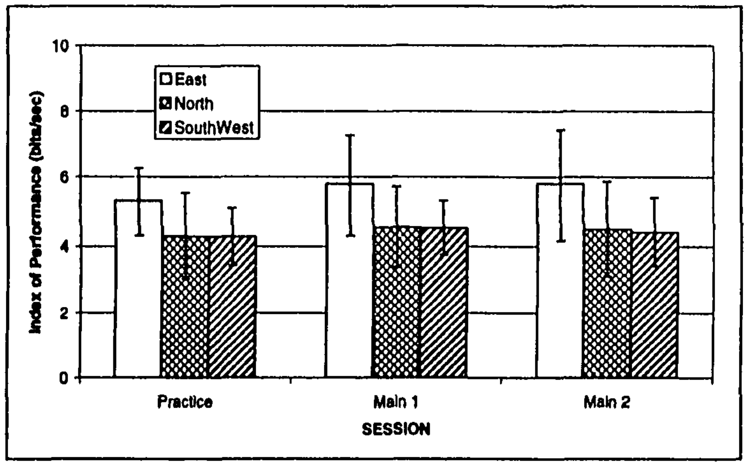
Figure 34. Trackball IP Mean and Standard Deviation by Session for the Unimpaired Group.



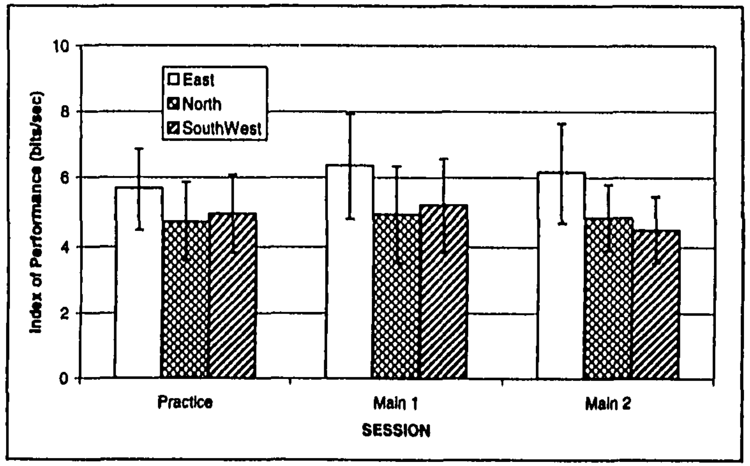
(a) Mean IP with Range for 0.5 CD Gain



(b) Mean IP with Range for 1.0 CD Gain

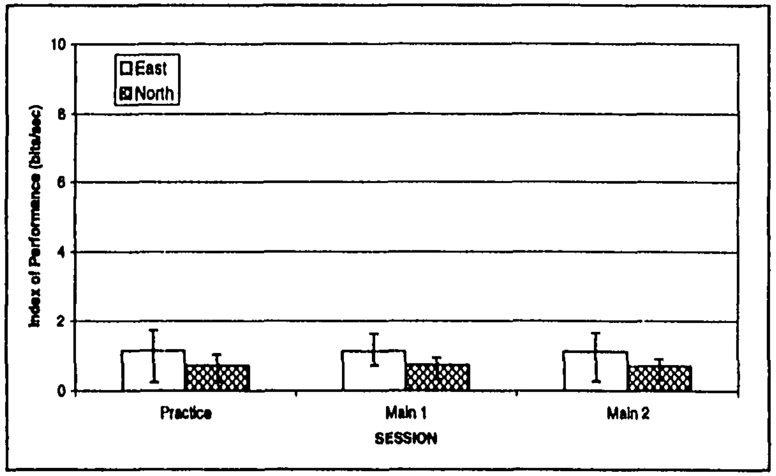


(c) Mean IP with Standard Deviation for 0.5 CD Gain

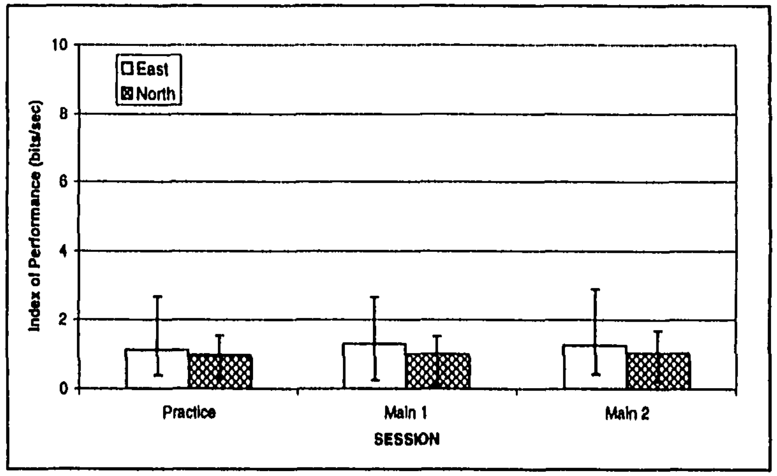


(d) Mean IP with Standard Deviation for 1.0 CD Gain

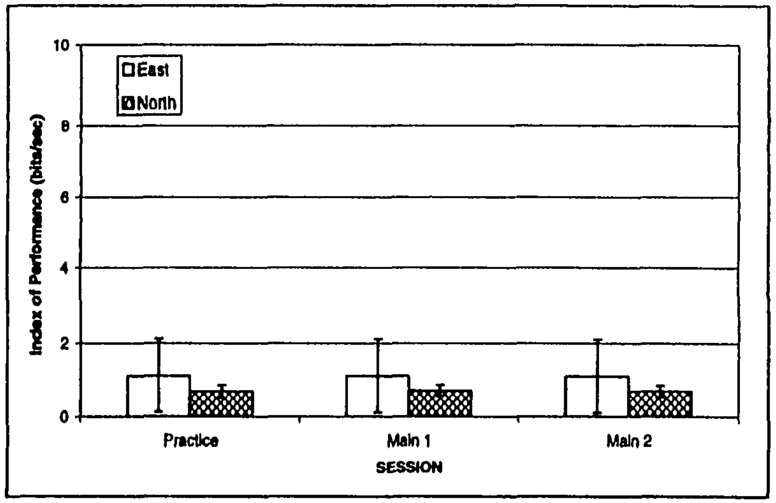
Figure 35. Mouse IP Mean and Standard Deviation by Session for the Unimpaired Group.



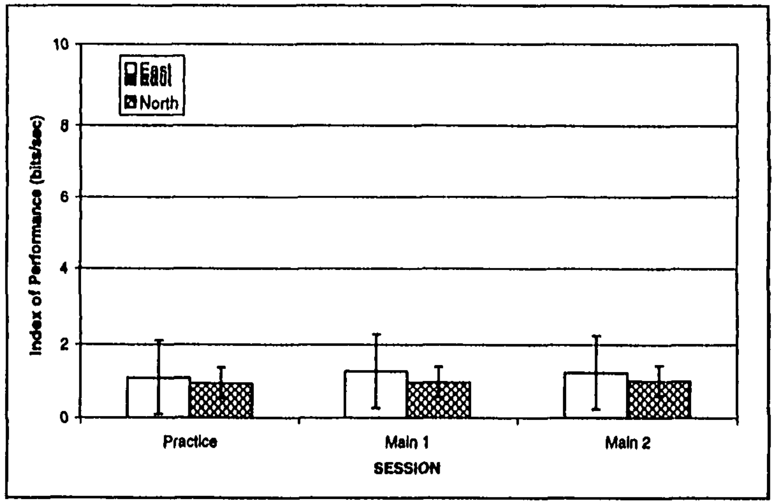
(a) Mean IP with Range for 0.5 CD Gain



(b) Mean IP with Range for 1.0 CD Gain

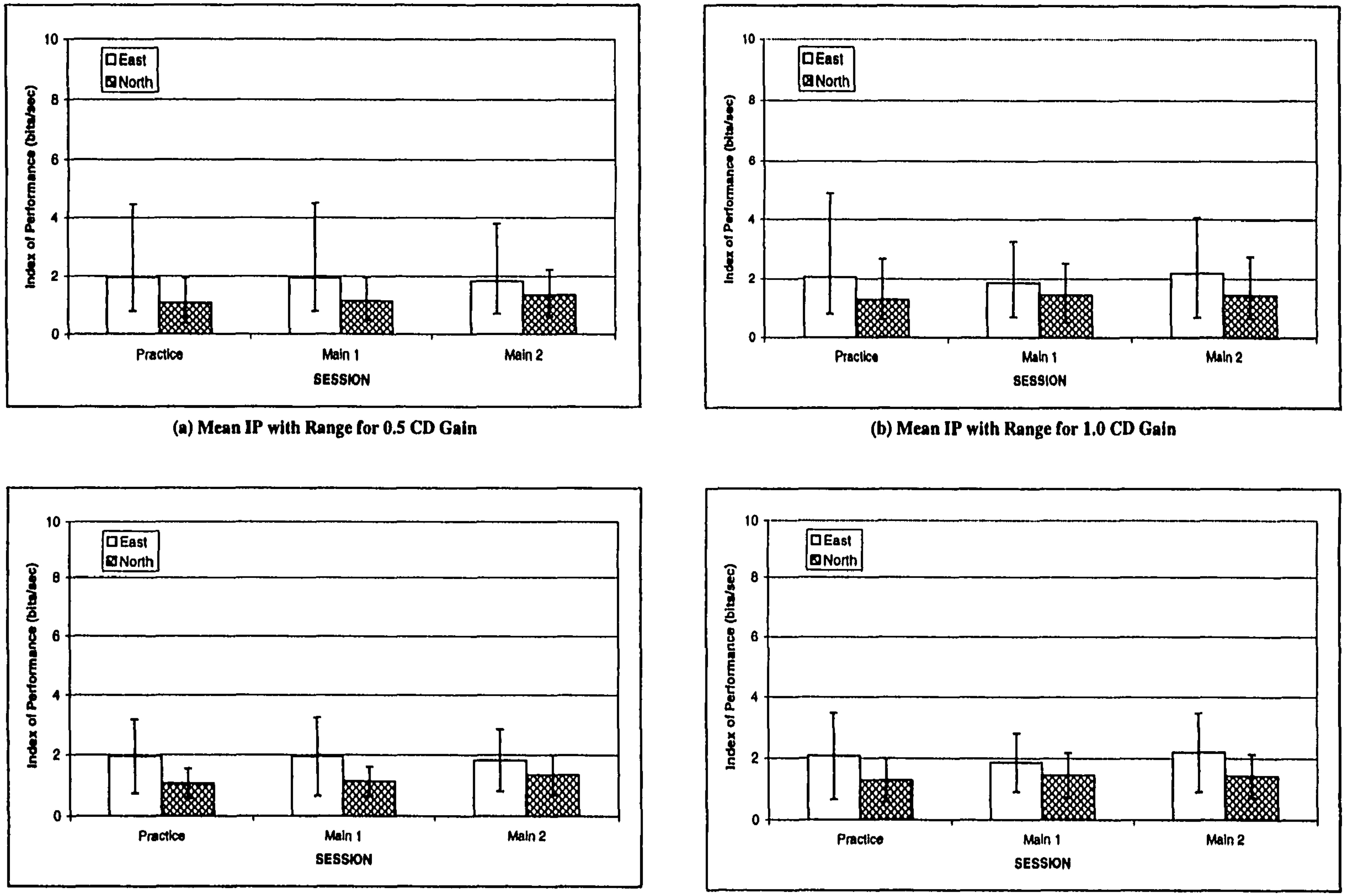


(c) Mean IP with Standard Deviation for 0.5 CD Gain



(d) Mean IP with Standard Deviation for 1.0 CD Gain

Figure 36. Joystick IP Mean and Standard Deviation by Session for the Impaired Group.



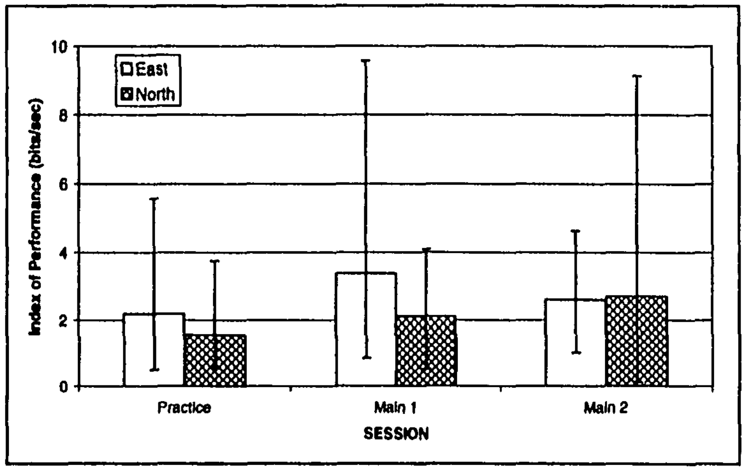
(a) Mean IP with Range for 0.5 CD Gain

(b) Mean IP with Range for 1.0 CD Gain

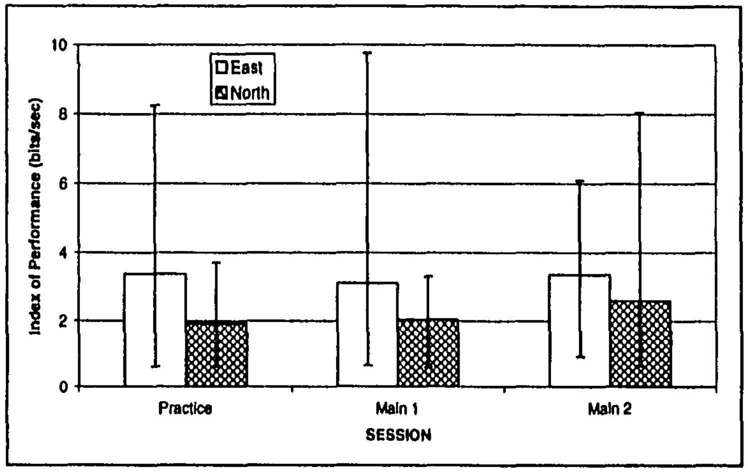
(c) Mean IP with Standard Deviation for 0.5 CD Gain

(d) Mean IP with Standard Deviation for 1.0 CD Gain

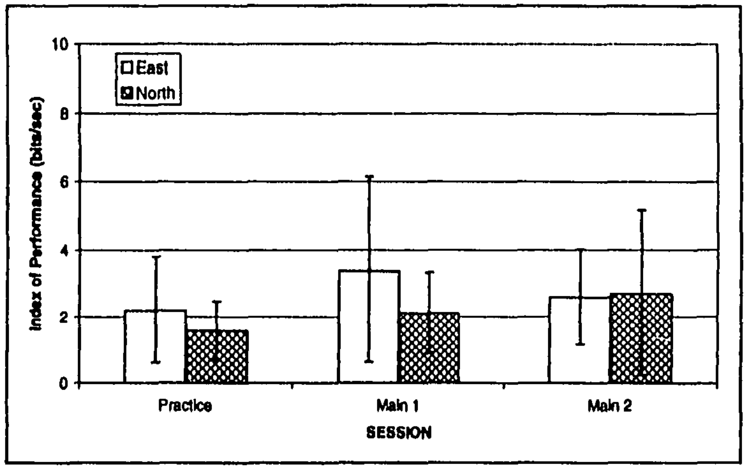
Figure 37. Trackball IP Mean and Standard Deviation by Session for the Impaired Group.



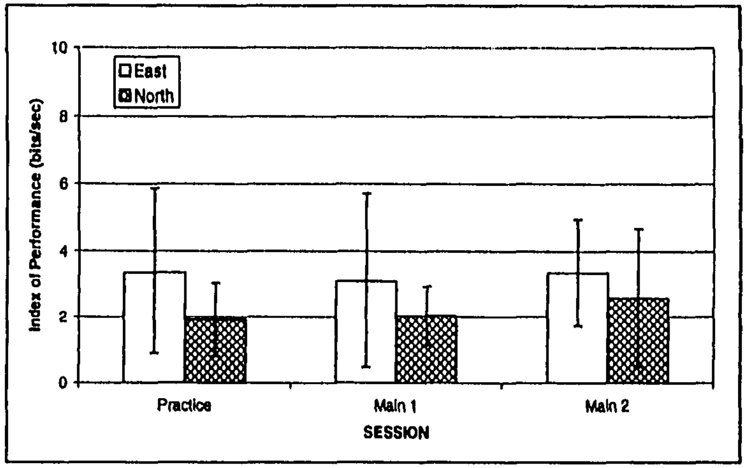
(a) Mean IP with Range for 0.5 CD Gain



(b) Mean IP with Range for 1.0 CD Gain



(c) Mean IP with Standard Deviation for 0.5 CD Gain



(d) Mean IP with Standard Deviation for 1.0 CD Gain

Figure 38. Mouse IP Mean and Standard Deviation by Session for the Impaired Group.

large for the mouse. One reason was that participant D02 performed extremely well in the East direction during the Main 1 session (9.56 bits/sec in 0.5 CD gain and 9.76 bits/sec in 1.0 CD gain), while participant D03 performed extremely poorly in the same condition (0.85 bits/sec in 0.5 CD gain and 0.67 bits/sec in 1.0 CD gain).

As shown in Figure 38, these results did not hold in the Main 2 session for the mouse, because participant D06 performed especially well in the North direction for both CD gains during the Main 2 session (9.14 bits/sec in 0.5 CD gain and 8.05 bits/sec in 1.0 CD gain), while participant D07 performed poorly in the same condition (0.77 bits/sec in 0.5 CD gain and 0.64 bits/sec in 1.0 CD gain). A critical finding of this analysis is that the high sensitivity of the mouse was a disadvantage for the impaired group participants. The high performance variability implied that mouse performance may be a clear indicator of individual differences.

For the joystick, greater variability in performance was found at higher CD gains for participants in the impaired group. This result was not apparent for the trackball and mouse. The mean IP varied slightly across the three input devices, but did not vary significantly across sessions.

6.8 Statistical Analysis of the Fitts' Law Task

Results of the SAS GLM full nested factorial model for both movement time and IP measures are presented in this section. Differences in mean predicted movement time at the middle ID value and mean index of performance were analyzed using the SAS statistical analysis software. To support statistical significance, various graphs are presented for interesting main effects and interactions. In addition, the results were analyzed in various ways to determine whether the response measures were meaningful with respect to the proposed goals of this study.

6.8.1 Movement Time (MT) Analysis

Table 29 summarizes the SAS GLM results for the mid-point movement time (MidMT). To avoid the inherent variability associated with the Fitts' Law slope and intercept, predicted movement time at the mid-point (MidMT) of the tested index of difficulty values (ID = 3.21) was analyzed. The effect of device was statistically significant, $F(2, 64) = 69.30, p < .0001$. As discussed in Section 5.5.2.2, the inherent gains of the input devices differed. In general, if a participant did not have any problems using input devices, the mouse was the fastest device, followed by the trackball and joystick. Multiple comparisons using Tukey's HSD test confirmed that the joystick was significantly slower than the other two devices, which were equivalent. Figure 39 presents the differences among input devices.

Movement direction was also significant, $F(1, 32) = 208.32, p < .0001$. Since the Fitts' Law program used in this study produced different movement rates for the East versus North movements (Table 18), this significant finding was expected. The difference between the two directions is shown in Figure 40. Unfortunately, it is not known how much of the difference is due to the software and how much is contributed by the human.

The effect of CD gain on MidMT was also significant, $F(1, 32) = 30.45, p < .0001$. Figure 41 illustrates the difference between the two CD gains. Devices with the higher CD gain produced higher variability across participants. This would imply that a higher CD gain may be a disadvantage for the impaired participants. In addition, higher CD gain enhances the ability to distinguish the level of impairment.

The effect of session was statistically significant, $F(1, 32) = 20.06, p < .0001$. The significant difference between the two sessions (Main 1 = 2064 ms and Main 2 = 2025 ms, respectively) implied that the participants still demonstrated a learning effect after the Practice session (Figure 42). However, Tukey's multiple comparison procedure in an analysis involving all three sessions showed that no significant

Table 29. SAS GLM Procedure Results for MidMT.

Source	df	SS	MS	F-value	Pr > F
Input Device [I]	2	236353172.80	118176586.4	69.30	<.0001
Direction [D]	1	96657381.28	96657381.28	208.32	<.0001
CD Gain [C]	1	22881208.78	22881208.78	30.45	<.0001
Session [T]	1	422960.37	422960.3737	20.06	<.0001
Group [G]	1	331194995.40	331194995.4	33.50	<.0001
IxD	2	21607355.16	10803677.58	26.35	<.0001
IxC	2	13249277.19	6624638.60	18.22	<.0001
DxC	1	6542616.06	6542616.056	39.98	<.0001
IxDxC	2	3407835.29	1703917.647	6.50	.0027
IxT	2	78889.03	39444.51348	2.17	.1230
DxT	1	35644.51	35644.51	3.31	.0781
IxDxT	2	1548.69	774.34	0.04	.9605
CxT	1	158644.17	158644.17	1.18	.2847
IxCxT	2	134876.95	67438.47	0.64	.5322
DxCxT	1	1967.51	1967.51	0.07	.8003
IxDxCxT	2	14470.60	7235.3	0.19	.8266
IxG	2	938461.30	469230.7	0.28	.7603
DxG	1	7077111.77	7077111.77	15.25	.0005
CxG	1	61005.25	61005.25	0.08	.7775
TxG	1	135490.71	135490.7129	6.43	.0163
IxDxG	2	1003850.42	501925.21	1.22	.3008
IxCxG	2	3226053.13	1613026.56	4.44	.0157
DxCxG	1	3696.99	3696.985	0.02	.8815
IxTxG	2	46913.04	23456.51971	1.29	.2829
DxTxG	1	457.35	457.35	0.04	.8380
CxTxG	1	181115.53	181115.53	1.35	.2536
IxDxCxG	2	813303.74	406651.868	1.55	.2199
IxCxTxG	2	89706.82	44853.41	0.42	.6564
IxDxTxG	2	1541.71	770.86	0.04	.9606
DxCxTxG	1	17469.47	17469.47	0.58	.4528
IxDxCxTxG	2	31287.80	15643.9	0.41	.6635
Subject [S(G)]	32	316383029.90	9886969.7	260.96	<.0001
IxS(G)	64	109136555.00	1705258.7	45.01	<.0001
DxS(G)	32	14847671.80	463989.7	12.25	<.0001
IxDxS(G)	64	26244514.90	410070.5	10.82	<.0001
CxS(G)	32	24048891.20	751527.8	19.84	<.0001
IxCxS(G)	64	23263762.60	363496.3	9.59	<.0001
DxCxS(G)	32	5236451.60	163639.1	4.32	<.0001
IxDxCxS(G)	64	16780169.20	262190.1	6.92	<.0001
TxS(G)	32	674738.60	21085.6	0.56	.9640
IxTxS(G)	64	1165716.80	18214.3	0.48	.9981
DxTxS(G)	32	344355.90	10761.1	0.28	.9999
IxDxTxS(G)	64	1227647.50	19182.0	0.51	.9964
CxTxS(G)	32	4288326.30	134010.2	3.54	<.0001
IxCxTxS(G)	64	6774970.90	105858.9	2.79	<.0001
DxCxTxS(G)	32	967805.40	30243.9	0.80	.7543
IxDxCxTxS(G)=Error	64	2424759.10	37886.9		
Total	815	13336212724.00			

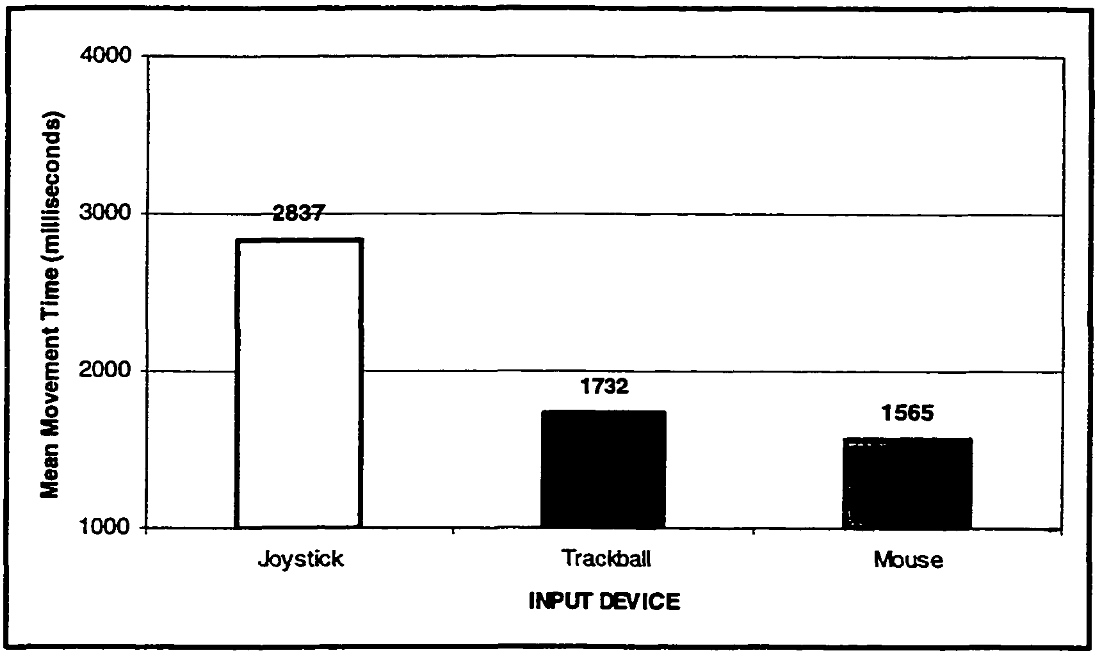


Figure 39. Input Device Comparison for MidMT.

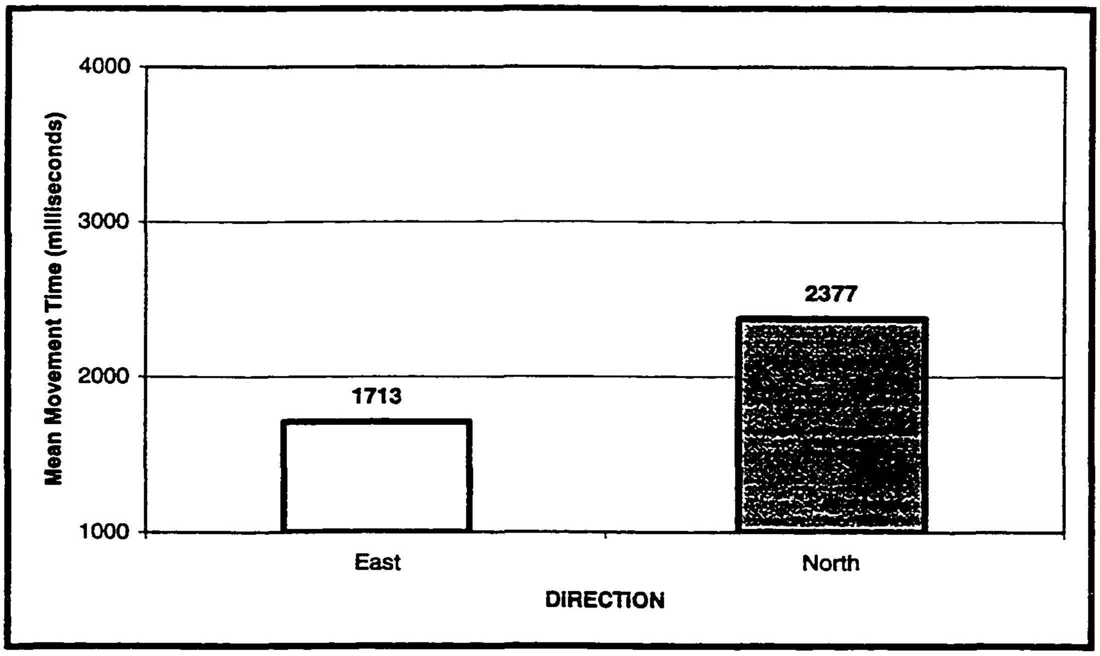


Figure 40. Direction Comparison for MidMT.

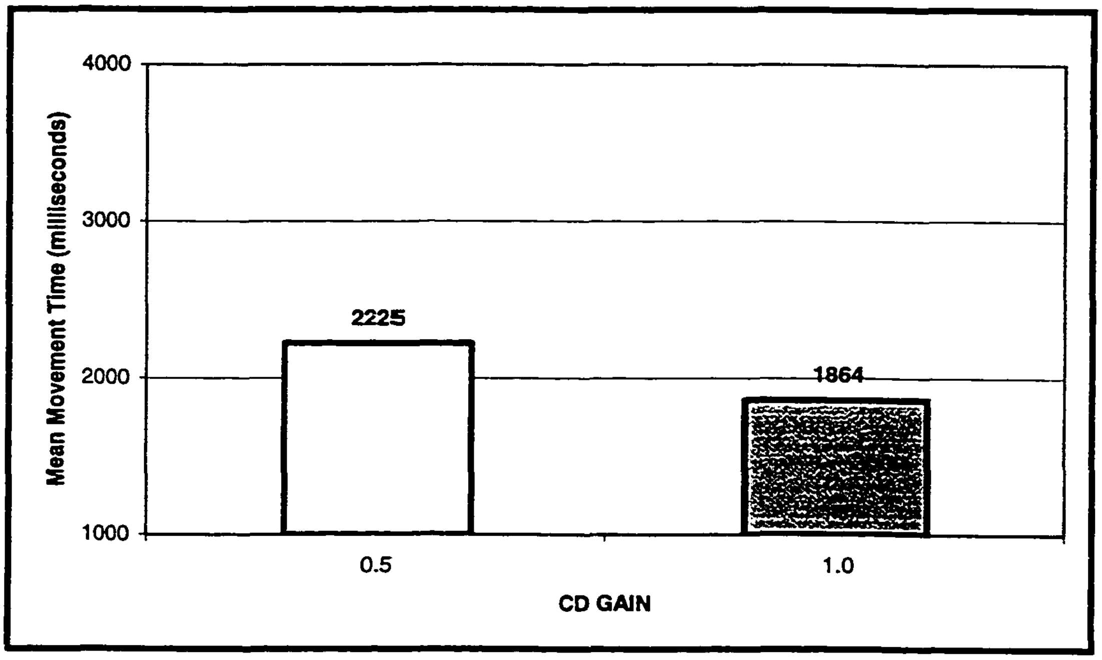


Figure 41. CD Gain Comparison for MidMT.

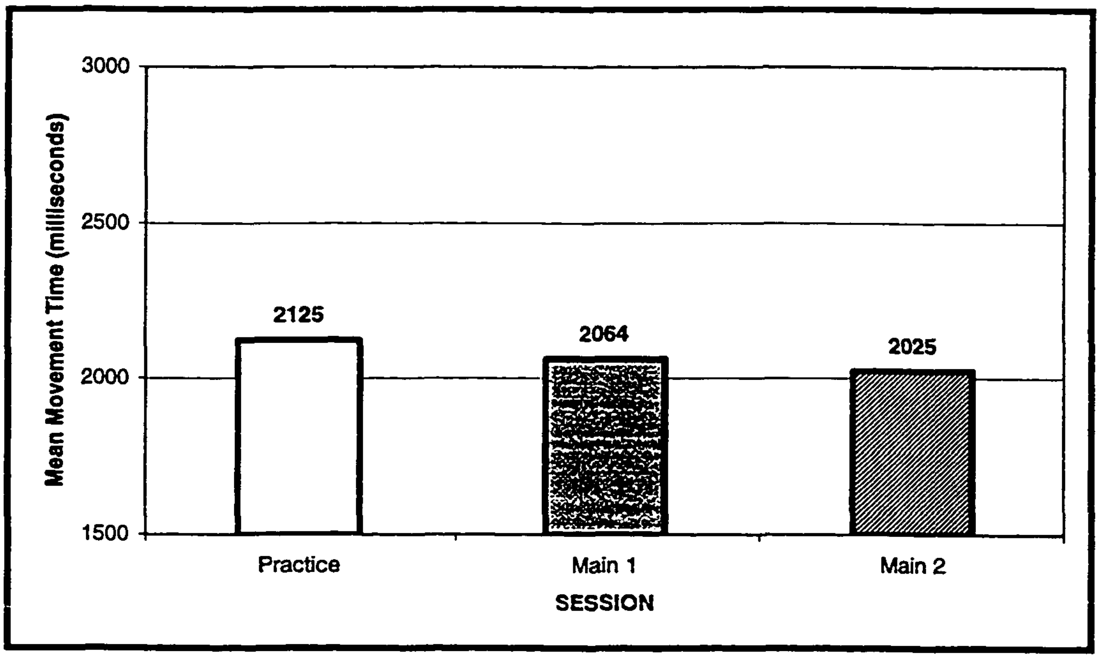


Figure 42. Session Comparison for MidMT.

difference existed between the two Main sessions. A significant difference did exist between the Practice session and the two Main sessions.

The effect of group was also significant, $F(1, 32) = 33.50$, $p < .0001$. As expected, the impaired group performed much slower than the unimpaired group. The mean movement time for the impaired group (mean = 2966 ms; SD = 1643 ms) was twice the time for the unimpaired group (mean = 1604 ms; SD = 732 ms). Figure 43 illustrates the difference between the groups.

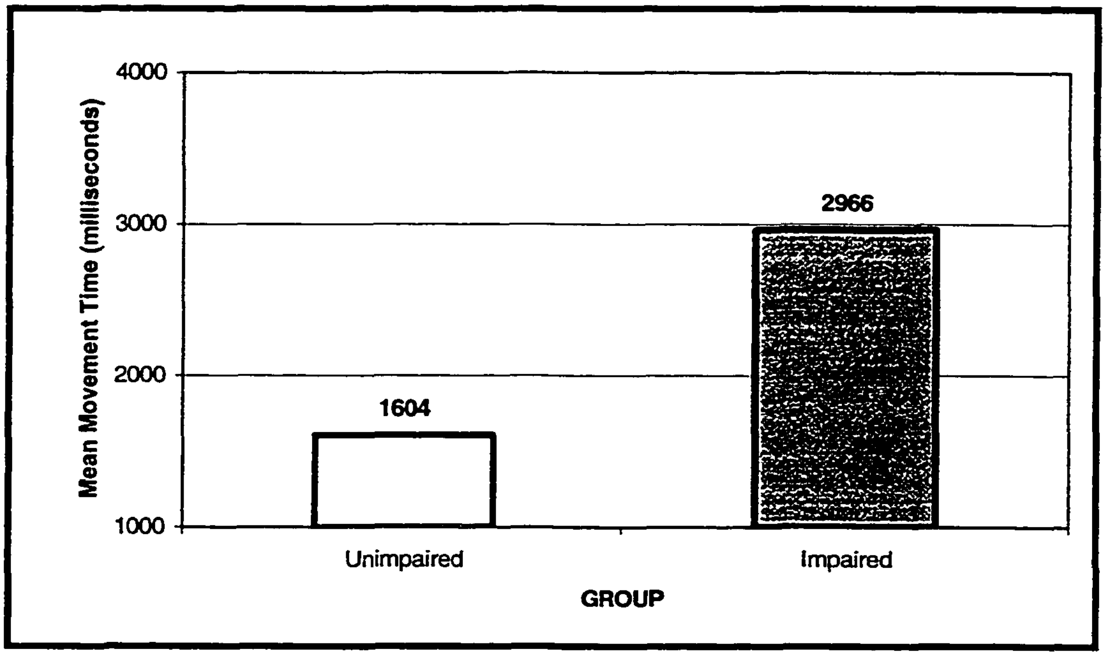


Figure 43. Group Comparison for MidMT.

There was no significant interaction between Input Device and Group, $F(2, 64) = 0.28$, $p < .7603$. As shown in Figure 44, both groups exhibited similar patterns of performance across the three devices.

On the other hand, there was a statistically significant interaction between Direction and Group, $F(1, 32) = 15.25$, $p < .0005$. As shown in Figure 45, the

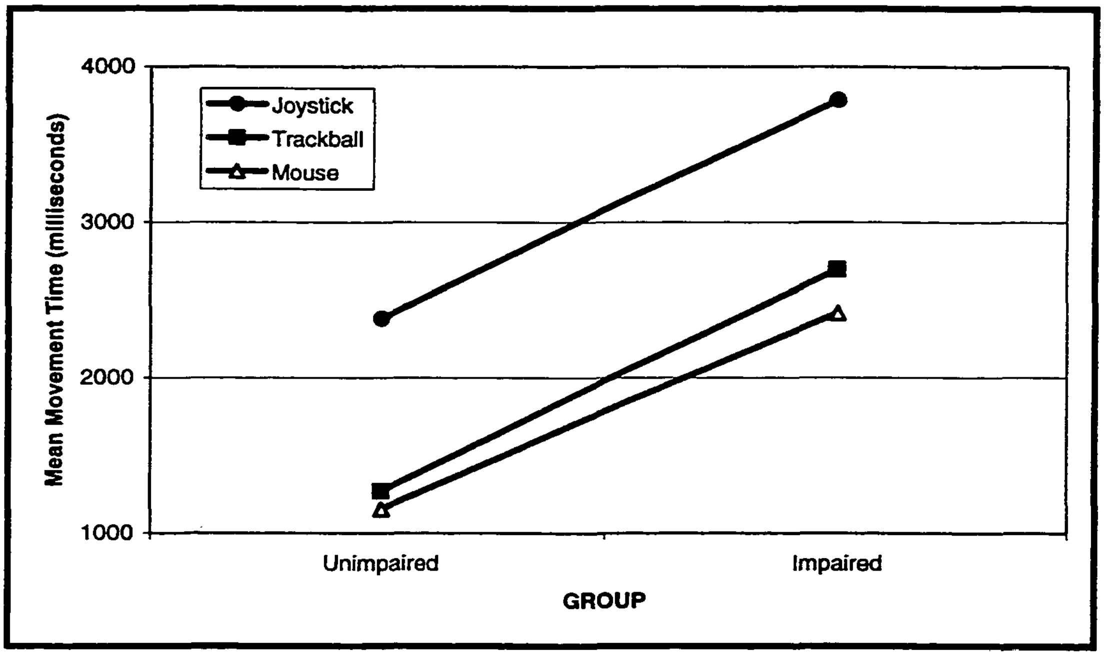


Figure 44. Interaction of Group and Input Device for MidMT.

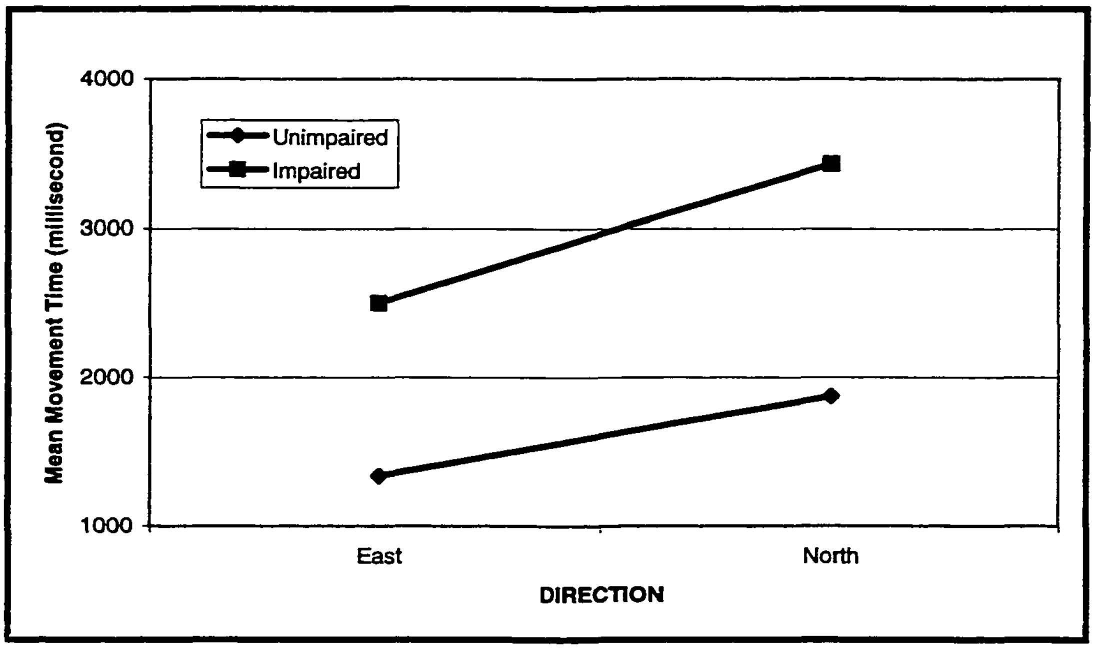


Figure 45. Significant Interaction of Group and Direction for MidMT.

impaired group showed a greater difference in movement times between the two directions (934 ms) than the unimpaired group (535 ms). This implies that the impaired group had significantly greater difficulty in the North direction. Moreover, the three-way interaction of Group × Input Device × Direction was not significant, $F(2, 64) = 1.22$, $p < .3008$. Therefore, the relative performance differences among input devices and directions were similar for the two groups.

No significant interaction existed between CD Gain and Group, $F(1, 32) = 0.08$, $p < .7775$. As shown in Figure 46, each group exhibited similar performance improvement from the CD gain of 0.5 to the CD gain of 1.0 (unimpaired group = 323 ms and impaired group = 336 ms). In addition, the Group × Direction × CD Gain interaction was not significant, $F(1,32) = 0.02$, $p < .8815$. The difference due to CD Gain for the East direction was 179 ms for the unimpaired group and 151 ms for the impaired group. The differences for the North direction were 568 ms and 522 ms, respectively.

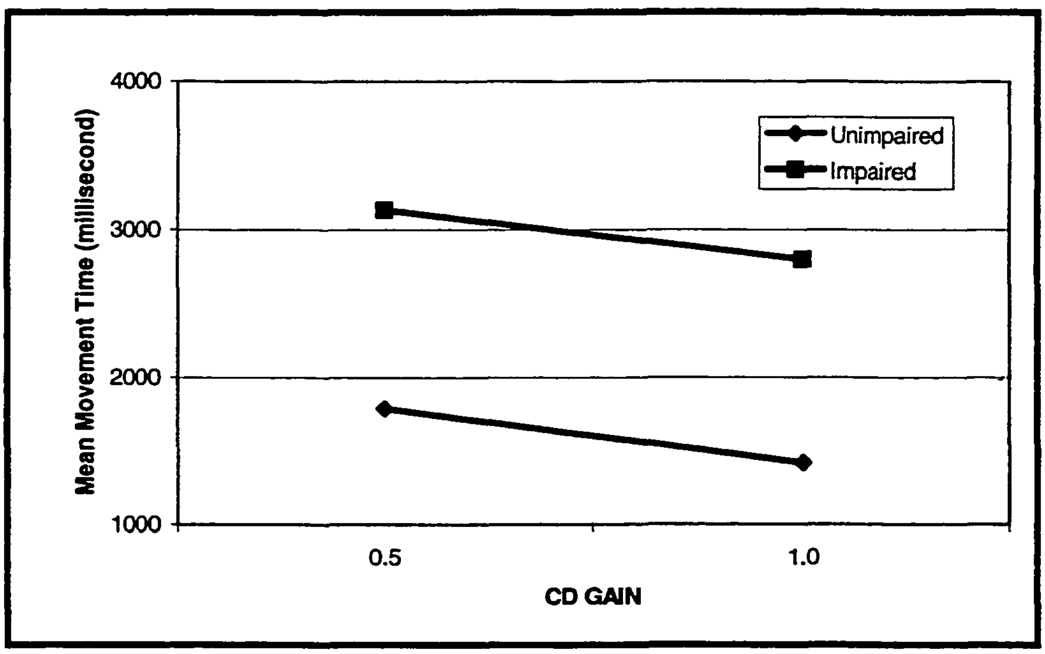


Figure 46. Interaction of Group and CD Gain for MidMT.

As shown in Table 29, the only statistically significant interactions with the Session factor were Group × Session and Subject × Session. Although statistically significant, the interaction between Session and Group, $F(1, 32) = 6.43$, $p < .0163$, was of little practical significance. The performance improvement was small (unimpaired group = 21 ms and impaired group = 76 ms) with the impaired group exhibiting a slightly greater learning effect (Figure 47).

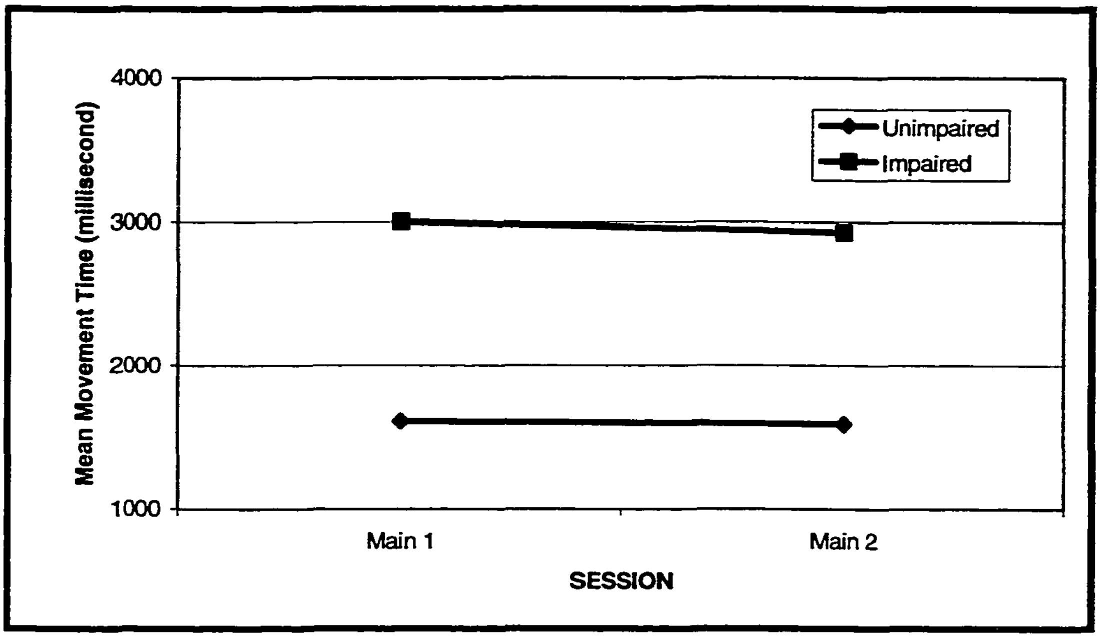


Figure 47. Significant Interaction of Group and Session for MidMT.

There was a significant interaction between Device and Direction, $F(2, 64) = 26.35$, $p < .0001$. As shown in Figure 48, the trackball and the mouse showed similar performance differences between directions (468 ms and 347 ms, respectively). On the other hand, the joystick showed a difference between directions of 1178 ms. These results suggest that (1) with the joystick used here, people perform better in East-West movements than in North-South movements, and (2) a trackball or mouse may work better for the impaired user. In addition, the Input Device × Direction × CD Gain interaction was significant, $F(2, 64) = 6.50, p < .0027$.

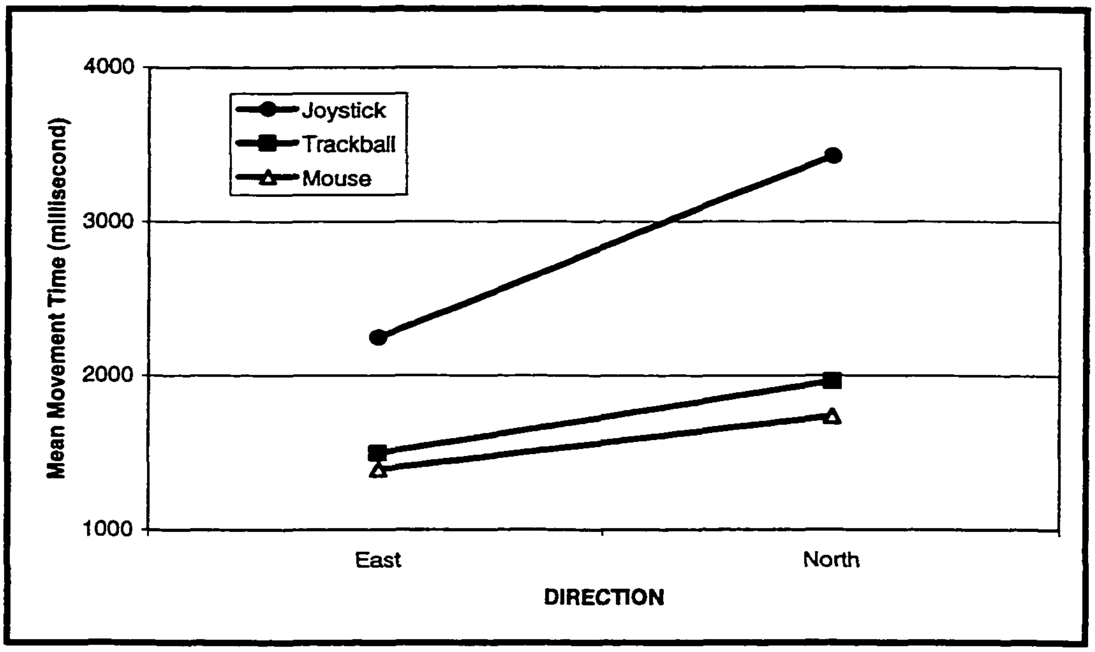


Figure 48. Significant Interaction of Input Device and Direction for MidMT.

There was a significant interaction between Input Device and CD Gain, $F(2, 64) = 18.22, p < .0001$. As shown in Figure 49, the trackball and the mouse showed similar performance improvement with increasing CD gain (170 ms and 109 ms, respectively). On the other hand, the joystick showed a significantly greater improvement (805 ms). This finding implies that the higher CD gain had a more profound effect on the joystick. The Group × Input Device × CD Gain interaction was significant, $F(2, 64) = 4.44, p < .0157$. For the two groups, the joystick showed a significantly different pattern of performance across the two CD gains than the other input devices.

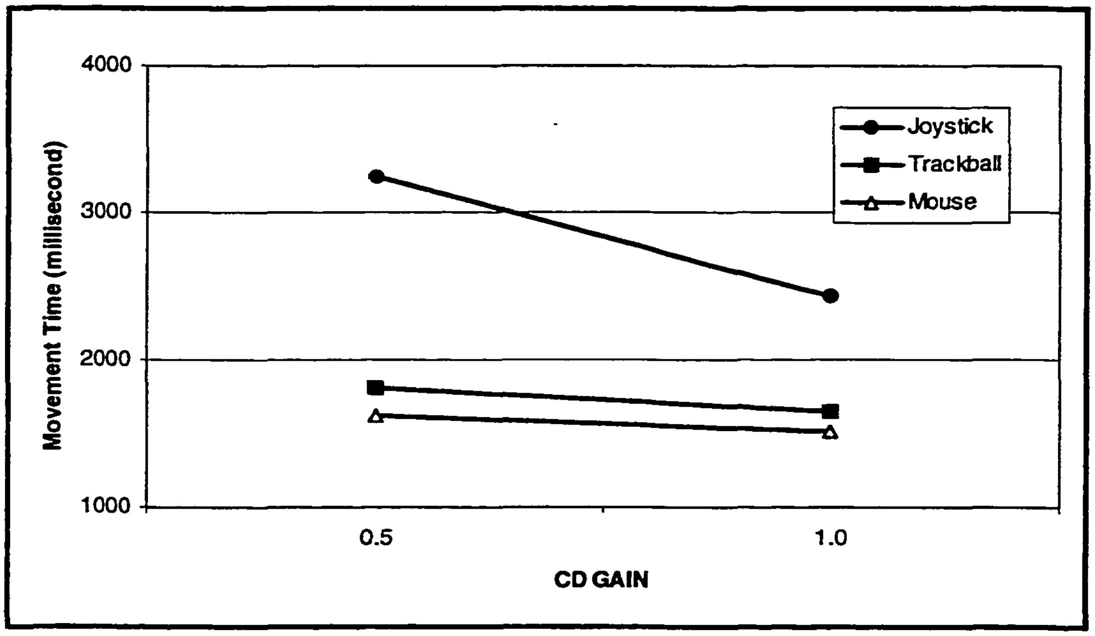


Figure 49. Significant Interaction of Input Device and CD Gain for MidMT.

As shown in Figure 50, there was a significant interaction between Direction and CD Gain, $F(1, 32) = 39.98$, $p < .0001$. Improvement with increasing gain was 553 ms for the North direction and 170 ms for the East direction. This finding implied that the participants benefited more from the higher sensitivity in the East-West movements than the North-South movements.

6.8.2 Individual Differences with MidMT

As expected, individual differences among participants were significant, $F(32, 64) = 260.96$, $p < .0001$. The minimum mean movement time for the impaired group was 1746 ms (participant D02), and the maximum was 5519 ms (participant D03). In comparison, the minimum mean movement time for the unimpaired group was 1445 ms (participant S03), and maximum mean MidMT was 1875 ms (participant S21). Obviously, the individual differences in the impaired group (3772 ms) were much larger than in the unimpaired group (429 ms). Due to the differing levels of

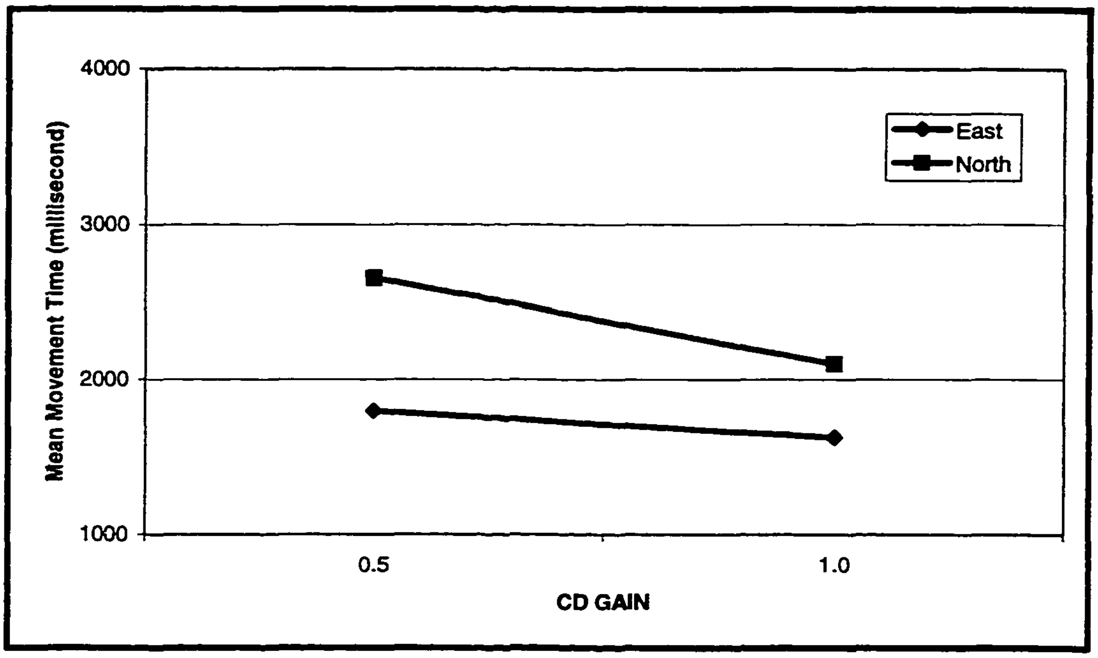


Figure 50. Significant Interaction of Direction and CD Gain for MidMT.

impairment found in the impaired group, performance differed greatly among the impaired participants.

Most two-way interactions involving the Subject factor were significant. The Session × Subject(Group) interaction was not significant, $F(32, 64) = 0.56$, $p < .9640$, demonstrating that performance across the two Main sessions was stable and unbiased by learning effects for all participants. Figures 51 to 54 show representative performance patterns for various categories of impairment. The majority of participants with lower or moderate levels of impairment performed as shown in Figure 51 (participants D01, D02, D04, D05, D06, D08, D10, and D11). These participants exhibited a minimal change in performance between the CD gains when using the trackball and the mouse, but a significant improvement with the joystick at a CD gain of 1.0. This implied that most participants with mild or moderate levels of impairment would benefit from using a joystick with a higher CD gain. On the other

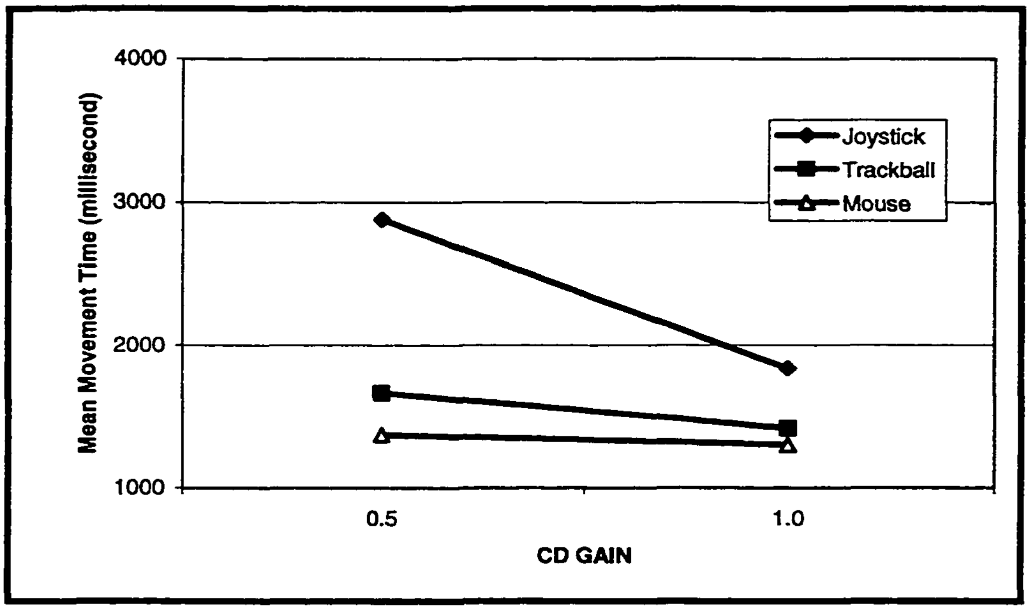


Figure 51. Mean MidMT by CD Gain and Input Device for Impaired Participant D02.

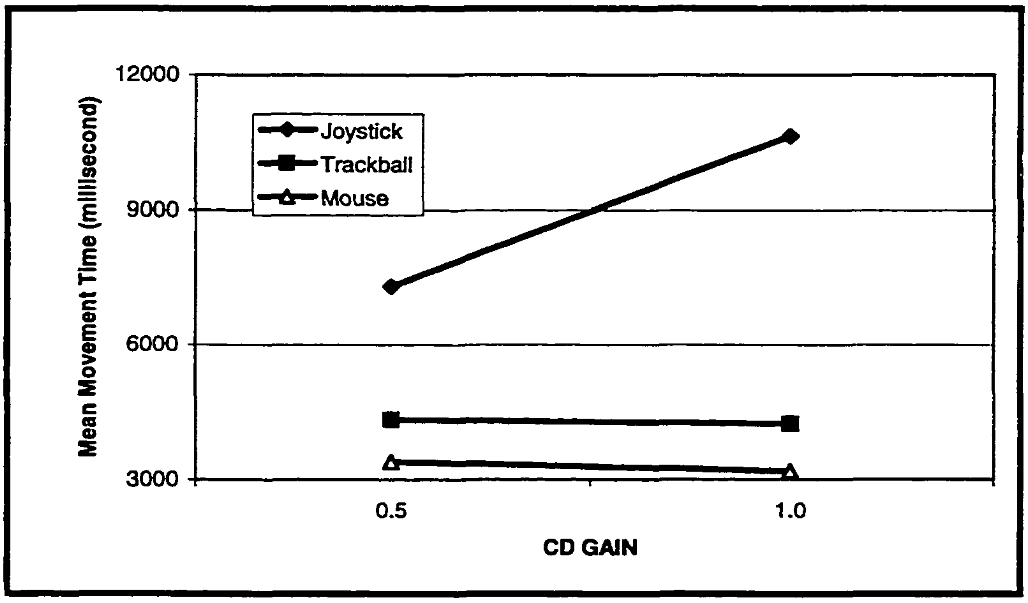


Figure 52. Mean MidMT by CD Gain and Input Device for Impaired Participant D03.

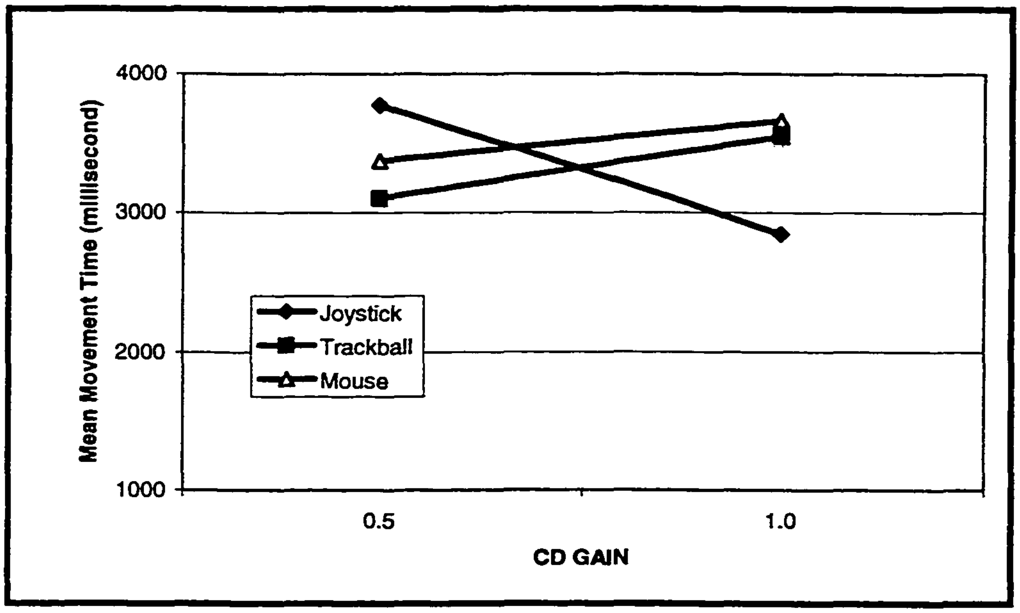


Figure 53. Mean MidMT by CD Gain and Input Device for Impaired Participant D09.

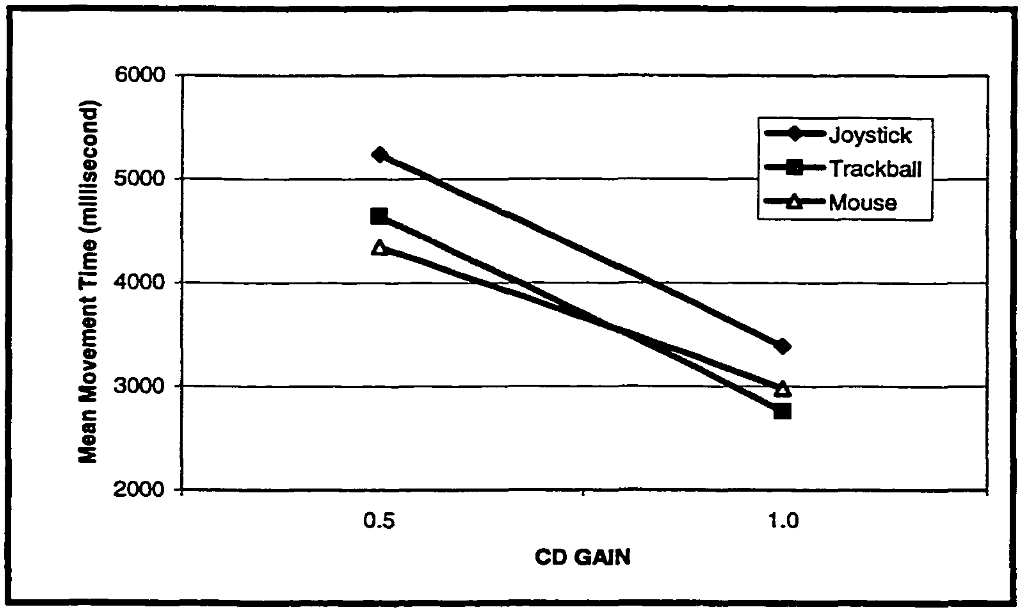


Figure 54. Mean MidMT by CD Gain and Input Device for Impaired Participant D07.

hand, participant D03, who had a severe level of impairment, was not able to take advantage of the higher CD gain (Figure 52). This participant had a difficult time acquiring the target when the CD gain was set at 1.0.

As shown in Figure 53, however, participant D09 performed better with the joystick at CD gain 1.0 than with the other devices. This participant had never used a computer before the testing, but had used a wheelchair joystick controller for more than 27 years. Hence, previous experience using a particular input device should be addressed when assessing the true effects of experience on performance. Participant D07 performed better at the higher CD gain for all three devices (Figure 54).

6.8.3 Index of Performance (IP) Analysis

Index of performance, the reciprocal of the regression slope, is an indicator of the rate of information processing for a given movement task. Table 30 summarizes the SAS GLM results for IP. IP differed significantly among the three devices, $F(2, 64) = 161.08$, $p < .0001$. Tukey's HSD procedure indicated that the IP for the mouse was significantly higher than for the trackball, which was significantly higher than for the joystick. Figure 55 shows the IP for each device.

Movement direction significantly impacted IP, $F(1, 32) = 98.47$, $p < .0001$, with the East direction showing a significantly higher value (Figure 56). As discussed in the previous chapter, this difference may have been influenced by software-related differences in directional response.

As shown in Figure 57, CD Gain also affected the IP value, $F(1, 32) = 33.29$, $p < .0001$. Since many participants in the impaired group were not able to take full advantage of the higher CD gain sensitivity, the potential performance improvement was not realized. IP was 2.85 bits/sec for the 0.5 CD gain and 3.30 bits/sec for the 1.0 CD gain. Input Device $\times$ CD Gain, $F(2, 64) = 1.41$, $p < .2512$, and Direction $\times$ CD Gain, $F(1, 32) = 0.07$, $p < .7863$ were not significant. In addition, the interaction

Table 30. SAS GLM Procedure Results for IP.

Source	df	SS	MS	F-value	Pr > F
Input Device [I]	2	895.99	448.00	161.08	<.0001
Direction [D]	1	145.11	145.11	98.47	<.0001
CD Gain [C]	1	25.83	25.83	33.29	<.0001
Session [T]	1	0.45	0.45	0.52	.4748
Group [G]	1	630.08	630.08	66.50	<.0001
I×D	2	8.68	4.34	4.11	.0209
I×C	2	1.87	0.93	1.41	.2512
D×C	1	0.06	0.06	0.07	.7863
I×D×C	2	0.90	0.45	1.12	.3339
I×T	2	0.20	0.10	0.14	.8669
D×T	1	1.40	1.40	1.75	.1956
I×D×T	2	1.64	0.82	0.83	.4391
C×T	1	0.004	0.004	0.01	.9359
I×C×T	2	0.66	0.33	0.59	.5588
D×C×T	1	0.34	0.34	0.56	.4600
I×D×C×T	2	0.71	0.35	0.59	.5594
I×G	2	129.69	64.85	23.32	<.0001
D×G	1	19.43	19.43	13.18	.0010
C×G	1	9.29	9.29	11.98	.0015
T×G	1	0.31	0.31	0.36	.5541
I×D×G	2	1.28	0.64	0.61	.5478
I×C×G	2	0.12	0.06	0.09	.9158
D×C×G	1	0.02	0.02	0.03	.8640
I×T×G	2	0.76	0.38	0.53	.5883
D×T×G	1	0.71	0.71	0.88	.3541
C×T×G	1	1.44	1.44	2.69	.1107
I×D×C×G	2	0.42	0.21	0.52	.5977
I×C×T×G	2	0.65	0.32	0.58	.5648
I×D×T×G	2	2.13	1.06	1.08	.3459
D×C×T×G	1	1.79	1.79	2.91	.0976
I×D×C×T×G	2	0.74	0.37	0.62	.5431
Subject [S(G)]	32	303.19	9.47	15.70	<.0001
I×S(G)	64	178.00	2.78	4.61	<.0001
D×S(G)	32	47.16	1.47	2.44	.0012
I×D×S(G)	64	67.53	1.06	1.75	.0135
C×S(G)	32	24.83	0.78	1.29	.1947
I×C×S(G)	64	42.34	0.66	1.10	.3573
D×C×S(G)	32	24.97	0.78	1.29	.1895
I×D×C×S(G)	64	25.83	0.40	0.67	.9449
T×S(G)	32	27.69	0.87	1.43	.1102
I×T×S(G)	64	45.45	0.71	1.18	.2585
D×T×S(G)	32	25.56	0.80	1.32	.1692
I×D×T×S(G)	64	63.11	0.99	1.63	.0258
C×T×S(G)	32	17.09	0.53	0.88	.6406
I×C×T×S(G)	64	36.01	0.56	0.93	.6100
D×C×T×S(G)	32	19.69	0.62	1.02	.4612
I×D×C×T×S(G)=Error	64	38.62	0.60		
Total	815	3317.54			

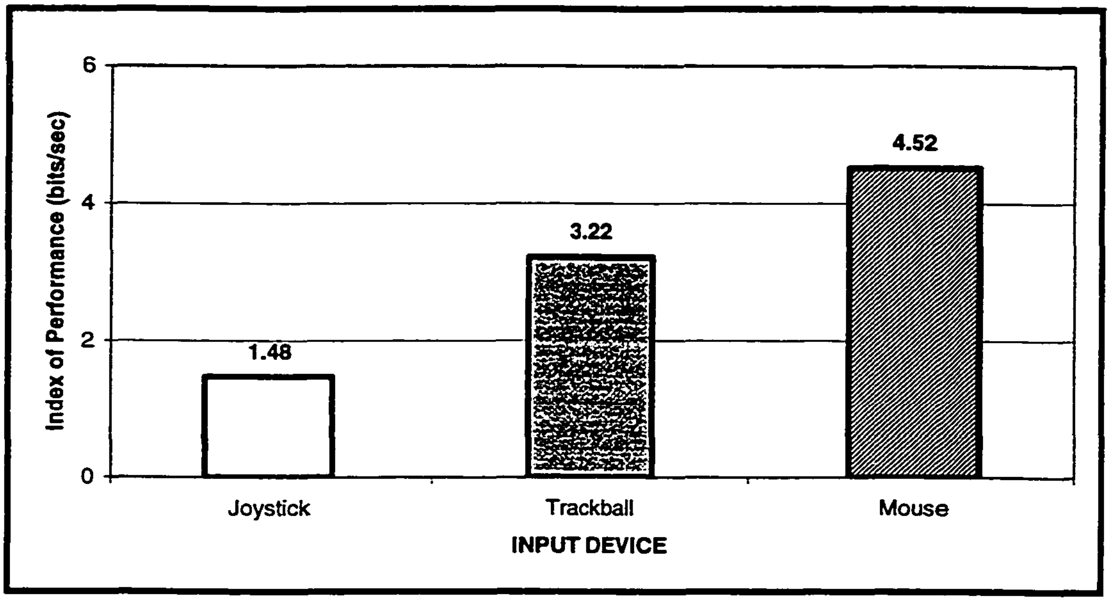


Figure 55. Input Device Comparison for IP.

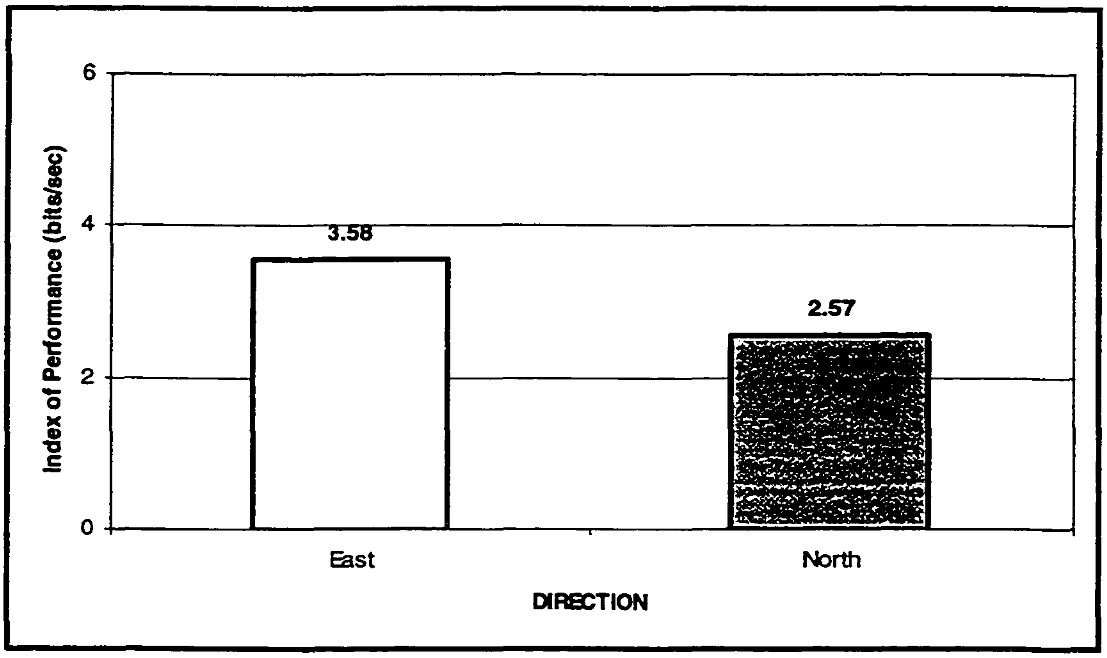


Figure 56. Direction Comparison for IP.

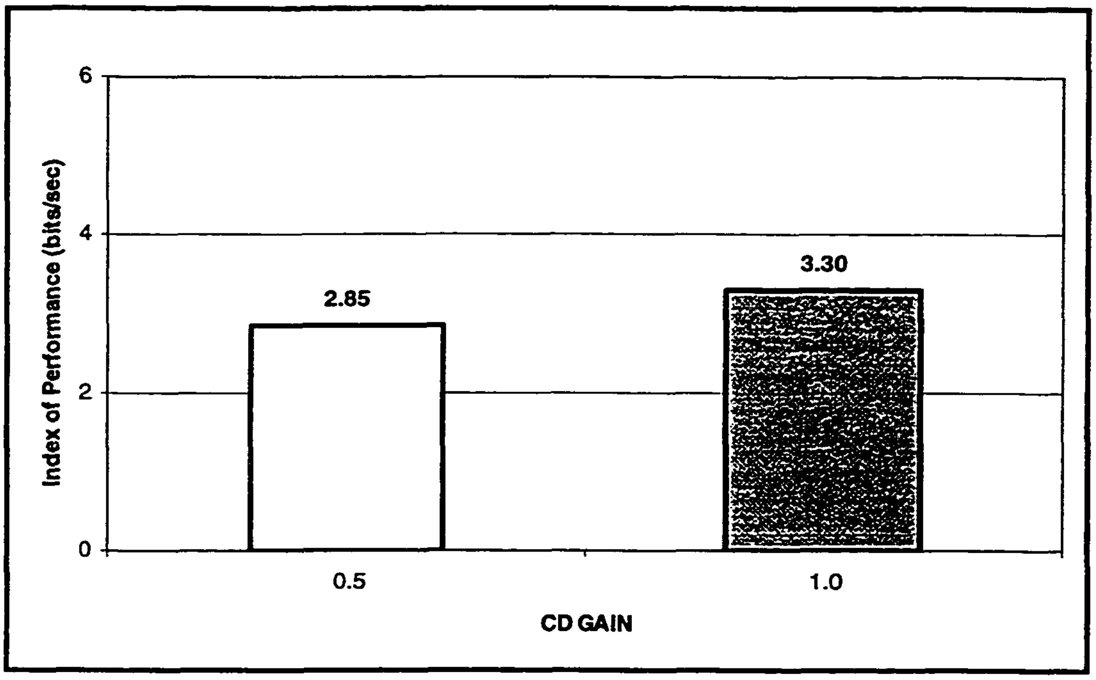


Figure 57. CD Gain Comparison for IP.

of Input Device × Direction × CD Gain was not significant, $F(2, 64) = 1.12, p < .3339$.

The effect of Session on IP was not significant, $F(1, 32) = 0.52, p < .4748$. In general, participants showed significant learning between the Practice session and the Main sessions (Figure 58). However, there were no significant performance changes between the main sessions (Main 1 = 3.09 bits/sec and Main 2 = 3.06 bits/sec). In addition, the interactions containing Session were not significant (Table 30).

The effect of Group was significant, $F(1, 32) = 66.50, p < .0001$, with the mean IP for the impaired group significantly lower than that for the unimpaired group. As shown in Figure 59, the mean IP for the unimpaired group (3.68 bits/sec) was more than twice that of the impaired group (1.80 bits/sec).

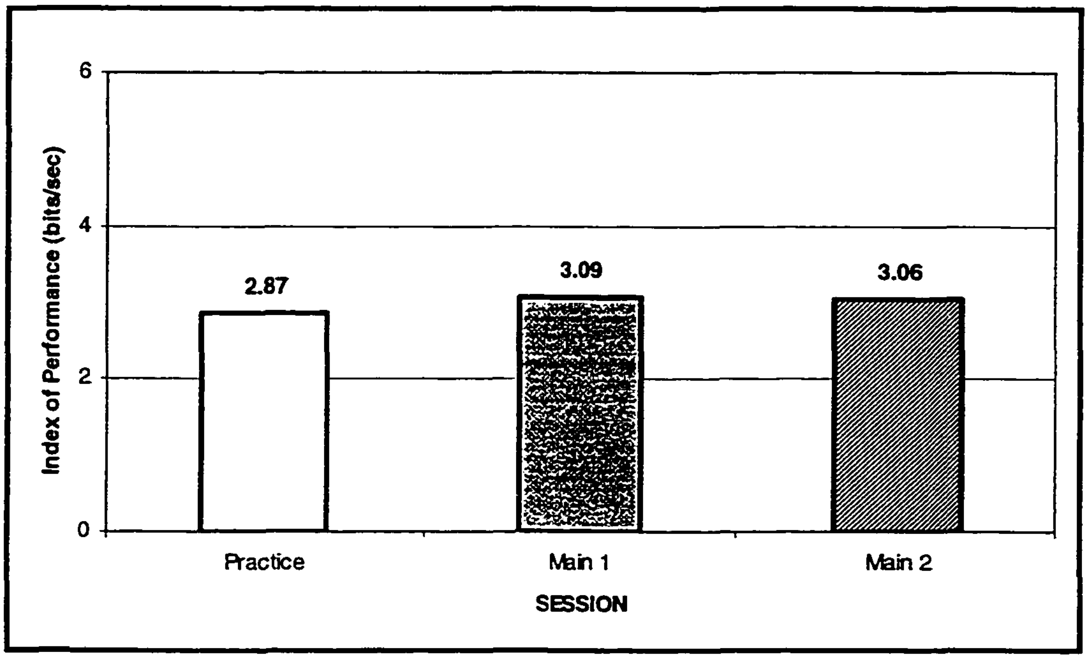


Figure 58. Session Comparison for IP.

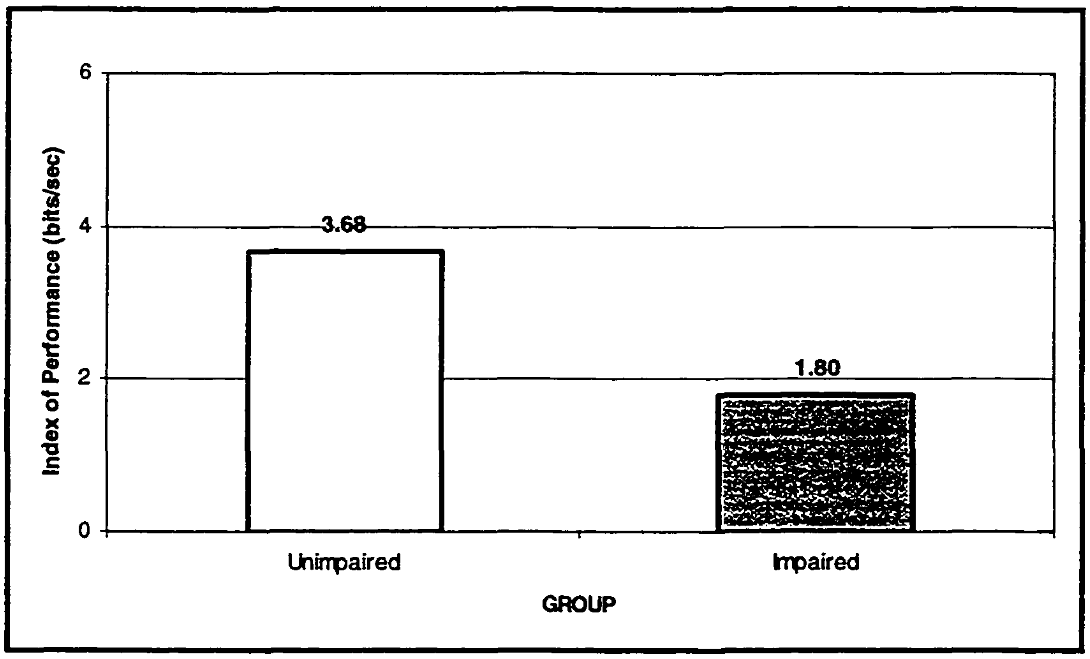


Figure 59. Group Comparison for IP.

Although the Group main effect was strongly significant, the majority of higher order interactions involving Group were not significant (except Group × Input Device, Group × Direction, and Group × CD Gain).

As shown in Figure 60, the joystick was responsible for a strong Group × Input Device interaction, while the trackball and mouse showed similar performance, $F(2, 64) = 23.32$, $p < .0001$. Interestingly, the unimpaired group performed significantly worse with the joystick than with the other devices.

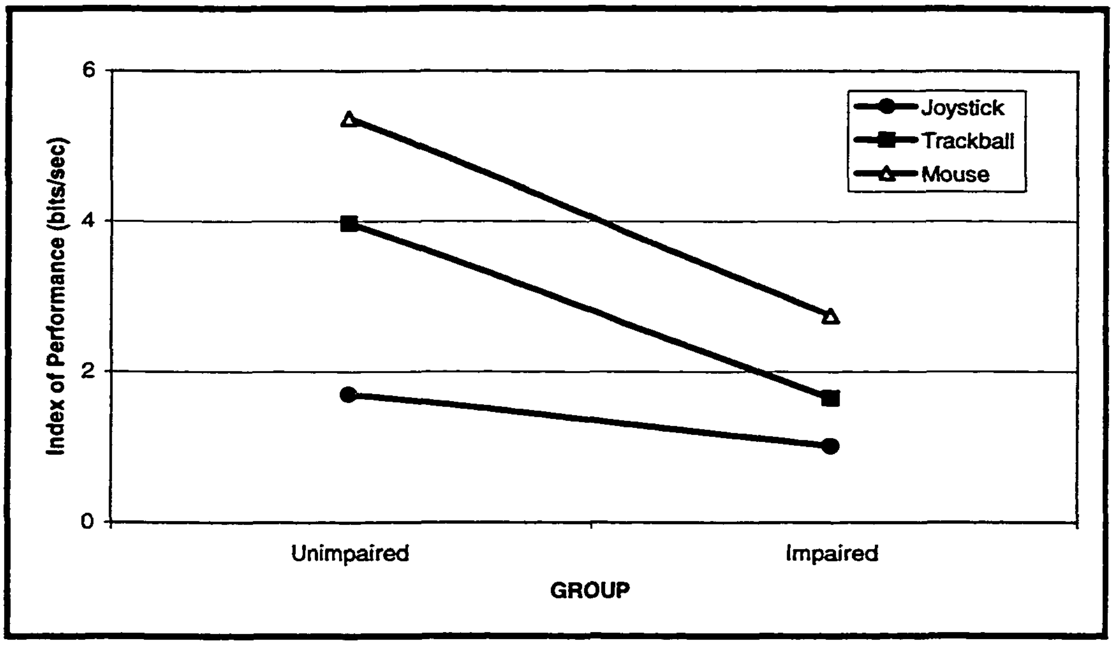


Figure 60. Significant Interaction of Group and Input Device for IP.

The Group × Direction interaction was significant, $F(1, 32) = 13.18$, $p < .0010$. The impaired group exhibited less change in IP (0.56 bits/sec) due to direction than the unimpaired group (1.22 bits/sec) (Figure 61). This provides important HCI guidelines for computer display layout for special user populations.

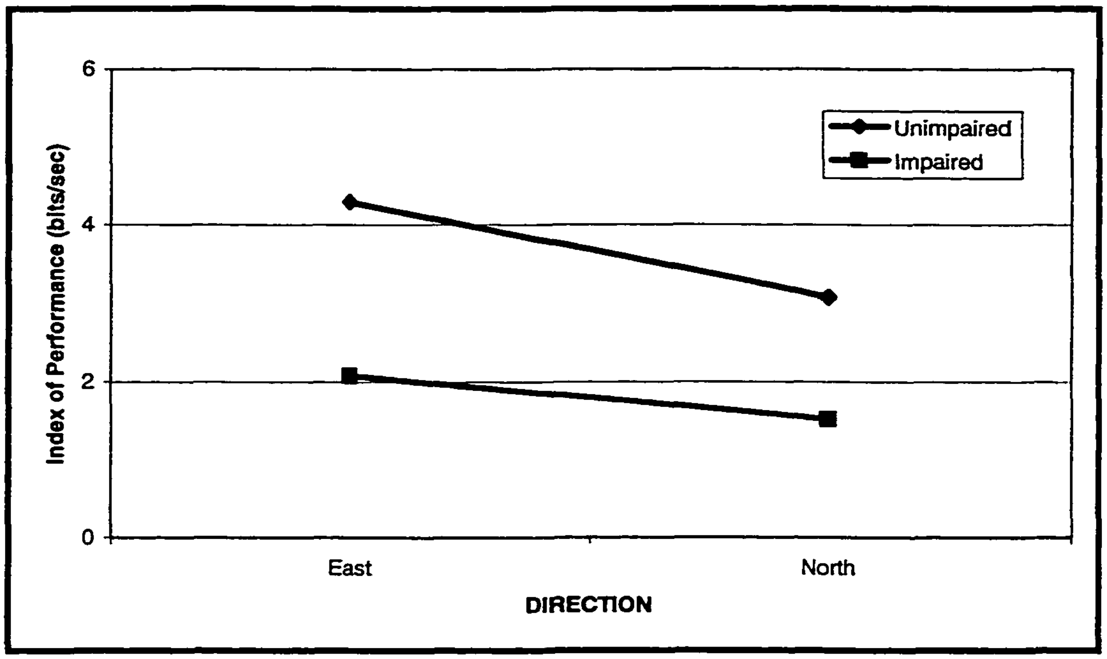


Figure 61. Significant Interaction of Group and Direction for IP.

The Group × CD Gain interaction was also significant, $F(1, 32) = 11.98$, $p < .0015$. As shown in Figure 62, the performance improvement for the unimpaired group (0.60 bits/sec) was much higher than the improvement for the impaired group (0.14 bits/sec).

The Group × Session interaction was not significant, $F(1, 32) = 0.36$, $p < .5541$. As shown in Figure 63, the performance change for both groups was negligible (impaired group = 0.09 bits/sec and unimpaired group = 0.01 bits/sec). This showed that group performance was stable following the Practice session.

The Input Device × Direction interaction was significant, $F(2, 64) = 4.11$, $p < .0209$. The performance difference between directions was very similar for the trackball and mouse (trackball = 1.21 bits/sec and mouse = 1.13 bits/sec), while the joystick (0.67 bits/sec) showed less change compared to the other two devices. For

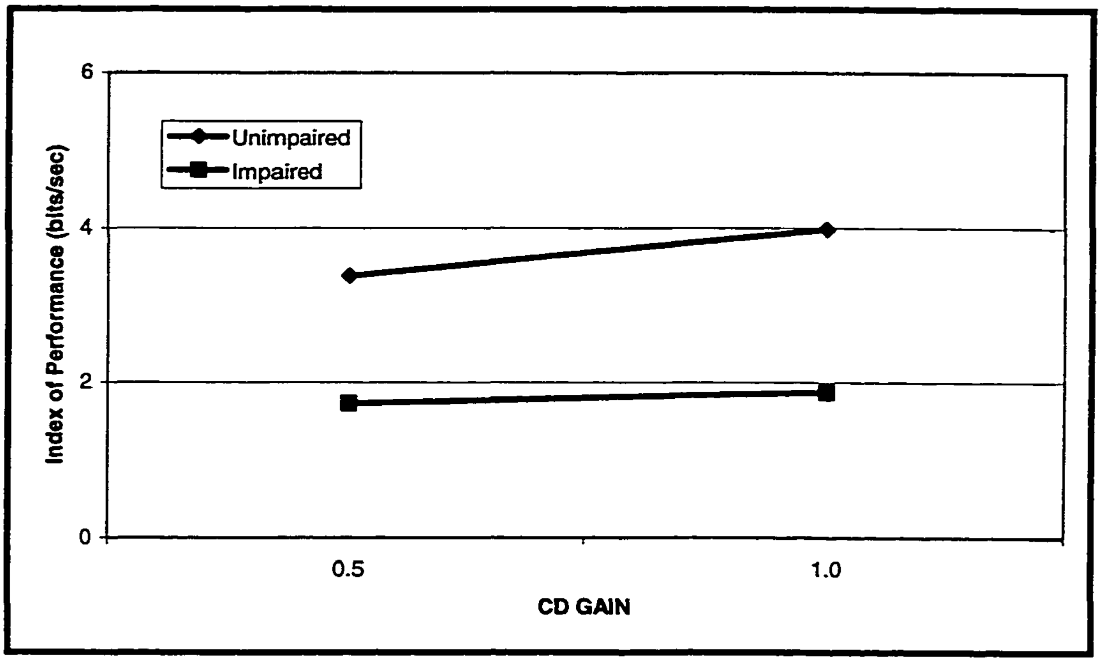


Figure 62. Significant Interaction of Group and CD Gain for IP.

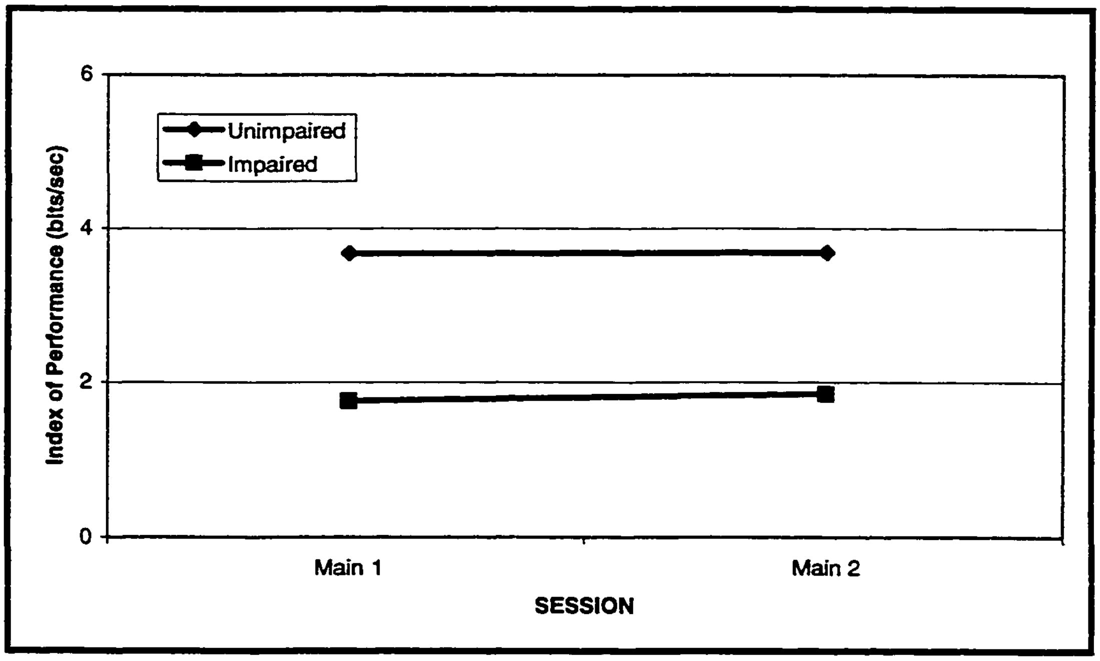


Figure 63. Interaction of Group and Session for IP.

the joystick, the IP difference in this interaction was much weaker than in the same interaction term for the MidMT measure (Figure 48). Moreover, Figure 64 clearly supports the relationship of the selected input devices between levels of upper-limb dexterity and device manipulation requirements that was proposed in the previous chapter (Figure 15).

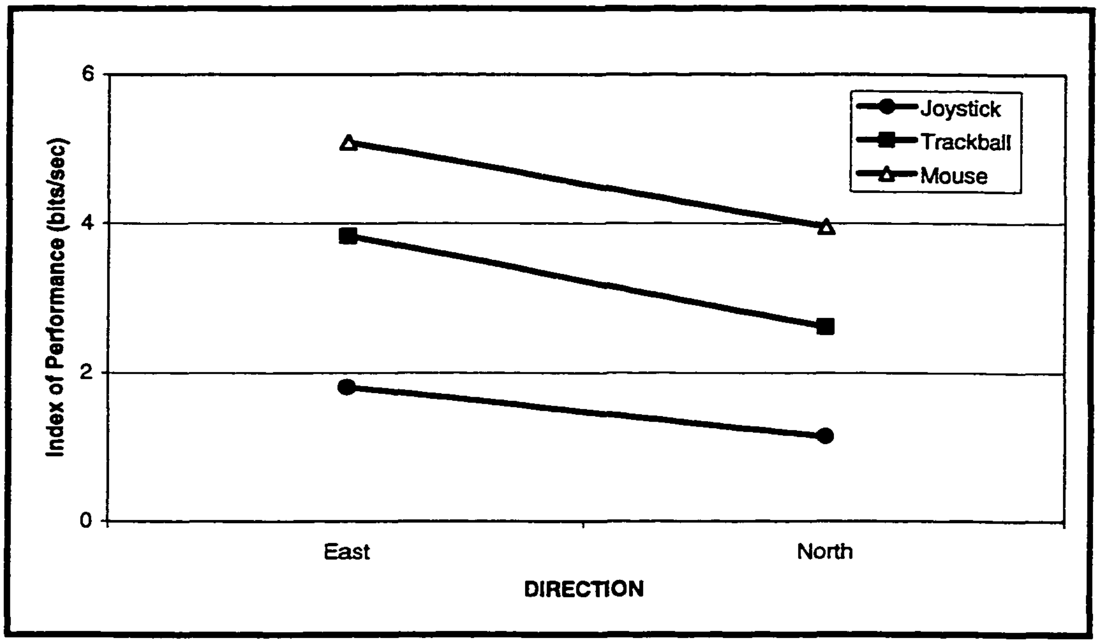


Figure 64. Significant Interaction of Input Device and Direction for IP.

6.8.4 Individual Differences with IP

Individual differences among participants were significant, $F(32, 64) = 15.70$, $p < .0001$. The minimum mean IP for the impaired group was 0.69 bits/sec (participant D03), and the maximum was 3.27 bits/sec (participant D03). The minimum mean IP for the unimpaired group was 3.11 bits/sec (participant S21), and the maximum was 4.80 bits/sec (participant S03). The individual differences in the impaired group were significantly larger than those for the unimpaired group.

The two-way interactions of Input Device × Subject(Group), $F(64, 64) = 4.61$, $p < .0001$, and Direction × Subject(Group), $F(32, 64) = 2.44$, $p < .0012$, were significant. As shown in Figures 55 and 56, Input Device and Direction effects were significant. The performance of individual participants in the impaired group varied greatly as a function of Input Device and Direction. In addition, the three-way interaction of Input Device × Direction × Subject(Group), $F(64, 64) = 1.75$, $p < .0135$, and the four-way interaction of Input Device × Direction × Session × Subject(Group), $F(64, 64) = 1.63$, $p < .0258$, were also significant.

Figures 65 to 68 show representative performance patterns for various impairment categories. Participants with a low level of impairment performed similar to participants without impairment. Figure 65 presents the performance by CD Gain and Input Device for participant D02. Participants D06 and D10 showed similar performance patterns. Based on the MMDT, the level of impairment for those three participants was assessed at a mild level. The performance among the three input devices was very different. The mouse produced the best performance for participants with mild impairment, while the trackball and joystick showed significantly poorer performance. As the CD gain increased, performance improved slightly for the mouse and trackball, but improved significantly for the joystick. Therefore, if the joystick is used by people with mild impairment, higher CD gain settings should be applied.

Participants D01, D04, and D05 were classified by the MMDT as having moderate impairment. As shown in Figure 66, overall performance was degraded compared to the participants with mild impairment. Particularly, the performance with the mouse exhibited a dramatic decrease. This finding suggests that effective use of the mouse decreases as the level of impairment is increased. The participants with moderate impairment showed a slight performance improvement as CD gain increased.

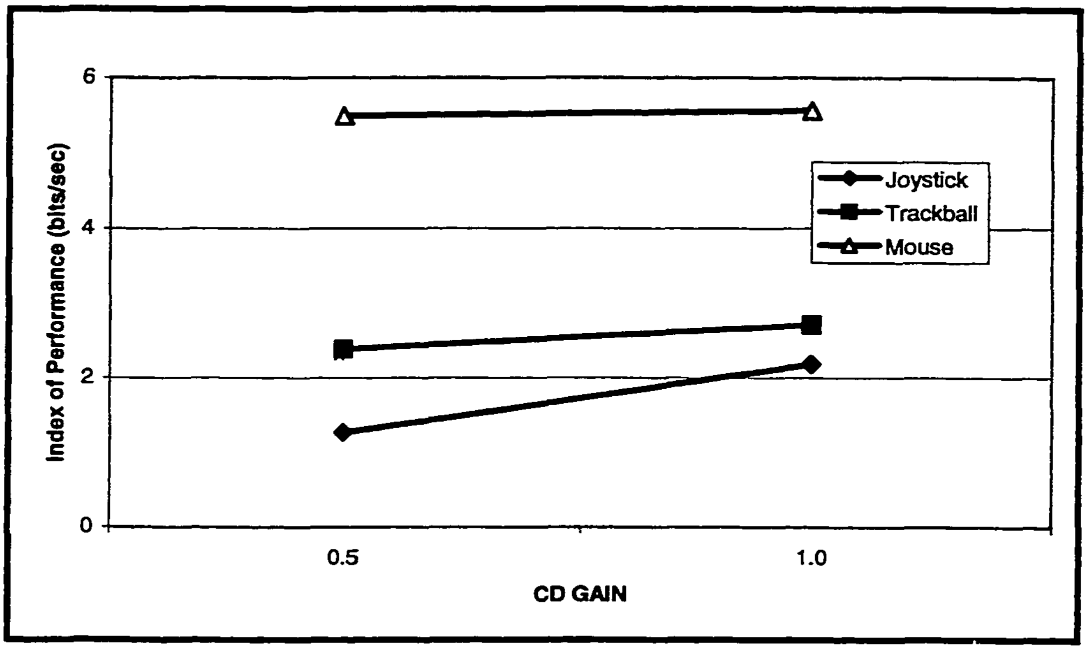


Figure 65. Mean IP by CD Gain and Input Device for a Mildly Impaired Participant (D02).

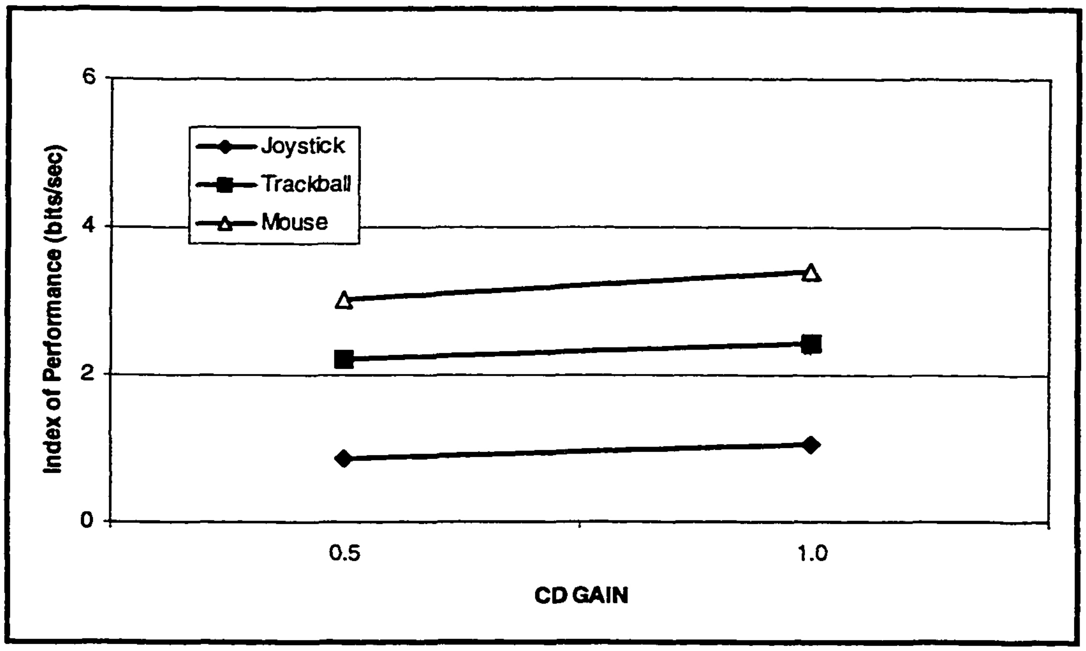


Figure 66. Mean IP by CD Gain and Input Device for a Moderately Impaired Participant (D04).

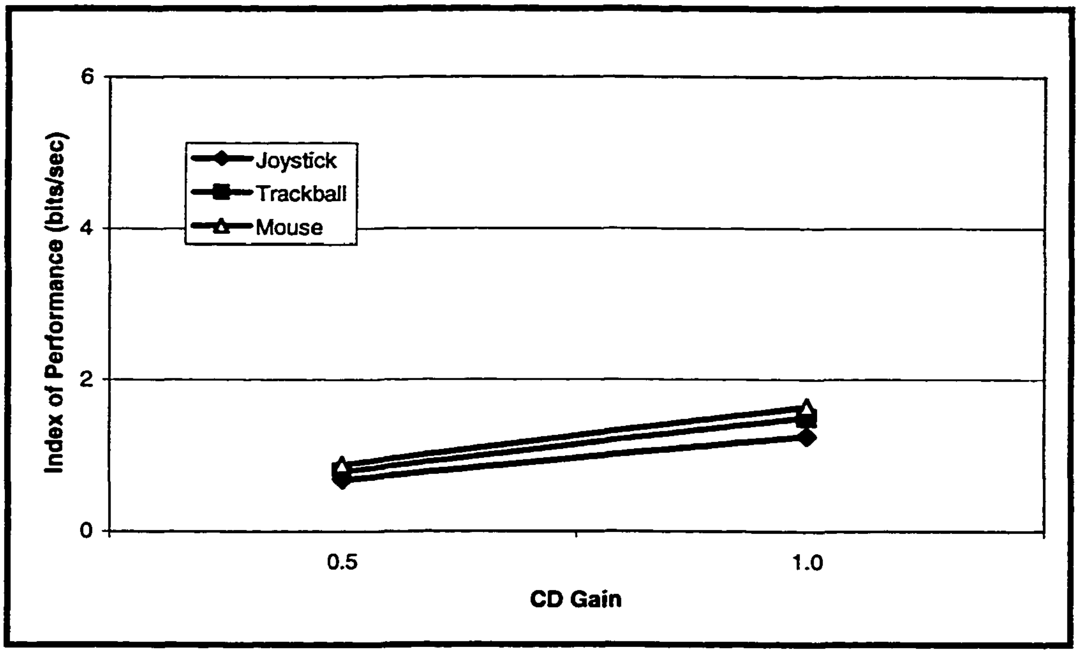


Figure 67. Mean IP by CD Gain and Input Device for a Severely Impaired Participant (D07).

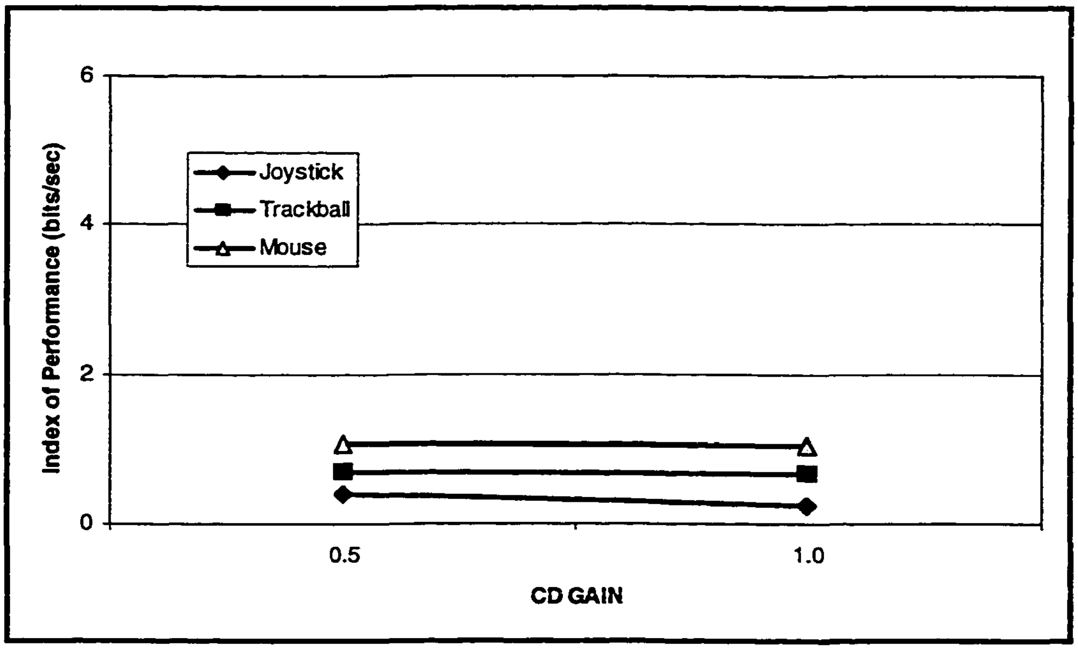


Figure 68. Mean IP by CD Gain and Input Device for a Severely Impaired Participant (D03).

Participants D03, D07 to D09, and D11 were classified as having severe impairment. The mean IP for those participants was less than 2 bits/sec. Very similar IP values were produced for all three input devices (Figures 67 and 68). Participants D07 and D11 showed performance improvement as CD Gain increased (Figure 67), while participants D03, D08, and D09 showed no performance improvement or performance decline with the higher CD gain (Figure 68). In order to propose appropriate input devices for people with impairments, an accurate assessment tool such as the MMDT or Fitts' Law task used in this study is essential.

CHAPTER 7

CONCLUSIONS AND RECOMMENDATIONS

The goals of this study were to develop and validate a methodology for assessing the level of impairment for people with upper-limb motor impairments, and to develop a matrix for recommending solutions which match assistive technology input devices to the assessed level of functional limitation. The results of this study provide a simplified method of assessing existing devices and promote the development of creative solutions for computer access by people with upper-limb motor impairments. With respect to the current level of technology in consumer products, some vital implications from this study are discussed. In addition, this chapter addresses the limitations of the study, and provides some recommendations for future research.

7.1 Conclusions

To investigate a wide range of problems encountered by computer input device users, the level of impairment for the participants in this study varied widely. Each participant was unique in the type and level of impairment and characteristics that affected performance when using computer input devices. A thorough assessment of individuals with upper-limb motor impairments is required to make accurate recommendations of appropriate assistive computer input devices. In addition, the performance of impaired participants using computer input devices is affected by previous experience with input devices.

Fitts' Law was found to be a valid predictor of performance for the unimpaired group using the mouse and trackball. However, joystick performance of the Fitts' task appeared to depend primarily on movement time rather than adjustment time. This was likely due to the design characteristics of the joystick. In contrast, the impaired participants performed better with the joystick and trackball. These findings confirmed that impaired participants had more problems with adjustment than with movement. Moreover, the majority of impaired participants had greater difficulty using the devices with the higher CD gain (1.0).

One of the goals for this study was to examine whether the Fitts' Law Index of Performance (IP) correlated with the MMDT. Since the intercept in a Fitts' Law linear regression line may contribute to overall Movement Time (MT), the IP often provides more meaningful results when the intercept is negative and large in magnitude. Strong correlations between the MMDT and the data collected from the computer-based target pointing task implied that the MMDT was a valid predictor for assessing the level of input device impairment. In addition, since this study found higher correlations for the North direction, further research is recommended to examine MMDT movements in an East-West direction. These findings may provide important guidelines for the design of graphical interface layouts in human-computer interface (HCI) applications for people with impairments.

For the same reasons as mentioned above, IP was also proven a valid measure for assessing the use of computer input devices by people with upper-limb motor impairments. Even though IP provided somewhat weaker correlations with the MMDT than did MidMT, it was useful in assessing input device performance. Participants, especially in the impaired group, identified a number of advantages related to the input devices employed in this study. Unfortunately, the most appropriate devices had not always been used previously by the impaired participants due to a lack of availability. This study helped to communicate critically useful information for selecting appropriate devices for people with upper-limb impairments.

Based on the performance comparisons between the MMDT test and the IP analysis within the impaired group, both analysis methods predicted the level of each participant's impairment with good accuracy. As shown in Table 31, the classified level of impairment was compared against their relative performance. In spite of the fact that participants D04, D06, and D09 showed inconsistent classification results for both analyses, the overall comparison results revealed that both analysis methods quite accurately assessed the level of impairment. For the case of participant D09, the MMDT classification may provide a more reasonable analysis because the participant performed significantly better with the joystick than with the other devices, which affected the overall IP data for the participant.

Table 31. Performance Comparisons Between MMDT Analysis and IP Analysis for the Impaired Group.

MMDT ANALYSIS			IP ANALYSIS		
ID	Relative Performance	Level of Impairment	ID	Relative Performance	Level of Impairment
D10	100.0	Mild	D02	100.0	Mild
D02	97.2		D06	90.3	
D04	92.6		D10	77.9	
D09	82.9	Moderate	D04	57.0	Moderate
D06	82.1		D01	53.5	
D01	81.3		D05	34.9	
D08	39.3	Severe	D07	17.1	Severe
D03	1.8		D08	15.9	
D11	0.0		D11	14.3	
D05	-		D09	13.6	
D07	-		D03	0.0	

Note: Two participants (D05 and D07) were not able to complete the MMDT test due to their capability limitations.

However, the other participants were consistently classified as having mild or severe impairments by both analyses. Participants D04 and D06 were marginal between mild and moderate based on the comparisons. Since both overall comparison results showed strong agreement between the two analyses, the ability of the assessment test to accomplish the goals of this study was successfully demonstrated.

Performance differences between the three devices followed the same pattern for the unimpaired group and the impaired group. This result was supported statistically by the lack of significance of the Group × Input Device interaction effect. The behavior of the two groups was very similar for all three input devices. However, it must be noted that the overall slope change for the mouse in the impaired group was much greater than that for the other devices. This revealed that the impaired participants had great difficulty using the mouse. Investigation of individual performance with the mouse revealed that participants who were classified with a severe level of impairment exhibited serious difficulties using the mouse. Therefore, severely impaired people should be able to use the trackball and joystick more effectively.

Individual differences often become more critical within impaired populations. The performance of the participants in the impaired group was found to exhibit several unique patterns. HCI designers should attempt to incorporate the individual needs of people with disabilities throughout all HCI design stages, including requirement gathering, task analyses, and usability testing.

It is strongly believed that applying existing HCI technology to the design of assistive computer input devices for people with disabilities will significantly improve the comfort and flexibility of currently available assistive technologies. However, even highly advanced assistive technologies may not be the best alternative without careful consideration of the individual differences. Therefore, this study supported the need for designers of computer input devices to become more aware of the individual differences of the impaired populations during the design process.

Hopefully, the design issues outlined in this study will be incorporated into mainstream HCI research.

Even though assistive technologies are essential for providing computer access to people with impairments, the majority of the available devices are very costly and exceed the budgets of many impaired people. Insurance companies are usually unwilling to cover the costs unless the device is a medical necessity. Fortunately, alternative sources of assistive technology funding are available. People with impairments should thoroughly investigate the various funding sources for which they are eligible (Appendix C). Some major sources of assistive technology funding include:

- Person-Client and Family Resources,
- Community-based waivered services (Medicaid),
- Department of Health and Human Services (Medicare),
- Private Insurance (Blue Cross, Blue Shield, Commercial Carriers, Disability Insurance, Health Maintenance Organization, and Preferred Provider Organization),
- Charity/Service Agencies (Muscular Dystrophy Association, American Business Clubs, and United Cerebral Palsy), and
- Philanthropic Organizations (Kiwanis Club, Rotary Club, and Shriners Hospitals for Children).

7.2 Recommendations for Future Research

This section addresses the limitations of the study, and provides some recommendations for future research. Several HCI design suggestions are offered as an expansion of the current research.

Despite the growing interest in human-computer interaction (HCI) research areas, significant gaps continue to exist between IT access requirements and available assistive technologies. People with disabilities as computer users are often overlooked during the HCI design process due to a lack of awareness, increased production cost, or insufficient market volumes. Moreover, the majority of impaired users are not able to freely access the current assistive technology due to budget constraints or a lack of information on assistive technology tools. Therefore, this study may play a vital role by facilitating the communication of critically useful information to people with upper-limb impairments.

7.2.1 Recommendations for the Fitts' Law Test

Even though numerous input devices exist that have been especially designed and developed for people with disabilities, many people with disabilities cannot take advantage of these tools for various reasons. One potential reason might be that the designers have overlooked individual differences within the impaired population. Therefore, research on input device selection using Fitts' Law modeling should be carefully conducted to investigate more precise device differences.

Since the movement rates were different for the East direction versus the North direction within the Fitts' Law program (Table 18), the software should be modified to provide the same rate of movement in each direction. Understanding movement behavior in each direction is very important. New Fitts' Law software should be developed to more consistently compare the interaction behavior in each direction.

Participants who were classified with a severe impairment had major difficulties in acquiring the 5 mm target due to critical problems in fine adjustment control. Currently, various interfaces under the Windows environment require more and more target pointing, dragging, or selecting tasks from the users. Therefore, target sizes and movement amplitudes are a major concern in the area of HCI research. This research interest must be expanded to the computer interface environment for people with impairments because impaired people need an even better-designed interface environment than unimpaired users. Therefore, further research must concentrate on identifying appropriate target sizes and movement amplitudes for computer users with impairments.

The individuals in the impaired group tended to take more time in target adjustment time than in travel time. This problem was more frequently observed with participants who were classified in the severe levels of impairment. Therefore, it is recommended that future research analyze the number of overshoots and undershoots during the target pointing task. In addition, the overall movement time should be split into two components, the travel time and the adjustment time.

Since the impaired participants in this study had a wide range of individual differences, the required sample size was questionable. In general, experimental procedures with people with motor impairments take more time and effort. A careful experimental protocol must be developed to interact with those special populations. It is very important to protect their human rights and welfare. In many cases, these requirements restrict the researcher's attempt to recruit impaired participants. For future studies, using the proposed dexterity assessment tools from this study may facilitate an efficient method to screen participants and achieve an appropriate sample size. As revealed in this study, the performance of the people in the impaired group followed several unique patterns. Therefore, a careful assessment of the level of dexterity and capability for each individual during recruiting may save time and effort, and help to build a more appropriate sample size.

7.2.2 HCI Design Implications and Future Recommendations

Even though the joystick used in this study was especially developed for people with impairments, the majority of the participants in the impaired group indicated that the joystick was not appropriate for them. This demonstrates the need for HCI designers to learn more about the needs of impaired populations and to place greater emphasis on these needs when assistive technology tools are developed. The resistive force of the joystick was too great for a number of the participants.

The telecommunication field is one of the most promising information technology industries of the 21st century. According to Shapley (2001), overall sales of mobile phones increased dramatically in the U.S. from seven million in 1990 to 700 million in 2000. Sales are projected to reach 1.7 billion by the year 2005. The wireless revolution made mobile phones accessible to Internet browsing and email communications. Moreover, Personal Digital Assistants (PDAs), which are small hand-held palm-size computers, are becoming more widely used. In spite of the benefits, small screen sizes and small text input devices are barriers to the effective application of these devices.

As a pioneer in the new IT research area, Silfverberg, MacKenzie, and Korhonen (2000) successfully applied the Fitts' Law model to mobile phone text entry methods. The model provided individual predictions for one-handed thumb and two-handed index finger use. Even though the impaired populations would benefit equally from the use of mobile phones, no serious research attempts are yet visible. Therefore, this study could be further extended to various telecommunications devices to identify more efficient accessibility issues for all people with disabilities.

Since there are many functional capability aspects involved in using computer input devices, alternative capabilities of impaired users should additionally be assessed. In general, if one part of the body does not function properly, the impaired person can learn to use some other body part to compensate for their disabilities. For example, people with shaking hands (tremor) may have difficulty using traditional input devices. However, if they have proper functioning of speech or vision, speech recognition or eyegaze can possibly be used. Table 32 summarizes these recommendations. It is strongly recommended that the two-dimensional (2D) matrix be expanded to a three-dimensional (3D) space in future research.

Table 32. Two-Dimensional Technology Match for Each Degree of Impairment.

Functional Capability		Upper Limbs		
Capacity	**Degree of Impairment**	**Mild**	**Moderate**	**Severe**
Vision	**Mild**	Traditional Keyboard or Mouse	Virtual Keypad	Eyegaze Virtual Keyboard
	Moderate	Traditional Keyboard or Mouse	Keyguard	High Contrast Virtual Keyboard
	Severe	Braille Keyboard	Braille Keyboard with Keyguard	No Current Solution
Head Control	**Mild**	Traditional Keyboard or Mouse	Hand-held with Head Joystick	Headstick Head Pointing
	Moderate	Traditional Keyboard or Mouse	Trackball or Force Joystick	Head Joystick
	Severe	Traditional Keyboard Mouse	Hand-held Keyboard	No Current Solution
Speech	**Mild**	Traditional Keyboard or Mouse	Speech Recognition System	Speech Recognition System
	Moderate	Traditional Keyboard or Mouse	Trackball or Force Joystick	No Current Solution
	Severe	Traditional Keyboard or Mouse	No Current Solution	No Current Solution
Mouth Control	**Mild**	Traditional Keyboard or Mouse	Mouthstick	Mouthstick or Sip-N-Puff
	Moderate	Traditional Keyboard or Mouse	Mouthstick or Sip-N-Puff	Sip-N-Puff
	Severe	Traditional Keyboard or Mouse	No Current Solution	No Current Solution
Lower Limbs	**Mild**	Traditional Keyboard or Mouse	Foot Mouse or Foot Touchpad	Foot Mouse or Food Touchpad
	Moderate	Traditional Keyboard or Mouse	Use other hand operative tools	No Current Solution
	Severe	Traditional Keyboard or Mouse	Use other hand operative tools	No Current Solution

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APPENDIX A

DISEASES AND INCIDENCE RATES OF MOTOR IMPAIRMENTS

Diseases and Incidence Rates of Mobility Impairments
(Source: Disease, Condition or General Health Topic, 2001)

Arthritis

- Inflammation of one or more joints.
- Arthritis can occur in males and females of all ages. About 37 million people in America have arthritis of some kind. That is almost 1 out of every 7 people.

Amputation/Congenital Deficiencies

- The complete loss of all limb elements below a certain point.
- The National Center for Health Statistics of the U.S. Public Health Service estimated a prevalence of 311,000 amputees in 1970. An incidence of approximately 43,000 new amputations per year is estimated, of which 77% occur in males, and 90% involve the legs.

Amyotrophic Lateral Sclerosis

- A disorder causing progressive loss of nervous control of voluntary muscles because of destruction of nerve cells in the brain and spinal cord.
- ALS affects approximately 1 out of 100,000 people. It appears in some cases to run in families. The disorder affects men more often than women. Symptoms usually do not develop until adulthood, often not until after age 50.

Ankylosing Spondylitis

- Spondylitis involves inflammation of one or more vertebrae. Ankylosing spondylitis is a chronic inflammatory disease that affects the joints between the vertebrae of the spine, and the joints between the spine and the pelvis. It eventually causes the affected vertebrae to fuse or grow together.
- With progressive disease, deterioration of bone and cartilage can lead to fusion in the spine or peripheral joints affecting mobility. It can be extremely painful and crippling. The heart, the lungs, and the eyes may also become affected. The disease most frequently begins between the ages of 20 and 40 but may begin before 10 years of age. It affects more males than females. Risk factors include a family history of ankylosing spondylitis and male gender. The incidence is 1 out of 10,000 people.

Carpal Tunnel Syndrome

- A condition that results from compression of the median nerve at the wrist.
- The condition occurs most often in women 30 to 60 years old, but it also occurs in men and in all age groups.

Cerebral Palsy

- A group of disorders characterized by loss of movement or loss of other nerve functions. These disorders are caused by injuries to the brain that occur during fetal development or near the time of birth.
- Classifications of cerebral palsy include spastic, dyskinetic, ataxic, and mixed cerebral palsy. Spastic cerebral palsy includes about 50% of cases. Dyskinetic (athetoid) cerebral palsy affects about 20%. It involves

development of abnormal movements (twisting, jerking, or other movements). Ataxic cerebral palsy involves tremors, unsteady gait, loss of coordination, and abnormal movements. It affects about 10%. The remaining 20% are classified as mixed, with any combination of symptoms.
- The incidence of cerebral palsy is approximately 2 to 4 individuals for every 1000 births. Cerebral palsy results from injury to the cerebrum (the largest portion of the brain, involved with higher mental faculties, sensations, and voluntary muscle activities).

Diabetes Mellitus
- A disorder caused by decreased production of insulin, or by decreased ability to use insulin. Insulin is a hormone produced by the pancreas that is necessary for cells to be able to use blood sugar.
- Diabetes mellitus affects up to 5% of the population in the U.S., almost 14 million people.

Friedreich's Ataxia (Spinocerebellar Degeneration)
- An inherited form of progressive dysfunction of the cerebellum, spinal cord, and peripheral nerves.
- The average age of onset is 13, with a range from 5 to 25 years of age. There is steady deterioration, and many patients are severely incapacitated by the time they reach their middle twenties.

Guillain-Barre Syndrome
- A disorder involving progressive muscle weakness or paralysis, usually following an infectious illness. It is related to inflammation of multiple nerves.
- Guillain-Barre syndrome affects approximately 8 out of 100,000 people. It may occur at any age but is most common in people of both sexes between the ages 30 and 50.

Huntington Disease
- An inherited disorder characterized by abnormal body movements and dementia.
- Huntington disease affects about 5 out of 1,000,000 people.

Multiple Sclerosis
- A disorder of the central nervous system (brain and spinal cord) involving decreased nerve function associated with the formation of scars on the covering of nerve cells
- Multiple sclerosis (MS) affects approximately 1 out of 1,600 people. Women are affected about 60% of the time. The disorder most commonly begins between 20 to 40 years old. MS is one of the major causes of disability in adults under age 65.

Muscular Dystrophy
- A group of disorders characterized by progressive muscle weakness and loss of muscle tissue.

- The group of diseases called muscular dystrophies includes many inherited disorders such as: Becker's muscular dystrophy, Duchenne's muscular dystrophy, Facioscapulohumeral muscular dystrophy, Limb-Girdle muscular dystrophy, Emery-Dreifuss muscular dystrophy, Myotonic dystrophy, and Myotonia congenital.
- Becker's muscular dystrophy occurs in approximately 3 out of 100,000 people. Symptoms usually appear in men between the ages of 7 and 26. Women rarely develop symptoms. Because this is an inherited disorder, risks include having a family history of Becker's muscular dystrophy.
- Duchenne's muscular dystrophy occurs in approximately 2 out of 10,000 people. Symptoms usually appear in males 1 to 6 years old. Females are carriers of the gene for this disorder but rarely develop symptoms. Because this is an inherited disorder, risks include a family history of Duchenne's muscular dystrophy.
- Facioscapulohumeral muscular dystrophy affects approximately 5 out of 100,000 people. It affects men and women equally.

Myasthenia Gravis

- A disorder characterized by chronic weakness of voluntary muscles, which improves with rest and worsens with activity.
- Myasthenia gravis affects about 3 out of 10,000 people. Except when the disorder is associated with thymus tumor (which is most common in elderly men), myasthenia gravis is most common in adult women. Symptoms may worsen with pregnancy or menstrual periods.

Osteoarthritis

- A chronic disease causing deterioration of the joint cartilage and other joint tissues with the formation of new bone (bone spurs) at the margins of the joints.
- It may first appear without symptoms between 20 and 30 years of age and is present in almost everyone by the age of 70. Symptoms appear in middle age. Before the age of 55 it occurs equally in both sexes; however, after 55 the incidence is higher in women. Approximately 4 out of 100 people are affected.

Osteoporosis

- A condition which is characterized by the progressive loss of bone density and thinning of bone tissue.
- Researchers estimate that about 23% of American women over the age of 50 have osteoporosis and between 40% and 56% of them have osteopenia, which is abnormally low bone density which may eventually deteriorate into osteoporosis if not treated. From these figures, researchers estimate that 50% of women over the age of 50 will suffer a fracture of the hip, wrist or vertebra. The risk of fracture in men of the same age group is about 13%.

Parkinson's Disease

- A disorder of the brain characterized by shaking and difficulty with walking, movement, and coordination. The disease is associated with damage to a part of the brain that controls muscle movement.
- The disease affects approximately 2 out of 1,000 people, and most often develops after age 50. It affects both men and women and is one of the most common neurologic disorders of the elderly.

Peripheral Neuropathy

- A general classification of disorders involving damage or destruction of nerves, not including the nerves of the brain or spinal cord.
- Peripheral neuropathy (peripheral neuritis) is fairly common. The incidence varies with the specific type of neuropathy.

Poliomyelitis

- A disorder caused by a viral infection (poliovirus) that affects the whole body including muscles and nerves. Severe cases may cause permanent paralysis or death.
- It once affected mostly infants and children, but now is mostly seen in people over 15 years old. It is more common in the summer and fall. Adults and young girls are more likely to be infected, but infection in young boys is more likely to result in paralysis.

Rheumatoid Arthritis

- A chronic inflammatory disease that primarily affects the joints and surrounding tissues.
- The disease can occur at any age, but the peak incidence of disease onset is between the ages of 25 and 55. Women are affected 3 times more often than men. The incidence increases with age. Approximately 3% of the population is affected.

Spinal Cord Injury

- Damage to the spinal cord that results from injury.
- Spinal-cord injuries occur in approximately 12,000 to 15,000 people per year in the U.S. About 10,000 of these people are permanently paralyzed, and many of the rest die as a result of their injuries. Most spinal-cord trauma occurs to young, healthy individuals. Males between 15 and 35 years old are most commonly affected.

Stroke (Cerebrovascular Accident, CVA)

- A group of brain disorders involving loss of brain functions that occur when the blood supply to any part of the brain is interrupted.
- A stroke affects about 4 out of 1,000 people. It is the 3rd leading cause of death in most developed countries, including the U.S. The incidence of stroke rises dramatically with age, with the risk doubling with each decade after age 35. About 5% of people over age 65 have had at least one stroke. The disorder occurs in men more often than women.

APPENDIX B

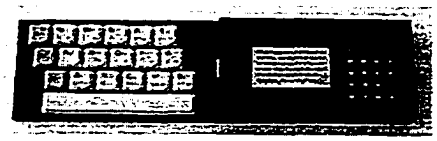
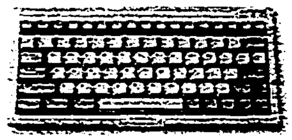
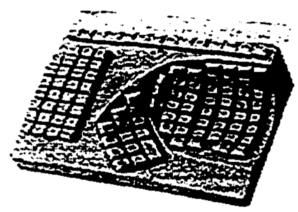
ASSISTIVE COMPUTER INPUT DEVICES

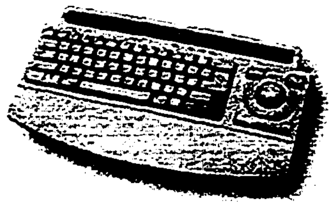
(Product Information and Manufacturers)

I. ALTERNATIVE KEYBOARD SYSTEMS

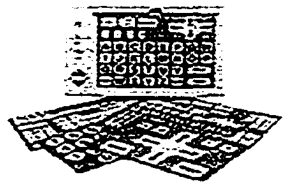
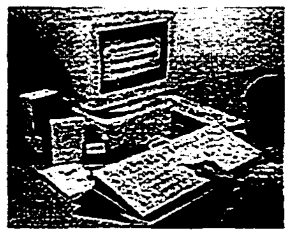
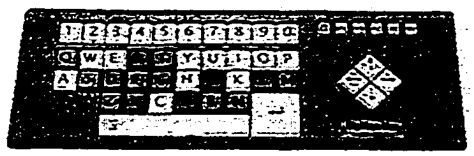
A. Different Sizes and Shapes

1. Mini Keyboards/Mini Mouse

Product Information	Features
Matias Half Keyboard **Matias Corporation** Address: 600 Rexdale Blvd, Suite 1204 Toronto, Ontario, M9W 6T4 Canada Phone: 416-675-3092 E-mail: info@halfkeyboard.com Web: http://halfkeyboard.com/	 The Matias Half Keyboard is a compact, inexpensive, handheld information appliance, designed specifically for word processing. Half Keyboard technology allows users to type with one hand, using their standard touch-typing skills. Price: $250.00
Mini Keyboard (C –131) **Keyboard Alternatives & Vision Solutions, Inc.** Address: 537 College Avenue Santa Rosa, CA 95404 Phone: 707-544-8000 Fax: 707-522-1343 E-mail: keyalt@keyalt.com Web: http://www.keyalt.com/	 This fully functional keyboard packs 80 keys into a frame that is less than a foot long and only six inches wide - leaving users plenty of room to put more stuff on their desk. Price: $85.00
MALTRON Single Handed Keyboard **PCD MALTRON Ltd.** Address: 15 Orchard Lane East Molesey Surrey KT8 0BN, England Phone/Fax: +44-181-398-3265 E-mail: sales@maltron.com Web: http://www.maltron.com/	 MALTRON single handed keyboards have been developed as a logical step forward to meet the needs of those who must perform keyboard operations with one hand. Price: £295.00

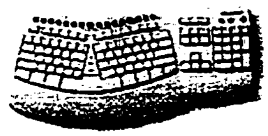
LittleFingers **Datadesk Technologies** Address: 10598 Valley Road NE, #100 Bainbridge Island, WA 98110 Phone: 408-272-0995 or 888-446-3222 Fax: 206-842-9219 E-mail: sales@datadesktech.com Web: http://www.datadesktech.com/	 The LittleFingers is a full functioned keyboard, ideal for users with smaller hands. Not only are the keys smaller, but they are also closer together. It also has an in-built trackball mounted on the right hand side, eliminating the need for the user to take their hands off the keyboard. Price: $49.95
The Magic Wand Keyboard: Miniature Computer Keyboard and Mouse for People with Disabilities **In Touch Systems** Address: 11 Westview Road Spring Valley, NY 10977 Phone: 800-332-6244 E-mail: susanc@magicwandkeyboard.com Web: http://www.magicwandkeyboard.com	 Allows users with limited or no hand movement to access any computer using only slight hand or head motion. The keyboard requires no strength or dexterity. Price: $1,660.00 (SMN33)
Little Mouse **Secret Seven Corp.** Address: 2416 London Road Suite 752 Duluth, MN 55812 Phone: 888-214-5611 or 218-525-9392 Fax: 218-525-9398 E-mail: squeak@littlemouse.com Web: http://www.littlemouse.com/	 The Little Mouse is the perfect size for kids and people with little hands. Price: $24.95

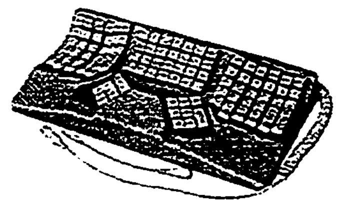
2. Large and Expanded Keyboards

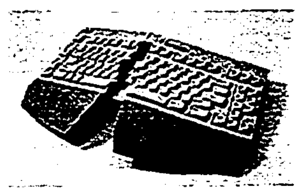
Product Information	Features
INTELLIKEYS **IntelliTools, Inc.** Address: 1720 Corporate Circle Petaluma, CA 949543553 Phone: 707-773-2000 Fax: 707-773-2001 E-mail: info@intellitools.com Web: http://www.intellitools.com/	 IntelliKeys provides a solution for the user who has difficulty pressing two keys simultaneously. Also, the arrow keys provides a possible way to the user who cannot use a mouse system. Price: $395.00 (IntelliKeys with PS/2 cable)
MALTRON Expanded Keyboard **PCD MALTRON Ltd.** Address: 15 Orchard Lane East Molesey Surrey KT8 0BN, England Phone/Fax: +44-181-398-3265 E-mail: sales@maltron.com Web: http://www.maltron.com/	 The MALTRON EXPANDED keyboard has been robustly designed with a strong steel construction to withstand heavy use, and a nylon coating for a smooth wipe-clean surface. It provides enhanced access for physically disabled and visually impaired users. Price: £545.00 (with integral keyguard)
Big Keys ***Plus***: PC version (BKPPCCQ) **Greystone Digital Inc** Address: P.O. Box 1888 Huntersville, NC 28078 Phone: 800-249-5397 Fax: 704-875-8936 E-mail: gdi@bigkeys.com Web: http://www.bigkeys.com/	 This keyboard is appropriate for those already well acquainted with the "standard" QWERTY keyboard layout; and for early learners, to both take advantage of computer learning programs and to become visually acquainted with the letter arrangement on a standard keyboard. Price: $169.00 (QWERTY/Color BKPPCCQ)

3. Ergonomic Keyboards

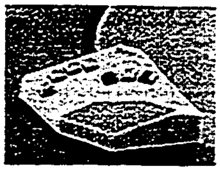
<table>
<tr><th>Product Information</th><th>Features</th></tr>
<tr><td>Microsoft Natural Keyboard Pro

Microsoft Corporation
Address: One Microsoft Way
Redmond, WA 98052-6399
Phone: 425-882-8080 (voice)
800-892-5234 (TT/TDD)
Web: http://www.microsoft.com/products/</td><td>
The split, gently sloped shape of the Natural Keyboard Pro encourages a natural hand, wrist and forearm position.
Price: $74.95</td></tr>
<tr><td>MALTRON Dual Handed Keyboard

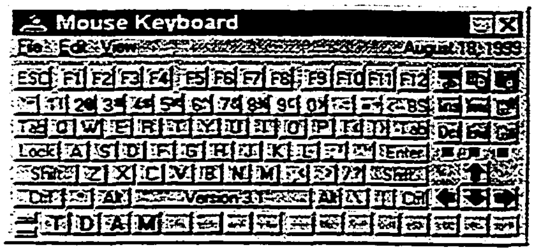
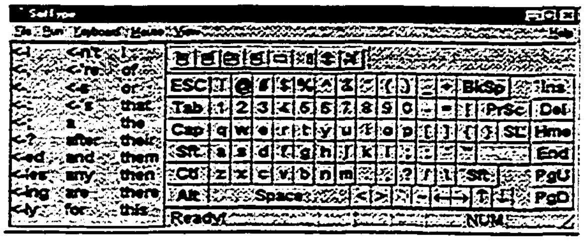
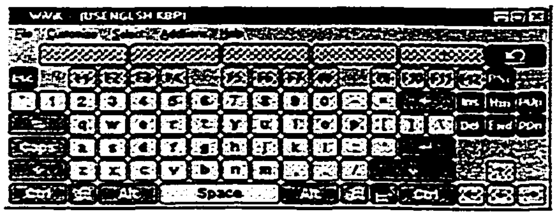
PCD MALTRON Ltd.
Address: 15 Orchard Lane
East Molesey
Surrey
KT8 0BN, England
Phone/Fax: +44-181-398-3265
E-mail: sales@maltron.com
Web: http://www.maltron.com/</td><td>
The fully ergonomic MALTRON (as shown in the above) fits the shape of hands and the different lengths of fingers to reduce movement and tension.
Price: £375.00</td></tr>
<tr><td>Maxim Adjustable Ergonomic Keyboard:
PC QWERTY layout (KB200PC)

Kinesis Corporation
Address: 22121 17th Avenue SE, Suite 112
Bothell, Washington 98021-7404
Phone: 425-402-8100
Fax: 425-402-8181
E-mail: sales@kinesis-ergo.com
Web: http://www.kinesis-ergo.com/</td><td>
The Maxim adjustable keyboard offers a more flexible, more comfortable design. Narrow footprint keeps your mouse close by. Padded, removable palm supports make for relaxed shoulder and neck muscles.
Price: $139.00</td></tr>
</table>

4. Chord Keyboards

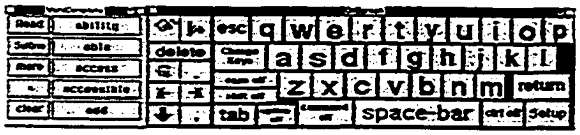
Product Information	Features
BAT Chord Keyboard **Infogrip, Inc.** Address: 1141 E. Main Street Ventura, CA 93001 Phone: 800-397-0921 or 805-652-0770 Fax: 805-652-0880 E-mail: sales@infogrip.com Web: http://www.infogrip.com/	 The BAT is the ultimate typing solution for persons with physical or visual impairments and is proven to increase productivity when used with graphic or desktop publishing software. Price: $199.00

B. Virtual On-Screen Keyboard

Product Information	Features
SPT Mouse Keyboard 3.1: On-screen typing keyboard. **Simply Powerful Technologies (SPT)** E-mail: info@simplypowerful.com Web: http://www.simplypowerful.com/	 Mouse Keyboard provides smooth, fast, on-screen typing. Utilize all the capabilities of touch screen, mouse, tablet, or other input device. Price: $49.99 (plus $4.95 S&H)
SofType: On-screen keyboards for Microsoft Windows. **Origin Instruments Corporation** Address: 854 Greenview Drive Grand Prairie, Texas 75050 Phone: 972-606-8740 Fax: 972-606-8741 E-mail: sales@orin.com Web: http://www.orin.com/	 SofType is an on-screen keyboard designed to allow users with motor impairments, which hinder use of a normal hardware keyboard, to type into Windows applications. Price: $300.00
WiViK2 REP: On-screen keyboard for the Windows environment. **Prentke Romich Company** Address: 1022 Heyl Road Wooster, OH 44691 Phone: 800-262-1984 Fax: 330-263-4829 E-mail: info@prentrom.com Web: http://www.prentrom.com/	 The image of a keyboard can be accessed using a mouse, trackball, HeadMaster 2000, JOUSE, or other mouse emulator. Price: $1,350.00 (End-user licenses, 5-Pack)

OnScreen (SW-7): On-screen keyboard for the Windows.

RJ Cooper & Assoc.
Address: 27601 Forbes Rd. Suite 39
Laguna Niguel, CA 92677
Phone: 949-582-2749
Fax: 949-582-3169
E-mail: info@rjcooper.com
Web: http://www.rjcooper.com/

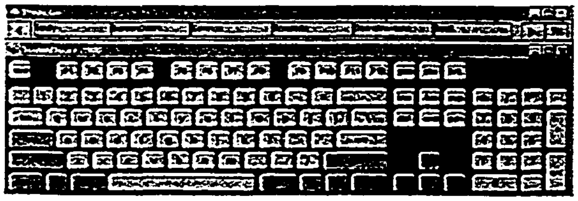


This on-screen keyboard allows the user to enter text into any application. Many special features based on feedback from actual on-screen keyboard users are included.

Price: $99.00 (OnScreen for Windows: SW-7)

ScreenDoors 2000: On-screen keyboard software for Windows.

Madenta Communications
Address: 3022 Calgary Trail South
Edmonton, Alberta
Canada T6J 6V4
Phone: 780-450-8926
Fax: 780-988-6182
E-mail: sales@madenta.com
Web: http://www.madentec.com/

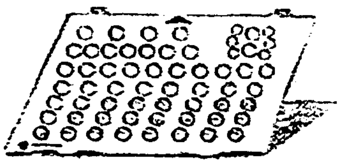
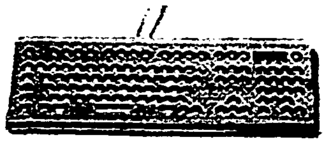


ScreenDoors 2000 is ideally suited for individuals with Quadriplegia, Cerebral Palsy, Multiple Sclerosis, Muscular Dystrophy, ALS, Carpal Tunnel Syndrome and any other disability where the user has little or no control of their hands to use a standard keyboard.
Price: $395.00

C. Mouth Sticks and Head Pointers

Product Information	Features
H-A Modular Mouthstick System **Extensions for Independence** Address: 555 Saturn Blvd. B-368 San Diego, CA 92154 Phone: 619-423-1748 Fax: 619-423-7709 E-mail: info@mouthstick.net Web: http://www.mouthstick.net/	 Company is a designer and manufacturer of home and office related equipment for the disabled. The disabled user can easily extend or shorten the mouthstick as needed. Price: $429.00 (plus shipping, Rehab Kit)
Clear-View Headpointer: SP-6000 **ORTHOBIONICS, Inc.** Address: 3530 Forest Lane, Suite 48 Dallas, Texas 75234 Phone: 214-350-6981 or 800-580-4768 Fax: 214-350-6982 Web: http://www.orthobionics.com/	 Unit extends from jaw level, permitting better vision and body positioning than a forehead pointer. User stays comfortably positioned, and minimal head movement is required. Lightweight aluminum yoke can be bent to adjust pointer angle. Price: $187.90 (SP-6000)

D. Keyguards

Product Information	Features
Keyguards for Standard Overlays **IntelliTools, Inc.** Address: 1720 Corporate Circle Petaluma, CA 94954-3553 Phone: 707-773-2000 Fax: 707-773-2001 E-mail: info@intellitools.com Web: http://www.intellitools.com/	 Keyguards can make a tremendous difference for people with disabilities. They prevent unintentional keystrokes and allow users to make more accurate choices. Price: $50.00 (IBM QWERTY: KG-IQ)
Tash Keyguard IBM PS/2 (#2470) **Tash Inc.** Address: 3512 Mayland Ct. Richmond VA 23233 Phone: 804-747-5020 Fax: 804-747-5224 E-mail: tashinc@aol.com Web: http://www.tashinc.com/	 A keyguard is a metal plate with holes that fits over a standard computer keyboard. Price: $70.00 (PS/2 #2470)

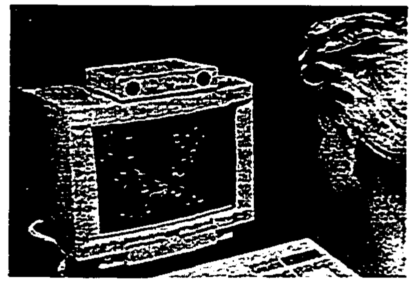
E. Voice (Speech) Recognition System

Product Information	Features
Dragon NaturallySpeaking® Preferred USB 4.0 **Dragon Systems, Inc.** Address: 320 Nevada Street Newton, MA 02460 Phone: 617-965-5200 Fax: 617-965-2374 E-mail: info@dragonsys.com Web: http://www.dragonsys.com/	 Dragon NaturallySpeaking v4.0 enables users to dictate naturally into their computer at up to 160 words per minute instead of keyboarding and fumbling with a mouse. The dictation is immediately and accurately transcribed on the screen and in the document. Price: $249.00
L&H Voice Xpress™ Professional Version 5 **Lernout & Hauspie** Address: 1420 Beverly Road McLean, VA 22101 Phone: 703-821-5000 Fax: 703-273-6098 E-mail: sales@lhsl.com Web: http://www.lhsl.com/	 L&H Voice Xpress™ Professional features dictation to virtually all Windows® based applications, as well as L&H's patented Natural Language Technology™ for the full suite of Microsoft® Office applications. Further, it works with the features of Office 2000. Price: $149.00

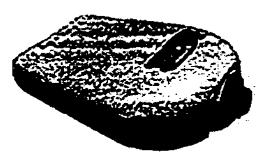
II. ALTERNATIVE POINTING SYSTEMS

A. Head Controls

<table>
<tr><th>Product Information</th><th>Features</th></tr>
<tr><td>HeadMouse: Head-controlled pointing for computer access.

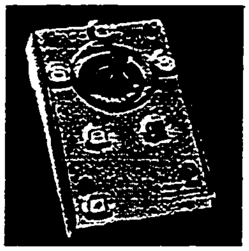
Origin Instruments Corporation
Address: 854 Greenview Drive
Grand Prarie, TX 75050
Phone: 972-606-8740
Fax: 972-606-8741
E-mail: sales@orin.com
Web: http://www.orin.com/</td><td>
Translates user's head movements into directly proportional movements of a computer mouse for those users who cannot use their hands.
Price: $1,795.00 + $100.00 (cable)</td></tr>
<tr><td>Headmaster Plus/Headmaster Remote Adapter: Head pointing system which provides full mouse control of computers to persons who cannot use their hands but who have good head control.

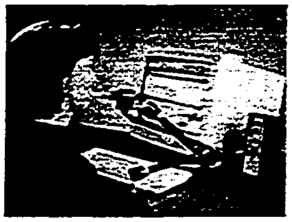
Prentke Romich Company
Address: 1022 Heyl Road
Wooster, OH 44691
Phone: 800-262-1984
Fax: 330-263-4829
E-mail: info@prentrom.com
Web: http://www.prentrom.com/</td><td>
Activating the puff switch or other external switch makes selections. On-screen keyboards allow for word processing and other text entry.
Price: $1,595.00</td></tr>
<tr><td>Tracker 2000: Head pointing system

Madenta Communications
Address: 3022 Calgary Trail South
Edmonton, Alberta
Canada T6J 6V4
Phone: 780-450-8926
Fax: 780-988-6182
E-mail: sales@madenta.com
Web: http://www.madentec.com/</td><td>
It allows users to smoothly move the cursor on the computer simply by moving their head, regardless of their disability.
Price: $1,895.00</td></tr>
</table>

B. Joystick

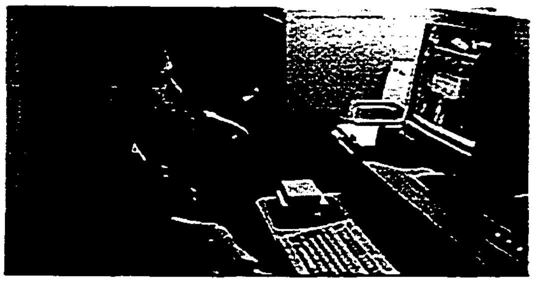
<table>
<tr><th>Product Information</th><th>Features</th></tr>
<tr><td>Penny & Giles Joystick Plus: Turns wheelchair joystick movements into mouse pointer movements.

Penny & Giles Computer Products
Address: 1 Embankment Way
Castleman Industrial Estate
RINGWOOD
Hampshire, BH24 1EU
United Kingdom
Phone: +44 (0) 1425 463100
Fax: +44 (0) 1425 463111
E-mail: sales@penny-gilescp.co.uk
Web: http://www.penny-gilescp.co.uk/</td><td>
The mouse pointer moves fastest when the joystick is pushed fully forward. The joystick illustrated has a built in guard and has a drag lock button.
Price: $450.00</td></tr>
<tr><td>JOUSE: Joystick-based system for head/mouth control of mouse and keyboard.

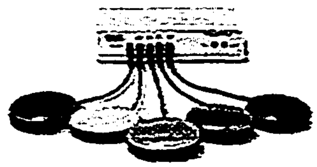
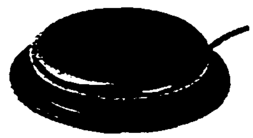
Prentke Romich Company
Address: 1022 Heyl Road
Wooster, OH 44691
Phone: 800-262-1984
Fax: 330-263-4829
E-mail: info@prentrom.com
Web: http://www.prentrom.com/</td><td>
JOUSE is a joystick-operated mouse that is controlled with mouth. Mouse button activations can be made with the sip, puff, and bite switches built into the JOUSE.
Price: $2,195.00</td></tr>
<tr><td>QuadJoy

Street Electric Manufacturing Co.
Address: N9096 Dairyland Dr.
Cleveland, WI 53015
Phone: 920-693-2824 or 877-736-2663
Fax: 920-693-2825
E-mail: tstreet@quadjoy.com
Web: http://www.quadjoy.com/</td><td>
The Quad Joy combines a joystick controller with a sip/puff switch. It offers complete control of one's computer without being attached to the computer. The device is mounted on a flexible gooseneck which can be locked into position.
Price: $490.00 (plus $18.00 US shipping)</td></tr>
</table>

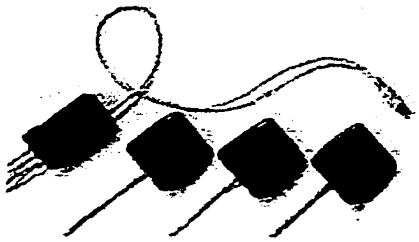
C. Sip and Puff

Product Information	Features
WISP 2000: Sip-and-Puff **Madenta Communications** Address: 3022 Calgary Trail South Edmonton, Alberta Canada T6J 6V4 Phone: 780-450-8926 Fax: 780-988-6182 E-mail: sales@madenta.com Web: http://www.madentec.com/	 WISP was developed for people who use Tracker or need to control a switch wirelessly. It is suitable for individuals with Quadriplegia, Cerebral Palsy, Multiple Sclerosis, Muscular Dystrophy, ALS, or any disability where remote switch activation is required. Price: $790.00 (WISP 2000 Wireless)
Access 2000 Mouse Emulator with a Sip-and-Puff Interface Module **Advanced Peripheral Technologies, Ltd.** Address: 14416 Erin Court Lockport, IL 60441 Phone: 708-301-4508 Fax: 708-301-4695 E-mail: apt@advancedperipheral.com Web: http://www.advancedperipheral.com	 The emulator lets individual use sip and puff mechanism to emulate mouse's actions. Price: Access-2000 Mouse Emulator $350.00 Access-2000 Joystick $50.00 Access-2000 Sip&Puff Interface $249.00 Access-2000 Sip&Puff Equipment Stand $85.00

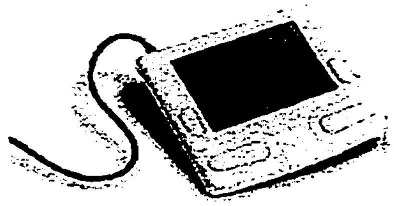
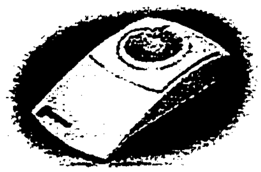
D. Switches

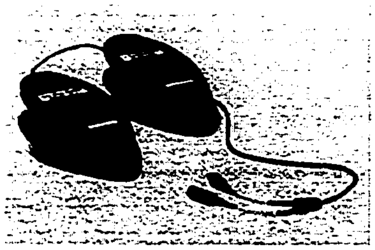
Product Information	Features
Mouse Mover: Combination of five single switches or any multiple switches **Tash Inc.** Address: 3512 Mayland Ct. Richmond VA 23233 Phone: 804-747-5020 Fax: 804-747-5224 E-mail: tashinc@aol.com Web: http://www.tashinc.com/	 People who cannot control the standard computer mouse, but can use single or multiple switches for access. Price: $275.00
Big Red Switch **AbleNet, Inc.** Address: 1081 Tenth Ave. SE Minneapolis, MN 55414 Phone: 612-379-0956 or 800-322-0956 Fax: 612-379-9143 E-mail: customerservice@ablenetinc.com Web: http://www.ablenetinc.com/	 The switch has a large colorful surface area which is ideal for people with visual, cognitive or physical requirements. Price: $42.00
GloSwitch **ORCCA Technology, Inc.** Address: 462 East High Street Lexington, Kentucky 40507 Phone: 606-226-9625 Fax: 606-226-0936 E-mail: orcca@mis.net Web: http://www.orcca.com/	 A switch with a back-lit, plastic dome that can be easily located by persons with visual impairments. Price: $50.00

<table>
<tr>
<td>
Step on It!: Foot Switches (for people with limited hand movements)

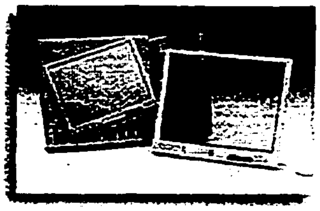
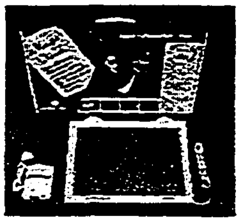
Bilbo Innovations, Inc.
Address: 1290 Oakmead Parkway #118
Sunnyvale, CA 94086
Phone: 408-736-6086
Fax: 408-736-6083
E-mail: bilbo@bilbo.com
Web: http://www.bilbo.com/
</td>
<td>

Three custom-programmable foot switches give keyboard control and emulate keystrokes, sequences or mouse clicks.
Price: $99.00 (Set of Three Pedals with Controller)
</td>
</tr>
</table>

E. Touchpad and Trackballs

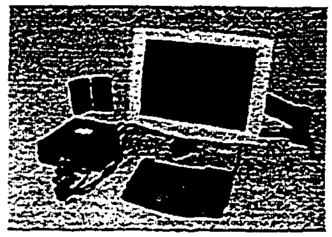
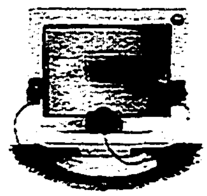
Product Information	Features
Cirque Smart Cat: Touchpad **Cirque Corporation** Address: 433 W. Lawndale Drive Salt Lake City, Utah 84115 Phone: 801-467-1100 Fax: 801-467-0208 E-mail: sales@cirque.com Web: http://www.cirque.com/	 Cirque Smart Cat sets a higher standard of performance for input devices. With the intelligent software, users can scroll and zoom in most applications. Price: $59.95
Expert Mouse Trackball (#64215) **Kensington Technology Group** Address: 2855 Campus Drive San Mateo, California 94403 Phone: 650-572-2700 Fax: 650-572-9675 E-mail: help@kensington.com Web: http://www.kensington.com/	 Four extra-large buttons are easy to click, comfortable to use, large ball offers more control and precision, less hand and arm movement, and symmetrical design fits left- or right-handed users and all hand sizes. Price: $99.99
MicroSpeed PC-Trac Deluxe **MicroSpeed Incorporated** Address: 11489 Woodside Ave Santee, CA 92071-4724 Phone: 619-448-2888 or 800-232-7888 Fax: 619-448-3044 E-mail: sales@microspeed.com Web: http://www.microspeed.com/	 The trackball is designed to easily accommodate both right and left hand users, as well as different size hands. No need to move a whole arm or to rotate a wrist from side to side. Price: $59.95

NoHands Mouse: Foot Mouse **Hunter Digital** Address: 11999 San Vicente Blvd., Suite 440 Los Angeles, CA 90049 Phone: 310-476-1874 Fax: 310-471-1669 E-mail: footmouse@earthlink.net Web: http://www.footmouse.com/	 With the NoHands Mouse, users can have complete contol of the cursor without having to take their hands off the keyboard, or their eyes off the monitor. Price: $289.95

F. Touch Screens and Light Pen

Product Information	Features
TouchWindow for Windows/DOS 902-1014 **Edmark Corporation** Address: Customer Service P.O. Box 97021 Redmond, WA 98073-9721 Phone: 425-556-8400 or 800-691-2986 E-mail: edmarkteam@edmark.com Web: http://www.edmark.com	 The TouchWindow is ideal for people who have trouble manipulating the mouse. It is especially effective for people with developmental or physical disabilities. Price: $335.00
MAGIC TOUCH TOUCHSCREEN **KEYTEC, Inc.** Address: 1293 North Plano Road Richardson, Texas 75081 Phone: 800-MAGIC-89 or 972-234-8617 Fax: 972-234-8542 E-mail: sales@magictouch.com Web: http://www.magictouch.com/	 This easy-to-use, and affordable Add-On Touch Screen Kit turns any style monitor into a touch interactive device. Price: $257.00 (KTMT-1700-USB)
MicroSpeed LP-213 External Interface Light Pen System w/nosetip & 2 side switch light pen **MicroSpeed Incorporated** Address: 11489 Woodside Ave Santee, CA 92071-4724 Phone: 619-448-2888 or 800-232-7888 Fax: 619-448-3044 E-mail: sales@microspeed.com Web: http://www.microspeed.com/	 The light pen operates without expensive special screens or clumsy overlays and does not experience calibration drift. Price: $550.00

G. EyeGaze

Product Information	Features
The Eyegaze System **LC Technologies, Inc.** Address: 9455 Silver King Court Fairfax, Virginia 22031-4713 Phone: 703-385-7133 or 800-393-4293 Fax: 703-385-7137 E-mail: requests@eyegaze.com Web: http://www.eyegaze.com/	 An educational discount of $1000 is available if the Eyegaze Development System is purchased by a college or university. Price: $17,900.00 (basic development system)
Eye Science Gaze Tracking System **EyeTech Digital Systems, Inc.** Address: 1750 East McClellan Rd. Mesa, AZ 85203 Phone: 480-610-1899 Fax: 602-728-9907 E-mail: info@eyetechds.com Web: http://www.eyetechds.com/	 This eyegaze system will be used for anyone who cannot use a hand operated mouse or anyone desiring a hands-free computer interface. Price: $7,490.00 (plus shipping)

APPENDIX C

ASSISTIVE TECHNOLOGY RESOURCE DIRECTORY

Assistive Technology Resource Directory

ABLEDATA

ABLEDATA is a federally funded project whose primary mission is to provide information on assistive technology and rehabilitation equipment available from domestic and international sources to consumers, organizations, professionals, and caregivers within the United States.

Address:	8630 Fenton Street, Suite 930 Silver Spring, MD 20910
Phone:	800-227-0216
TTY:	301-608-8912
Fax:	301-608-8958
E-mail:	abledata@macroint.com
Web Page:	http://www.abledata.com/

Access Board

Access board is an independent federal agency. Contains information on Section 508 of the Rehabilitation Act, as amended requiring that electronic and information technology developed, procured, maintained, or used by the federal government be accessible to people with disabilities. In 1998, the Board established an Electronic and Information Technology Access Advisory Committee (EITAAC) to help the Board develop standards under Section 508.

Address:	1331 F St., NW, Suite 1000 Washington, D.C. 20004-1111
Phone:	800-USA-ABLE (1-800-872-2253) or 202-272-5434
TTY:	800-993-2822 or 202-272-5449
Fax:	202-272-5447
E-mail:	info@access-board.gov
Web Page:	http://www.access-board.gov/

American Business Clubs (AMBUCS)

AMBUCS is a national service organization composed of a diverse group of men and women dedicated to creating independence and opportunities for people with disabilities.

Address:	3315 North Main St. High Point, NC 27265
Phone:	336-869-2166

Fax:	336-887-8451
E-mail:	ambucs@ambucs.com
Web Page:	http://www.ambucs.com/

Americans with Disabilities Act (ADA)

The ADA protects the right of people with disabilities to have equal access to the basic institutions of State and local government. The Department has sought to eliminate physical, communication, and policy barriers in law enforcement, town halls, jails, courtrooms, and legislative chambers.

Address:	Disability Rights Section Civil Rights Division U.S. Department of Justice Post Office Box 66738 Washington, DC 20035-6738
Phone:	800-514-0301 (Voice) 800-514-0383 (TDD)
Web Page:	http://www.usdoj.gov/crt/ada/adahom1.htm

AZtech, Inc.

AZtech is a full-service market research and technology transfer company offering a complete range of services, including focus groups, interviews, surveys, literature searches, industry profiles and trends, technology transfer, invention commercialization and business consulting. AZtech provides professional services to businesses and inventors with strong support from the consumers of assistive technology products.

Address:	2495 Main Street, Suite 418 Buffalo, NY 14214
Phone:	716-833-7870
Fax:	716-833-7874
E-mail:	kohler@acsu.buffalo.edu
Web Page:	http://cosmos.ot.buffalo.edu/aztech/

Alliance for Public Technology (APT)

The Alliance for Public Technology (APT) is a nonprofit membership organization based in Washington, DC. Membership is open to all nonprofit organizations and individuals, not members of the affected industries, concerned with fostering access to affordable and useful information and communication services and technologies by all people.

Address:	P.O. Box 27146 Washington, DC 20038-7146

Phone:	202-263-2970 (Voice & TTY)
Fax:	202-263-2960
E-mail:	apt@apt.org
Web Page:	http://www.apt.org/

Alliance for Technology Access (ATA)

The Alliance for Technology Access (ATA) seeks to redefine human potential by making technology a regular part of the lives of people with disabilities. The ATA is accomplishing this by raising public awareness and implementing programs and initiatives that provide access to conventional, assistive and information technologies, related services and resources.

Address:	2175 East Francisco Blvd., Suite L San Rafael, CA 94901
Phone:	800-455-7970 or 415-455-4575
E-mail:	atainfo@ataccess.org
Web Page:	http://www.ataccess.org/

Assistive Technology Industry Association (ATIA)

The Assistive Technology Industry Association (ATIA) is a not-for-profit membership organization of organizations manufacturing or selling technology-based assistive devices for people with disabilities, or providing services associated with or required by people with disabilities.

Address:	526 Davis Street Suite 217 Evanston, Illinois 60201-4686
Phone:	877-687-2842 or 847-869-1282
Fax:	847-869-5689
E-mail:	ATIA@northshore.net
Web Page:	http://www.atia.org/

Assistive Technology, Training and Information Center (ATTIC)

The ATTIC's mission is to provide support, information and education for individuals with disabilities and for families of children with special needs, and the professionals who assist these families.

Address:	P.O. Box 2441 3354 Pine Hill Drive Vincennes, Indiana 47591
Phone:	800-96-ATTIC or 812-886-0575

Fax:	812-886-1128
E-mail:	inattic1@aol.com
Web Page:	http://www.theattic.org/

Center for Applied Special Technology (CAST)

Founded in 1984, CAST is a not-for-profit organization whose mission is to expand opportunities for individuals with disabilities through the development of and innovative uses of technology. CAST pursues this mission through research, product development, and work in schools and educational settings.

Address:	39 Cross Street, Suite 201 Peabody, MA 01960
Phone:	978-531-8555
TTY:	978-538-3110
Fax:	978-531-0192
E-mail:	cast@cast.org
Web Page:	http://www.cast.org/

Center for Assistive Technology (CAT)

The Center for Assistive Technology (CAT) at the University at Buffalo conducts research, education and service to increase knowledge about assistive devices for persons with disabilities.

Address:	515 Kimball Tower University at Buffalo Buffalo, NY 14214-3079
Phone:	716-829-3141
TDD/TTY:	800-628-2281
Fax:	716-829-3217
E-mail:	ot-web@cosmos.ot.buffalo.edu
Web Page:	http://wings.buffalo.edu/ot/cat/

Consortium for Citizens with Disabilities (CCD)

CCD is a working coalition of more than 100 national consumer, advocacy, provider, and professional organizations working together with and on behalf of the 54 million children and adults with disabilities and their families living in the United States. The CCD has several task forces on various disability issues, such as Employment and Training, Developmental Disabilities, Health, Social Security, Long-Term Services and Supports, Telecommunications and Technology, and Rights, etc.

Address:	1730 K Street, NW, Suite 1212 Washington, DC 20006
Phone:	202-785-3388
Fax:	202-467-4179
E-mail:	Info@c-c-d.org
Web Page:	http://www.c-c-d.org/

Center for Disease Control and Prevention (CDC)

The Centers for Disease Control and Prevention (CDC) performs many of the administrative functions for the Agency for Toxic Substances and Disease Registry (ATSDR), a sister agency of CDC, and one of eight federal public health agencies within the Department of Health and Human Services. The Director of CDC also serves as the Administrator of ATSDR.

Address:	1600 Clifton Rd. Atlanta, GA 30333
Phone:	800-311-3435 or 404-639-3311, 3534
E-mail:	netinfo@cdc.gov
Web Page:	http://www.cdc.gov/

Center for Information Technology (CIT)

The main mission of the CIT is to provide, coordinate, and manage information technology to be a vital partner in the discovery of biomedical knowledge.

Address:	12 South Drive MSC 5651 Bethesda, MD 20892-5651
Phone:	301-435-6595
TDD:	301-496-8294
Fax:	301-402-2754
E-mail:	citio@mail.nih.gov
Web Page:	http://www.cit.nih.gov/

Center for Information Technology Accommodation (CITA)

Established in 1984, the Center for IT Accommodation (CITA) is a nationally recognized model demonstration facility influencing accessible information environments, services, and management practices. To achieve this goal, CITA works with an expanding network of public and private sector partners, also making legislation and policies on information systems accessibility including the Assistive Technology Act of 1998.

Address:	U.S. General Services Administration,

Center for IT Accommodation (CITA)
1800 & F Street, NW, Room 1234, MC:MKC
Washington, DC 20405-0001

Phone:	202-501-4906
TTY:	202-501-2010
Fax:	202-501-6269
Web Page:	http://www.itpolicy.gsa.gov/cita/

Closing The Gap

Closing The Gap is an organization that focuses on computer technology for people with special needs through its bi-monthly newspaper, annual international conference and extensive web site.

Address:	526 Main Street, P.O. Box 68 Henderson, MN 56044
Phone:	507-248-3294
Fax:	507-248-3810
E-mail:	info@closingthegap.com
Web Page:	http://www.closingthegap.com/

disABILITY Information and Resources

This site was created and is maintained by Jim Lubin, who is a C2 quadriplegic, completely paralyzed from the neck down and dependent on a ventilator to breathe.

Address:	PO Box 82433 Kenmore, WA 98028-0433
E-mail:	jlubin@eskimo.com
Web Page:	http://www.makoa.org/

Equal Access to Software and Information (EASI)

EASI is part of the Teaching, Learning, and Technology Group, an affiliate of the American Association of Higher Education. EASI's mission is to serve as a resource to the education community by providing information and guidance in the area of access-to-information technologies by individuals with disabilities.

Address:	TLT Group P.O. Box 18928 Rochester, NY 14618
Phone:	716-244-9065
E-mail:	easi@tltgroup.org

Web Page: http://www.rit.edu/~easi/

Kiwanis International

Kiwanis International was founded in 1915 and is headquartered in Indianapolis, Indiana. Kiwanis International is a thriving organization of service- and community-minded individuals who support children and young adults around the world. More than 600,000 Kiwanis-family members in 76 countries make their mark by responding to the needs of their communities and pooling their resources to address worldwide issues. Through these efforts, Kiwanis International truly is "Serving the Children of the World."

Address:	3636 Woodview Trace Indianapolis, IN 46268-3196
Phone:	317-875-8755
Fax:	317-879-0204
E-mail:	kiwanismail@kiwanis.org
Web Page:	http://www.kiwanis.org/

Muscular Dystrophy Association (MDA)

The Muscular Dystrophy Association is a voluntary health agency - a dedicated partnership between scientists and concerned citizens aimed at conquering neuromuscular diseases that affect more than a million Americans.

Address:	3300 E. Sunrise Drive Tucson, AZ 85718
Phone:	800-572-1717
E-mail:	mda@mdausa.org
Web Page:	http://www.mdausa.org/

National Rehabilitation Information Center (NARIC)

NARIC is a library and information center on disability and rehabilitation. More than 50,000 National Institute on Disability and Rehabilitation Research (NIDRR)-funded, other federal agencies, and private disability-related publications are held and abstracted by NARIC in their REHABDATA database, searchable online.

Address:	1010 Wayne Avenue, Suite 800 Silver Spring, MD 20910
Phone:	800-346-2742 or 301-562-2400
TTY:	301-495-5626
Fax:	301-562-2401
E-mail:	naricinfo@kra.com

Web Page: http://www.naric.com/

National Center for the Dissemination of Disability Research (NCDDR)

The Southwest Educational Development Laboratory (SEDL) was awarded a new five-year grant from the National Institute on Disability and Rehabilitation Research (NIDRR) to maintain the National Center for the Dissemination of Disability Research (NCDDR). Established in 1995, the NCDDR research activities are designed to collect information that will assist in identifying the needs and most likely strategies that will assist in matching dissemination practices with intended user groups.

Address: 211 East Seventh Street, Suite 400
Austin, Texas 78701-3281
Phone: 800-266-1832 or 512-476-6861
Fax: 512-476-2286
E-mail: NCDDR@sedl.org
Web Page: http://www.ncddr.org/

National Institute on Disability and Rehabilitation Research (NIDRR)

NIDRR, part of the U.S. Department of Education, manages and funds more than 300 projects on disability and rehabilitation research, including 56 state and U.S. territory Assistive Technology projects and several Rehabilitation Engineering Research Centers.

Address: 400 Maryland Avenue, SW
Washington, DC 20202-2572
Phone: 202-205-8134
TTY: 202-205-4475
Web Page: http://www.ed.gov/offices/OSERS/NIDRR/

National Institutes of Health (NIH)

The mission of NIH is to uncover new knowledge that will lead to better health for everyone. NIH works toward that mission by: conducting research in its own laboratories; supporting the research of non-Federal scientists in universities, medical schools, hospitals, and research institutions throughout the country and abroad; helping in the training of research investigators; and fostering communication of medical information.

Address: National Institutes of Health (NIH)
Bethesda, Maryland 20892
Phone: 301-496-1776
E-mail: nihinfo@od.nih.gov
Web Page: http://www.nih.gov/

National Organization on Disability (NOD)

The National Organization on Disability promotes the full and equal participation of people with disabilities in all aspects of life. NOD was founded in 1982 at the conclusion of the United Nations International Year of Disabled Persons. Funded entirely by private sector contributions, NOD is the only national disability network organization concerned with all disabilities, all age groups and all disability issues.

Address:	910 Sixteenth Street, N.W. Suite 600 Washington, D.C. 20006
Phone:	202-293-5960
TDD:	202-293-5968
Fax:	202-293-7999
E-mail:	ability@nod.org
Web Page:	http://www.nod.org/

President's Committee on Employment of People with Disabilities (PCEPD)

The President's Committee on Employment of People with Disabilities' mission is to communicate, coordinate and promote public and private efforts to enhance the employment of people with disabilities. The Committee provides information, training, and technical assistance to America's business leaders, organized labor, rehabilitation and service providers, advocacy organizations, families and individuals with disabilities. The President's Committee reports to the President on the progress and problems of maximizing employment opportunities for people with disabilities.

Address:	1331 F Street, N.W. Suite 300 Washington D.C. 20004
Phone:	202-376-6200
TDD:	202-376-6205
Fax:	202-376-6219
E-mail:	info@pcepd.gov
Web Page:	http://www.pcepd.gov/

Rehabilitation Engineering and Assistive Technology Society of North America (RESNA)

RESNA is an interdisciplinary association of people with a common interest in technology and disability. The main purpose of RESNA is to improve the potential of people with disabilities to achieve their goals through the use of technology. RESNA serves that purpose by promoting research, development, education, advocacy, and the provision of technology and by supporting the people engaged in these activities. RESNA was founded in 1979 as a not-for-profit professional organization.

Address:	1700 North Moore Street, Suite 1540 Arlington, VA 22209-1903
Phone:	703-524-6686
TTY:	703-524-6639
Fax:	703-524-6630
E-mail:	info@resna.org
Web Page:	http://www.resna.org/

Rotary International

Rotary is an organization of business and professional leaders united worldwide who provide humanitarian service, encourage high ethical standards in all vocations, and help build goodwill and peace in the world. In more than 160 countries worldwide, approximately 1.2 million Rotarians belong to more than 29,000 Rotary clubs.

Address:	One Rotary Center 1560 Sherman Ave. Evanston, IL 60201
Phone:	847-866-3000
Fax:	847-328-8554 or 847-328-8281
E-mail:	pid@rotaryintl.org
Web Page:	http://www.rotary.org/

Shrine and Shriners Hospitals for Children

The Shrine of North America is an international fraternity of approximately 515,000 members throughout the United States, Mexico, Canada and Panama. The Shrine's official philanthropy is Shriners Hospitals for Children, a network of 22 hospitals that provide expert, no-cost orthopedic and burn care to children under 18.

Address:	International Shrine Headquarters 2900 Rocky Point Dr. Tampa, FL 33607-1460
Phone:	800-237-5055 or 813-281-0300
Web Page:	http://shriners.com/

Trace Research & Development Center

The Trace Center conducts research aimed at improving technology that can benefit individuals with disabilities by making it more accessible in four main areas: communication; control; computer access; and next generation communication information and transaction systems.

Address:	5901 Research Park Boulevard Madison, WI 53719-1252
Phone:	608-262-6966
TTY:	608-263-5408
Fax:	608-262-8848
E-mail:	web@trace.wisc.edu
Web Page:	http://trace.wisc.edu/

United Cerebral Palsy (UCP)

The main mission of UCP is to advance the independence, productivity and full citizenship of people with cerebral palsy and other disabilities.

Address:	1660 L Street, NW, Suite 700 Washington, DC 20036
Phone:	800-872-5827 or 202-776-0406
TTY:	202-973-7197
Fax:	202-776-0414
E-mail:	webmaster@ucp.org
Web Page:	http://www.ucp.org/

U.S. Department of Veterans Affairs (VA)

The missions of VA are to serve America's veterans and their families with dignity and compassion and be their principal advocate in ensuring that they receive medical care, benefits, social support, and lasting memorials promoting the health, welfare, and dignity of all veterans in recognition of their service to this Nation.

Address:	Vermont Ave., NW Washington, DC 20420
Phone:	800-827-1000
E-mail:	public.inquiry@mail.va.gov
Web Page:	http://www.va.gov/

APPENDIX D

INFORMED CONSENT FORM
FOR ADULTS

INFORMED CONSENT FORM

Signing this form constitutes your consent for participation in a research project conducted under the auspices of the School of Industrial Engineering, the University of Oklahoma, Norman, Oklahoma.

Project Title: Methodology for the Selection and Evaluation of Computer Input Devices for People with Functional Limitations.
Investigator: Byeong-cheol Hwang, Graduate Student, School of Industrial Engineering, University of Oklahoma.
Advisors: Dr. Robert E. Schlegel, Dr. Randa L. Shehab, School of Industrial Engineering, University of Oklahoma

This study will focus on the ability of various input devices to provide people with upper-limb motor impairments better access to computers. A methodology for specifying alternative assistive input devices as a function of type and degree of functional limitation is important for improving access to computer technology. The current research will develop a matrix for matching assistive technology input devices to the assessed level of functional limitation. Since there are few reliable input device assessment instruments for people with impairments, this research also hopes to develop and validate a methodology for assessing the level of impairment for people with upper-limb motor impairments. It is expected that the results of this work will enable a better evaluation of existing devices and will promote the development of creative solutions for computer access by people with motor impairments.

This study will require approximately two hours of your time. You will be provided with instructions and adequate practice time before the main work begins. There will be two different tasks: a hand dexterity test (Minnesota Manual Dexterity Test) and a computer-based target pointing task. For the hand dexterity test, you will be asked to place blocks into designated spaces as quickly as you can. For the computer-based target pointing task, you will be asked to use three different input devices (Trackball, Joystick, and Mouse) to point to items that will appear in various locations on a computer screen. You will be asked to complete six runs using each of the three input devices. Each run will take approximately 10 minutes to complete. You will have at least a two-minute rest period after each run.

The risks of the study are minimal. However, if you are not used to using computers, eye or wrist fatigue may result. If you are aware of any condition that might prove detrimental to your health, please refrain from participating in the study. If you have any questions about your rights as a research subject, you can contact the University of Oklahoma Office of Research Administration at (405) 325-4757.

Any personal information that you provide will remain strictly confidential. You will suffer no repercussions or penalty for refusing to participate. You may withdraw and/or discontinue participation in the study at any time without penalty. There will be no compensation for participation or for any injuries. If you have any questions about the research itself, please contact Byeong-cheol Hwang or Dr. Robert E. Schlegel at (405) 325-3721.

This is to certify that I, ______________________________, hereby understand the purpose of the research and the implications of being a research participant. I volunteer to participate in the research with an understanding that I am free to refuse to participate and to withdraw from the study at any time without prejudice to me.

______________________________ ______________
Participant's Signature Date

APPENDIX E

INFORMED ASSENT FORM AND PARENTAL INFORMED CONSENT FORM FOR HIGH SCHOOL STUDENTS

INFORMED ASSENT FORM

Signing this form constitutes your consent for participation in a research project conducted under the auspices of the School of Industrial Engineering, the University of Oklahoma, Norman, Oklahoma.

Project Title: Methodology for the Selection and Evaluation of Computer Input Devices for People with Functional Limitations.
Investigator: Byeong-cheol Hwang, Graduate Student, School of Industrial Engineering, University of Oklahoma.
Advisors: Dr. Robert E. Schlegel, Dr. Randa L. Shehab, School of Industrial Engineering, University of Oklahoma

This study will focus on the ability of various input devices to provide people with upper-limb motor impairments better access to computers. A methodology for specifying alternative assistive input devices as a function of type and degree of functional limitation is important for improving access to computer technology. The current research will develop a matrix for matching assistive technology input devices to the assessed level of functional limitation. Since there are few reliable input device assessment instruments for people with impairments, this research also hopes to develop and validate a methodology for assessing the level of impairment for people with upper-limb motor impairments. It is expected that the results of this work will enable a better evaluation of existing devices and will promote the development of creative solutions for computer access by people with motor impairments.

This study will require approximately two hours of your time. You will be provided with instructions and adequate practice time before the main work begins. There will be two different tasks: a hand dexterity test (Minnesota Manual Dexterity Test) and a computer-based target pointing task. For the hand dexterity test, you will be asked to place blocks into designated spaces as quickly as you can. For the computer-based target pointing task, you will be asked to use three different input devices (Trackball, Joystick, and Mouse) to point to items that will appear in various locations on a computer screen. You will be asked to complete six runs using each of the three input devices. Each run will take approximately 10 minutes to complete. You will have at least a two-minute rest period after each run. If you have any questions, please feel free to ask at any time.

This is to certify that I, ________________________________, hereby understand the purpose of the research and the implications of being a research participant. I volunteer to participate in the research with an understanding that I am free to refuse to participate and to withdraw from the study at any time without prejudice to me.

________________________________ ____________________
Participant's Signature Date

PARENTAL INFORMED CONSENT FORM

Signing this form constitutes your consent for your child's participation in a research project conducted under the auspices of the School of Industrial Engineering, the University of Oklahoma, Norman, Oklahoma.

Project Title: Methodology for the Selection and Evaluation of Computer Input Devices for People with Functional Limitations.
Investigator: Byeong-cheol Hwang, Graduate Student, School of Industrial Engineering, University of Oklahoma.
Advisors: Dr. Robert E. Schlegel, Dr. Randa L. Shehab, School of Industrial Engineering, University of Oklahoma

This study will focus on the ability of various input devices to provide people with upper-limb motor impairments better access to computers. A methodology for specifying alternative assistive input devices as a function of type and degree of functional limitation is important for improving access to computer technology. The current research will develop a matrix for matching assistive technology input devices to the assessed level of functional limitation. Since there are few reliable input device assessment instruments for people with impairments, this research also hopes to develop and validate a methodology for assessing the level of impairment for people with upper-limb motor impairments. It is expected that the results of this work will enable a better evaluation of existing devices and will promote the development of creative solutions for computer access by people with motor impairments.

This study will require approximately two hours of your child's time. Your child will be provided with instructions and adequate practice time before the main work begins. There will be two different tasks: a hand dexterity test (Minnesota Manual Dexterity Test) and a computer-based target pointing task. For the hand dexterity test, they will be asked to place blocks into designated spaces as quickly as they can. For the computer-based target pointing task, they will be asked to use three different input devices (Trackball, Joystick, and Mouse) to point to items that will appear in various locations on a computer screen. They will be asked to complete six runs using each of the three input devices. Each run will take approximately 10 minutes to complete. They will have at least a two-minute rest period after each run.

The risks of the study are minimal. However, if they are not used to using computers, eye or wrist fatigue may result. If they are aware of any condition that might prove detrimental to their health, please refrain from participating in the study. If they have any questions about their rights as a research subject, they can contact the University of Oklahoma Office of Research Administration at (405) 325-4757.

Any personal information that they provide will remain strictly confidential. They will suffer no repercussions or penalty for refusing to participate. They may withdraw and/or discontinue participation in the study at any time without penalty. There will be no compensation for participation or for any injuries. If they have any questions about the research itself, please contact Byeong-cheol Hwang or Dr. Robert E. Schlegel at (405) 325-3721.

This is to certify that I, ______________________________________, hereby understand the purpose of the research and the implications of being a research participant. My child volunteers to participate in the research with an understanding that he/she is free to refuse to participate and to withdraw from the study at any time without prejudice to him/her.

______________________________________ ____________________
Parent's Signature Date

APPENDIX F

TASK INSTRUCTIONS

HAND DEXTERITY TEST INSTRUCTIONS
(Minnesota Manual Dexterity Test)

This test is designed to measure the eye-hand coordination necessary in many computer input tasks using various input devices. This test uses a board that has spaces to hold 58 round blocks.

The object of this test is to see how quickly you can place the blocks into the holes. You will be provided one run to practice performing the test. Do not try for speed during this practice run since it will not count in your score. Begin at your right. Put the bottom right block into the top hole at the right edge. Then place the block second from the bottom on the right into the second hole from the top at the right (The experimenter will demonstrate). Continue down the line until all four rows have been filled. Repeat this procedure for the rest of the columns, working from right to left, until you finish putting in the rest of the blocks. Use only one hand, either right or left. Rest the free hand on the board if you wish.

After you have finished the practice run, you will do four more runs. Your time will be recorded for each run separately. When you finish a run, stop and wait for instruction to start the next run. The experimenter will say "**READY**" and "**GO**". At the word "**GO**", begin and work as fast as you can. You will be allowed a short break between runs in order to prevent any tendency to become tense. Relax between runs, but in doing the test, speed is important.

Please feel free to ask the experimenter any questions at any time.

Thank you very much for your participation!

COMPUTER-BASED TARGET POINTING TASK INSTRUCTIONS

You will be asked to use three different input devices (Trackball, Joystick, and Mouse) to point to target items that will appear in various locations on a computer screen. When a target item appears, you will use the input device to move the cursor (+ symbol) as quickly and accurately as possible until it touches the target item. You must leave the cursor within the boundaries of the target until it disappears. A video camera will be used to record your movements.

The initial screen will contain two symbols: a start point and a target. The start point is a purple square, and the target is a white square. When you press the select key, the purple square will be replaced with the cursor (+ symbol). As quickly as possible, move the cursor until the center of the cursor is positioned within the boundary of the target. Leave the cursor inside of the target until the target disappears. The cursor is correctly inside the target if the target surrounds more than the half of the + symbol. If the cursor is not correctly positioned, the target will not disappear. If this occurs, move the cursor inside the target as quickly as you can. Once you correctly select a target, the process repeats.

You will be provided with complete instructions and time to practice before the main experiment begins. Take enough time to become comfortable with the equipment and procedures before you begin. Each run will contain 108 targets. Proceed through the targets as quickly and accurately as possible without resting between selections. At the end of each testing run, you will be given an opportunity to rest. Each run will take approximately ten minutes to complete. You will be asked to complete one run for the practice and two runs for the main test for a CD gain using each of the three input devices.

After you have completed all trials, you will complete a survey that will ask you questions about your preferences for the input devices and their ease of use.

Please feel free to ask the experimenter any questions at any time.

Thank you very much for your participation!

APPENDIX G

PARTICIPANT SURVEY FORM

PARTICIPANT SURVEY FORM

(to be completed after data collection)

This study is focused on the ability of various input devices to provide people with upper-limb motor impairments better access to computers. It is believed that the results of this work will enable a better evaluation of existing devices and will promote the development of creative solutions for computer access by people with motor impairments. Please be honest and answer completely. Suggestions for improving computer access to upper-limb motor impaired people are welcome.

1. Name: ________________________________

2. Age: __________

3. Gender: Male ( ) Female ( )

4. Primary Hand Usage: Left-handed ( ) Right-handed ( )

5. Do you have any functional disabilities that affect your use of computer input devices?
   Yes ( ) No ( )

   If yes, please describe your disability and how long you have had it.

   Type of disability: ________________________________

   Time since onset: ____________________

6. Have you ever used the following computer input devices? If yes, please indicate the amount of experience using each input device.

Input Device	Feature	No	Yes	If yes, how long?
Trackball				
Joystick				
Mouse				

7. Please mark the box under the rating that best describes the usability of the input devices you used in this experiment.

Input Device	Very Easy	Easy	Slightly Difficult	Difficult	Very Difficult
Trackball					
Joystick					
Mouse					

8. Please rank the devices in order of your preference from most preferred to least preferred.

Most Preferred 1. _____ a. Trackball

2. _____ b. Joystick

Least Preferred 3. _____ c. Mouse

9. When you used each computer input device, what difficulties did you experience during use?

____

____

____

____

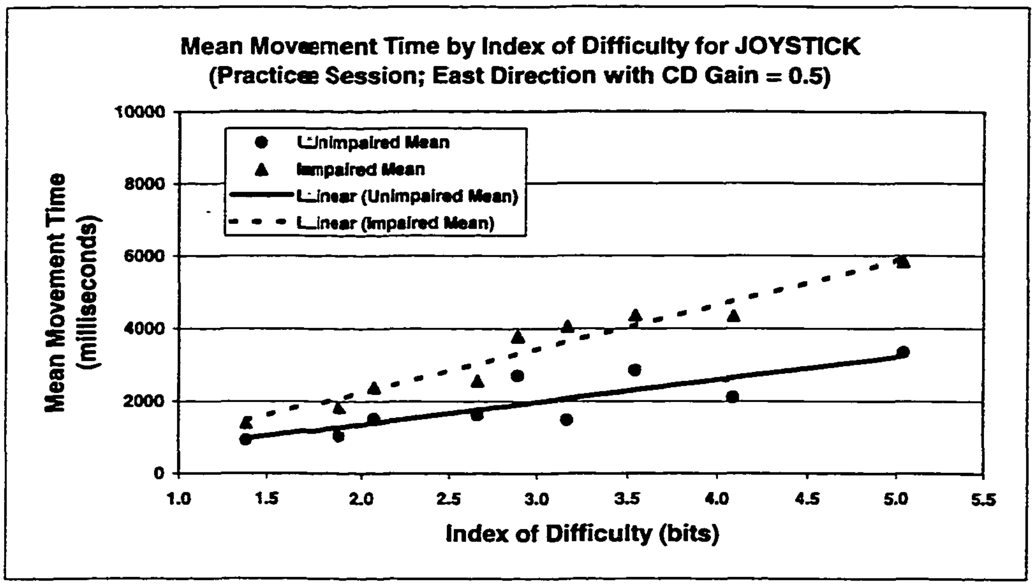
____

____

Thank you very much for your participation!

APPENDIX H

GRAPHS OF MEAN MOVEMENT TIME BY INDEX OF DIFFICULTY



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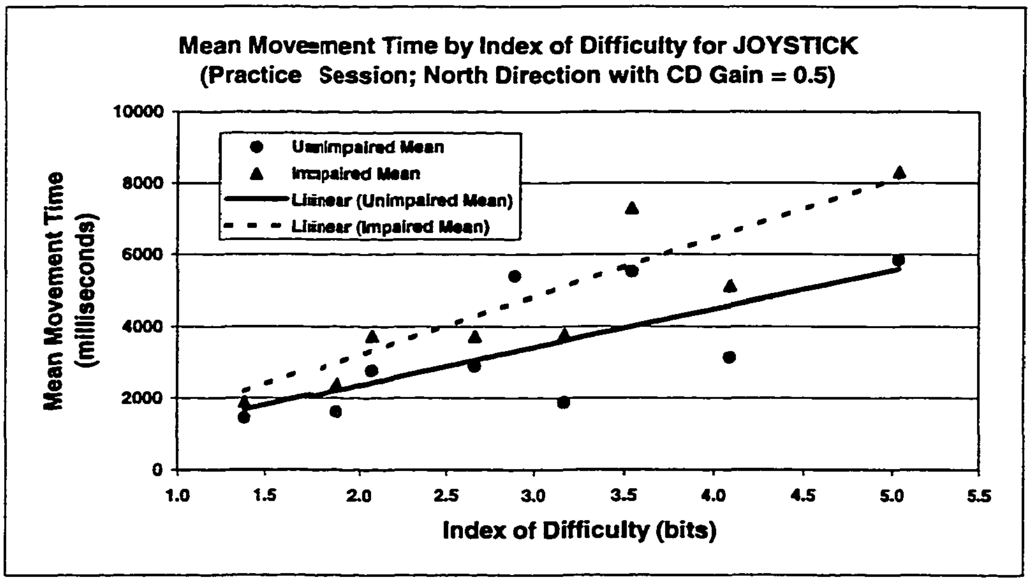
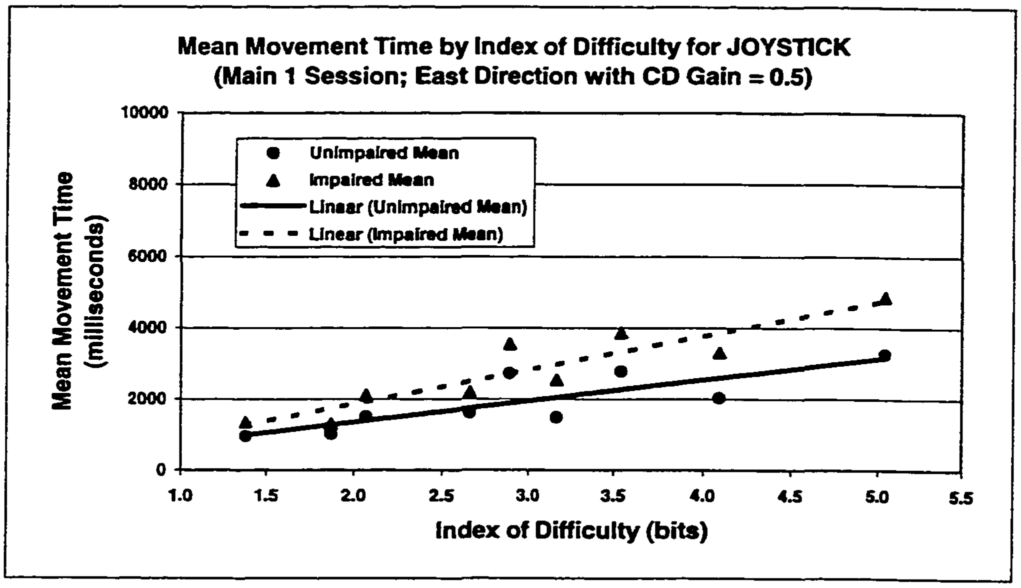


(b) North Direction

Mean Movement Time by Index of Difficulty for the Joystick during Practice with the 0.5 CD Gain.



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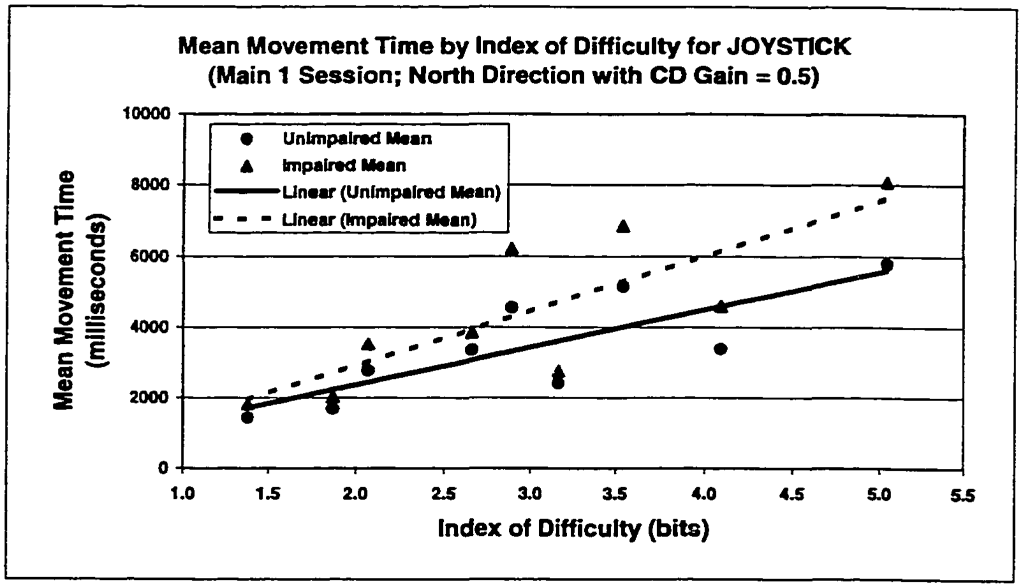
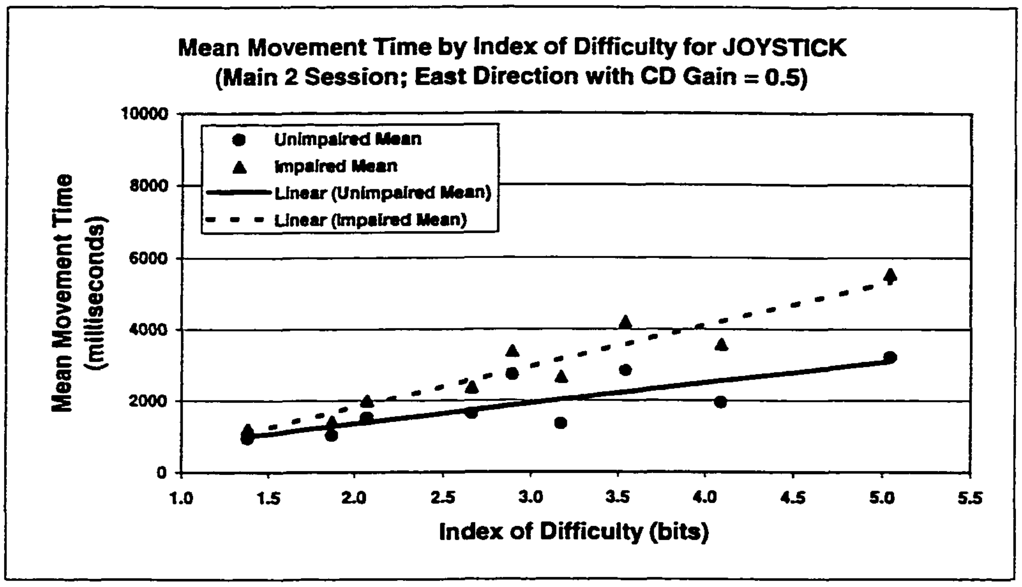


(b) North Direction

Mean Movement Time by Index of Difficulty for the Joystick during Main 1 with the 0.5 CD Gain.



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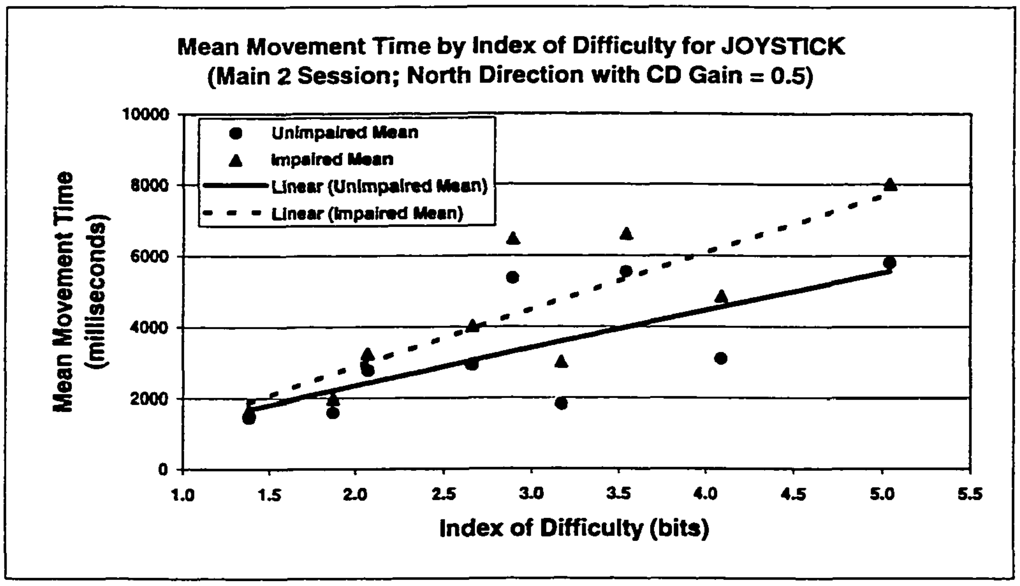

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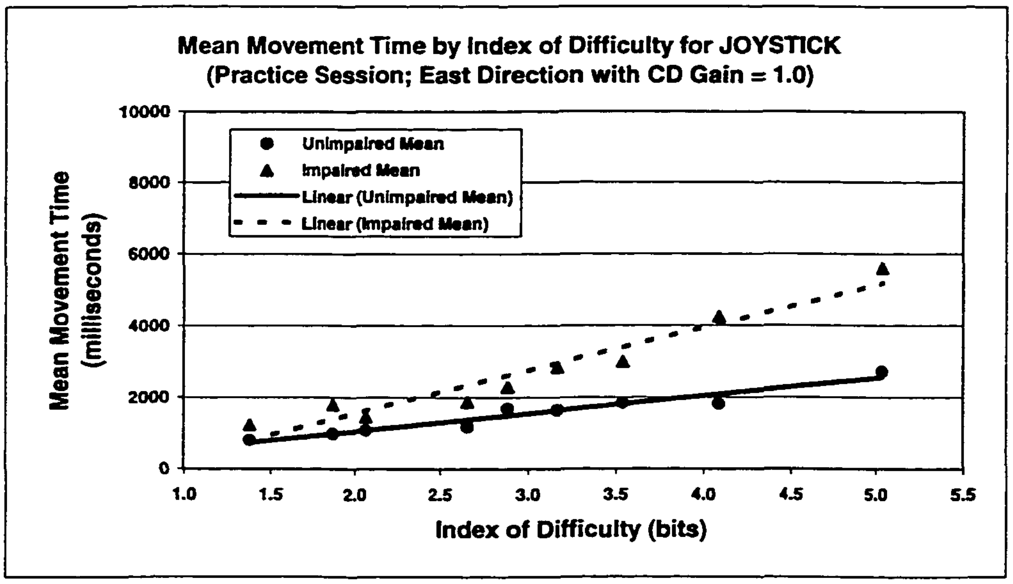
Mean Movement Time by Index of Difficulty for the Joystick during Main 2 with the 0.5 CD Gain.



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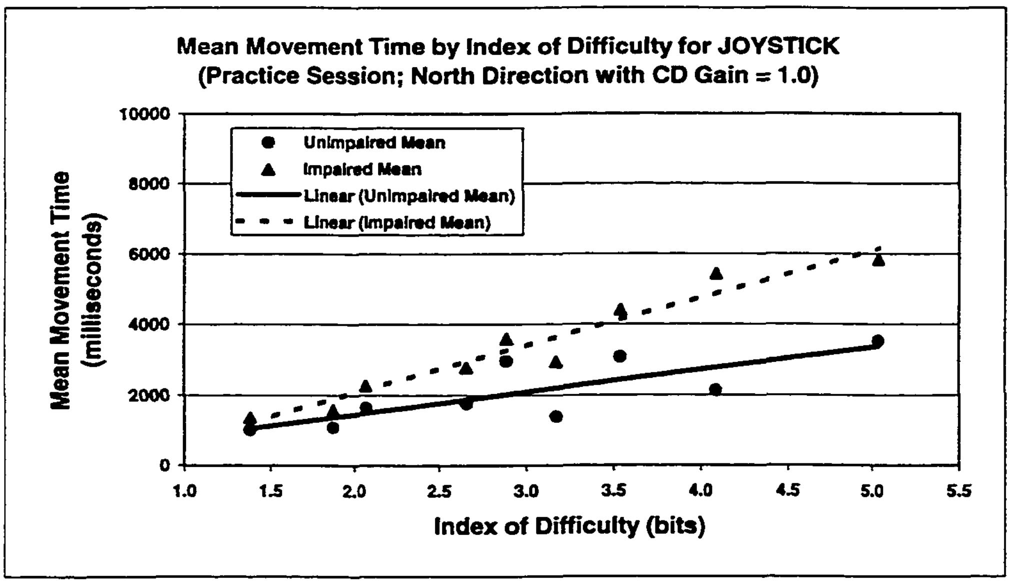
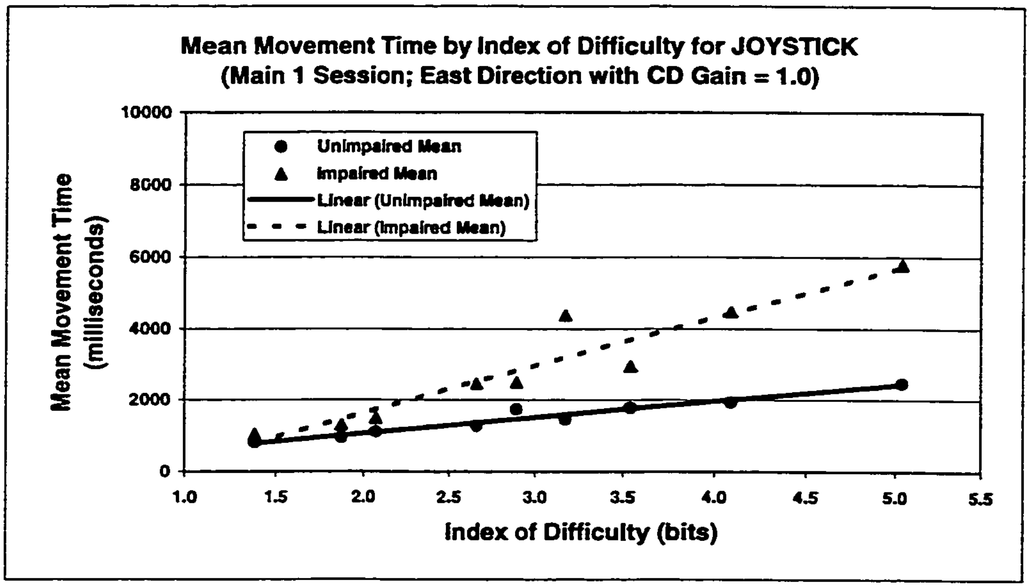


(b) North Direction

Mean Movement Time by Index of Difficulty for the Joystick during Practice with the 1.0 CD Gain.



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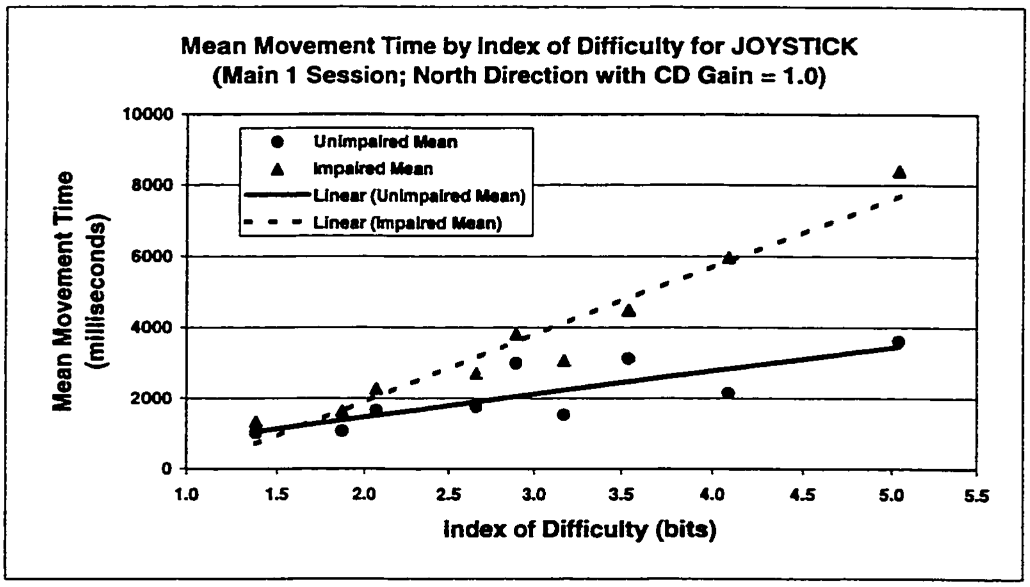

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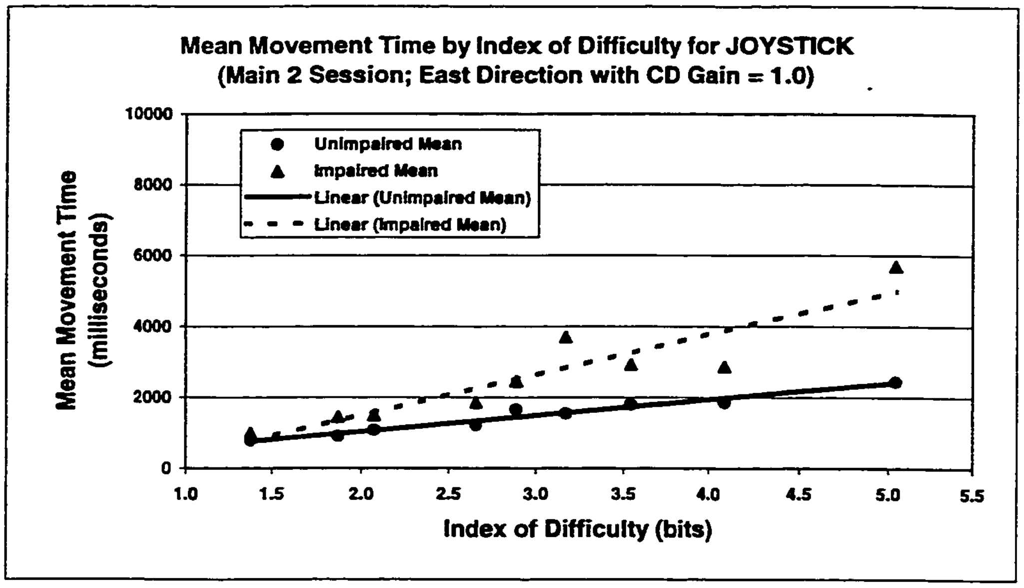
Mean Movement Time by Index of Difficulty for the Joystick during Main 1 with the 1.0 CD Gain.



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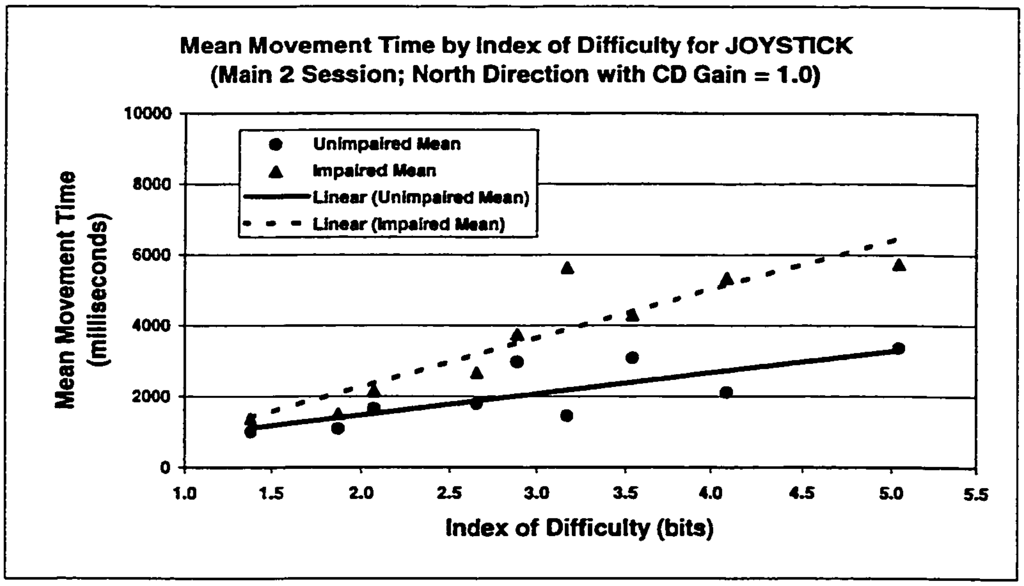

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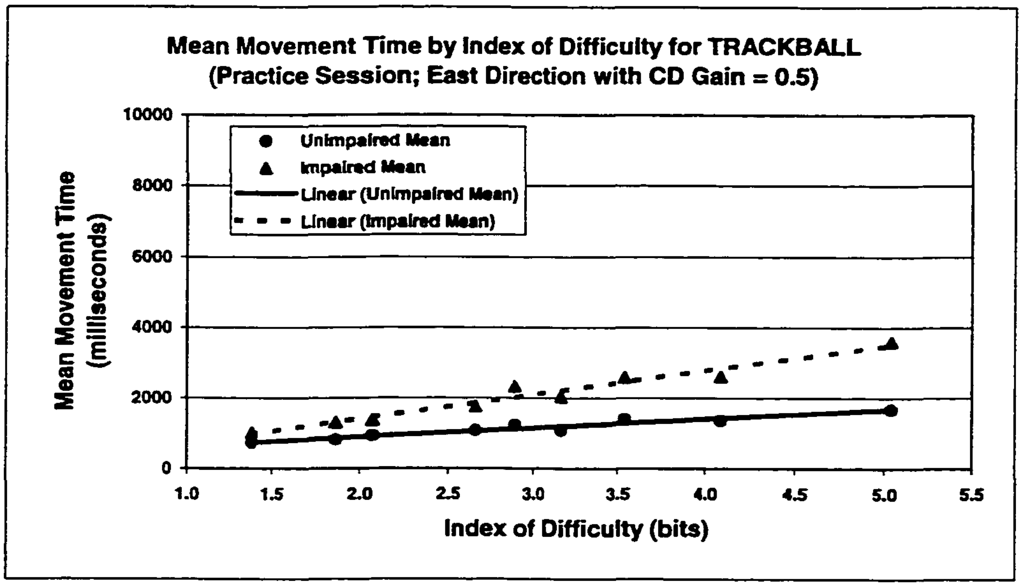
Mean Movement Time by Index of Difficulty for the Joystick during Main 2 with the 1.0 CD Gain.



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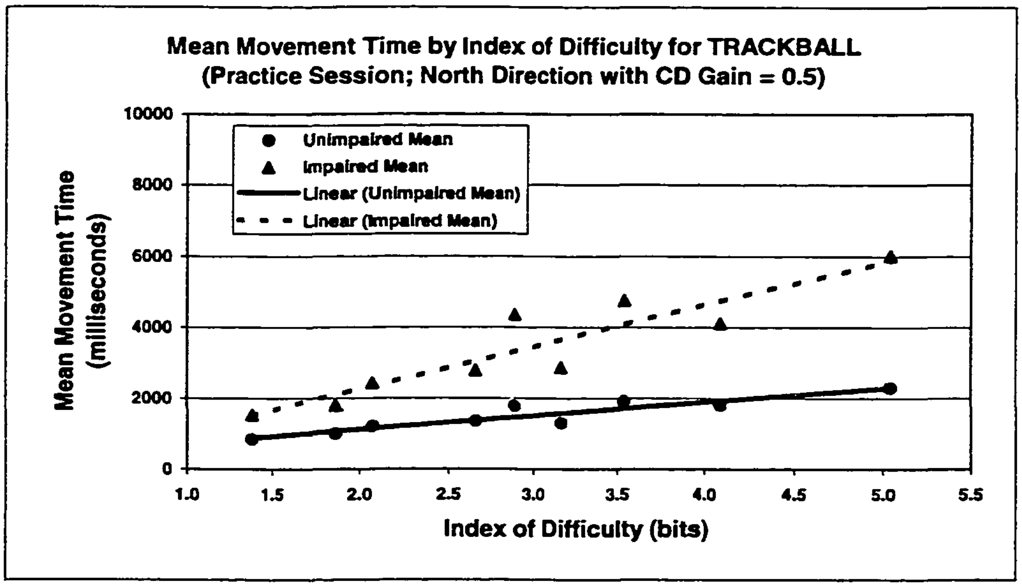
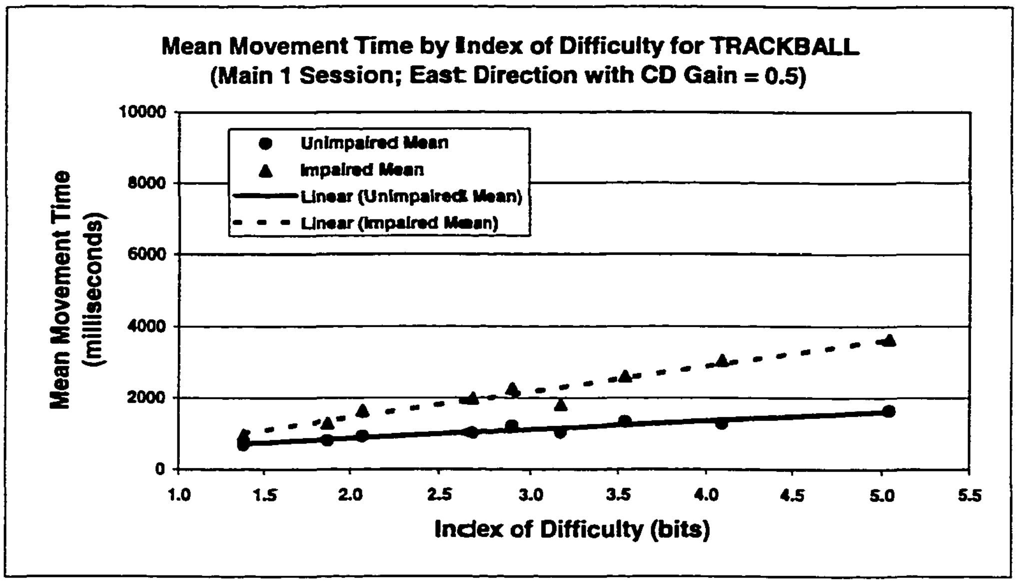


(b) North Direction

Mean Movement Time by Index of Difficulty for the Trackball during Practice with the 0.5 CD Gain.



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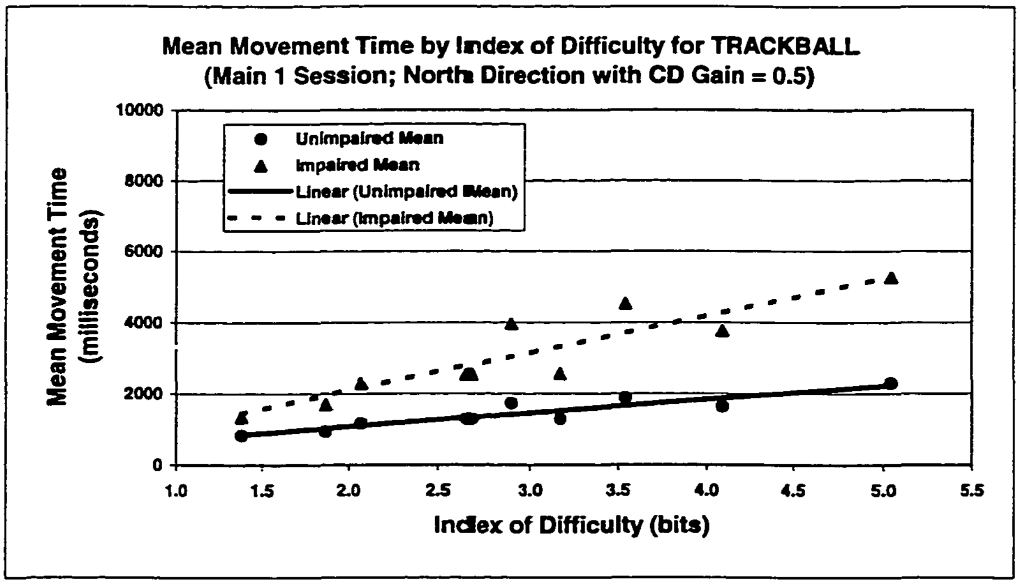

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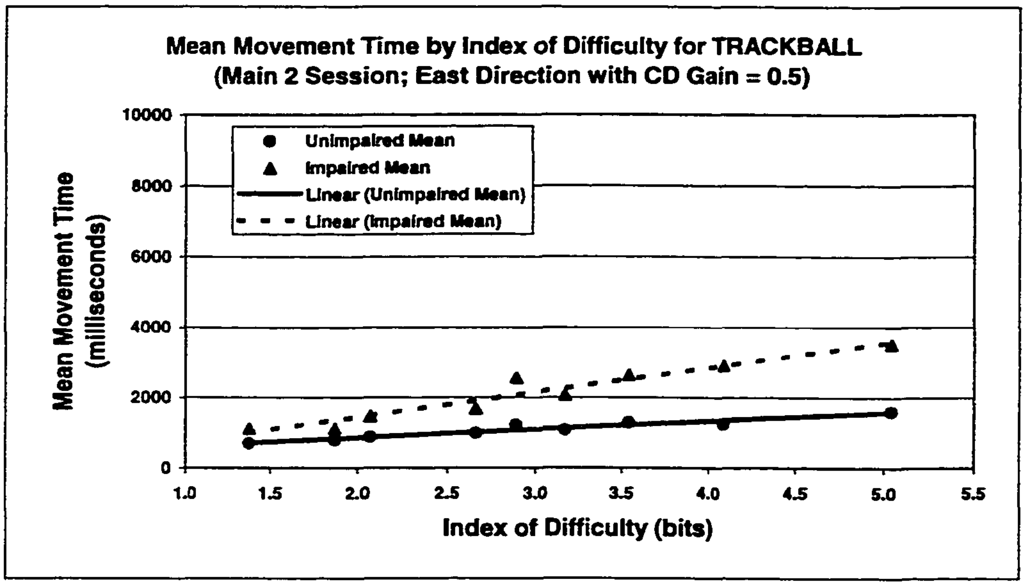
Mean Movement Time by Index of Difficulty for the Trackball during Main 1 with the 0.5 CD Gain.



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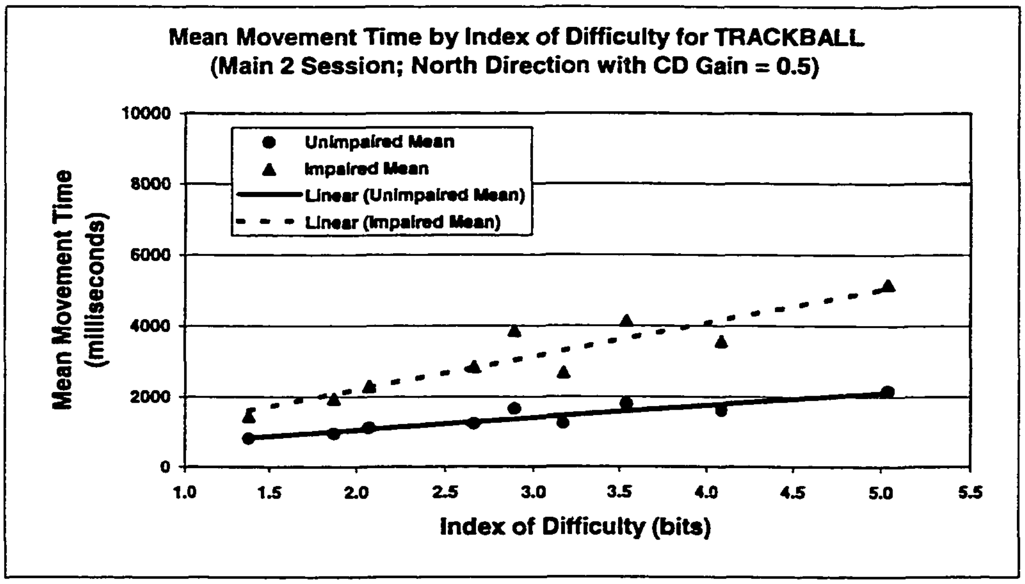

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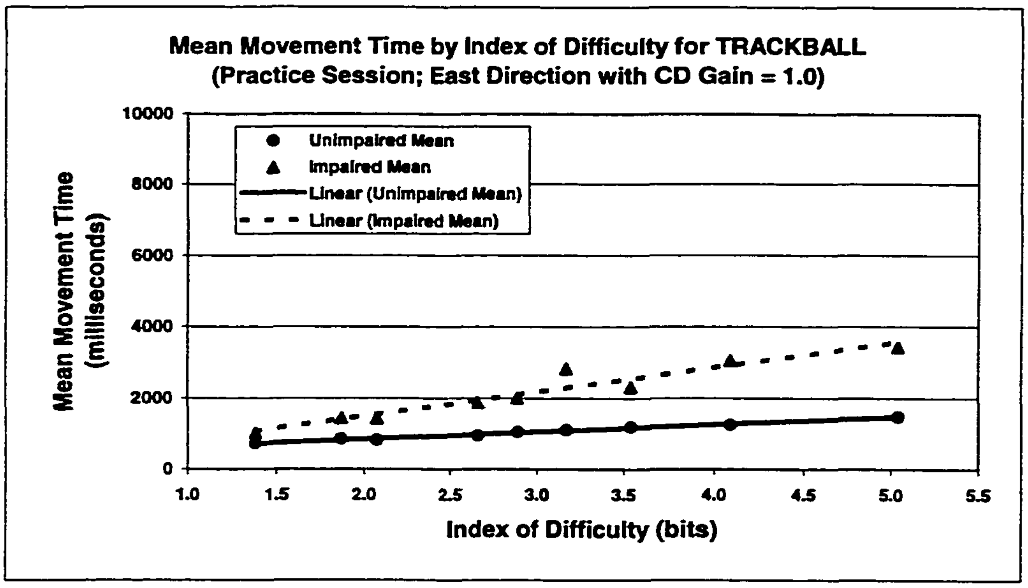
Mean Movement Time by Index of Difficulty for the Trackball during Main 2 with the 0.5 CD Gain.



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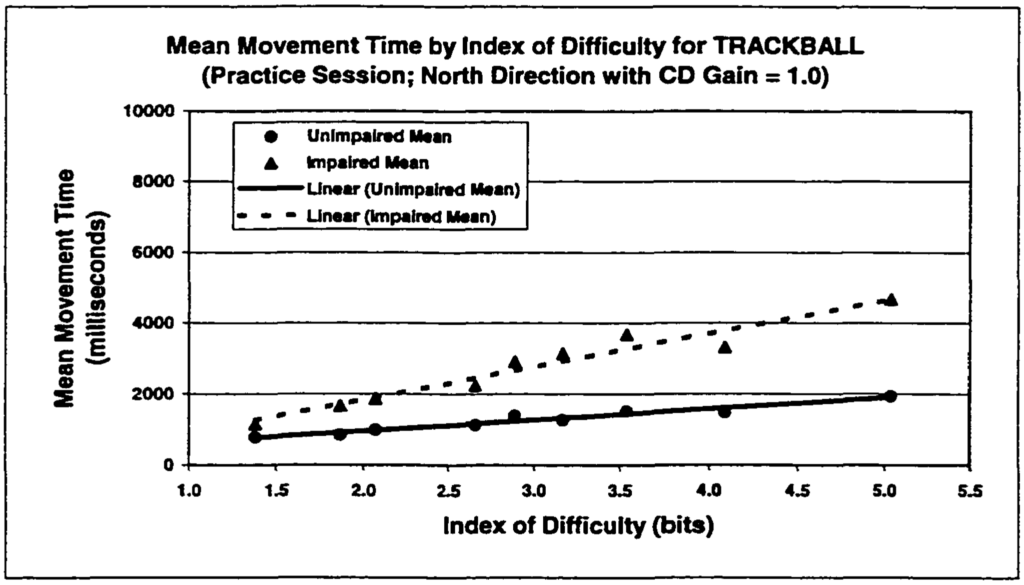
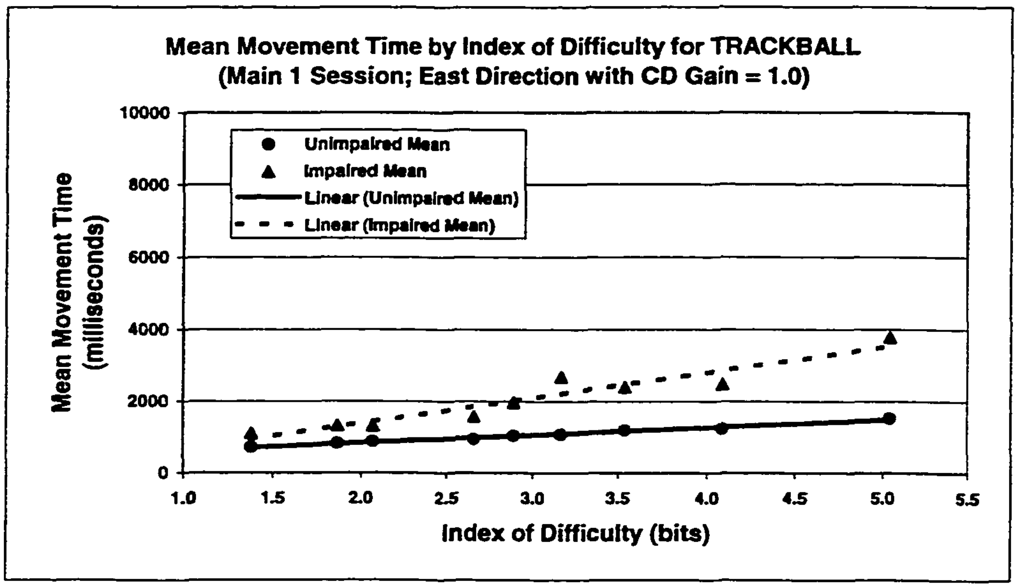


(b) North Direction

Mean Movement Time by Index of Difficulty for the Trackball during Practice with the 1.0 CD Gain.



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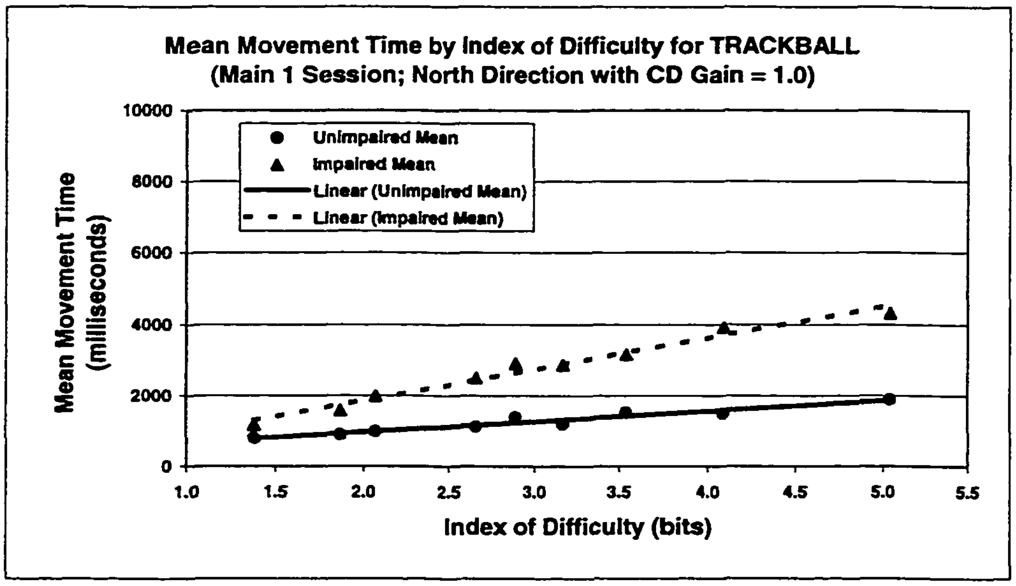

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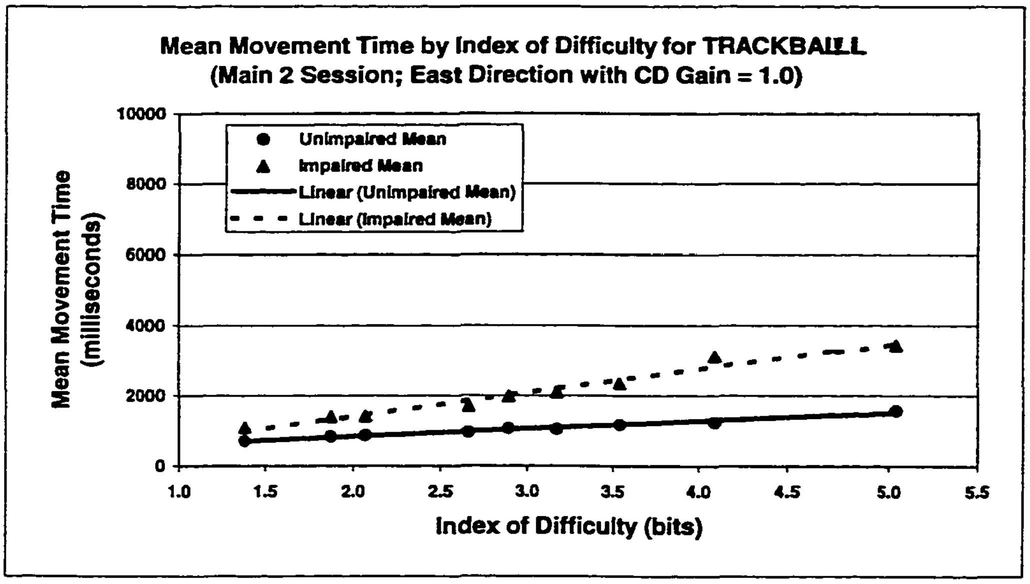
Mean Movement Time by Index of Difficulty for the Trackball during Main 1 with the 1.0 CD Gain.



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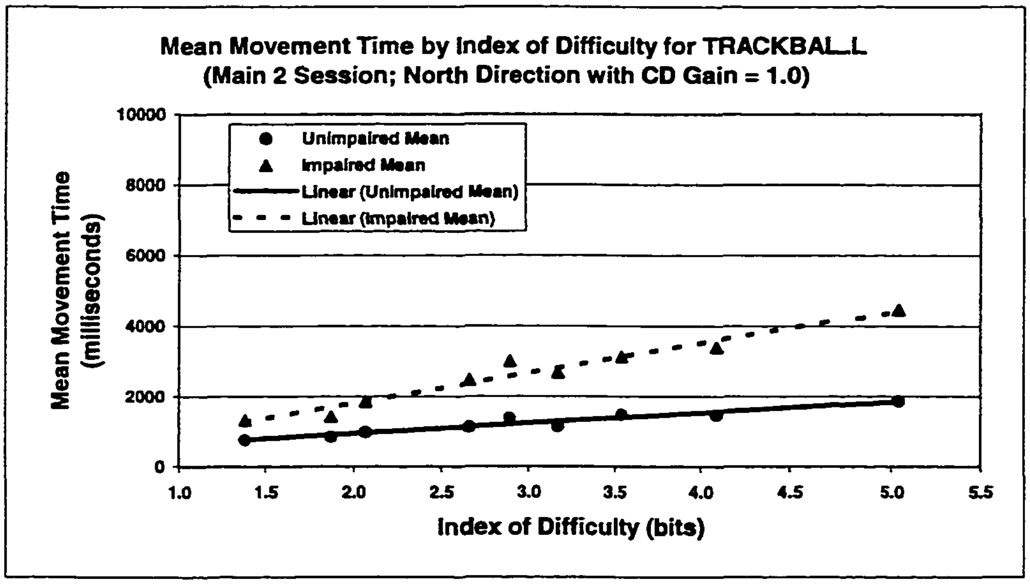

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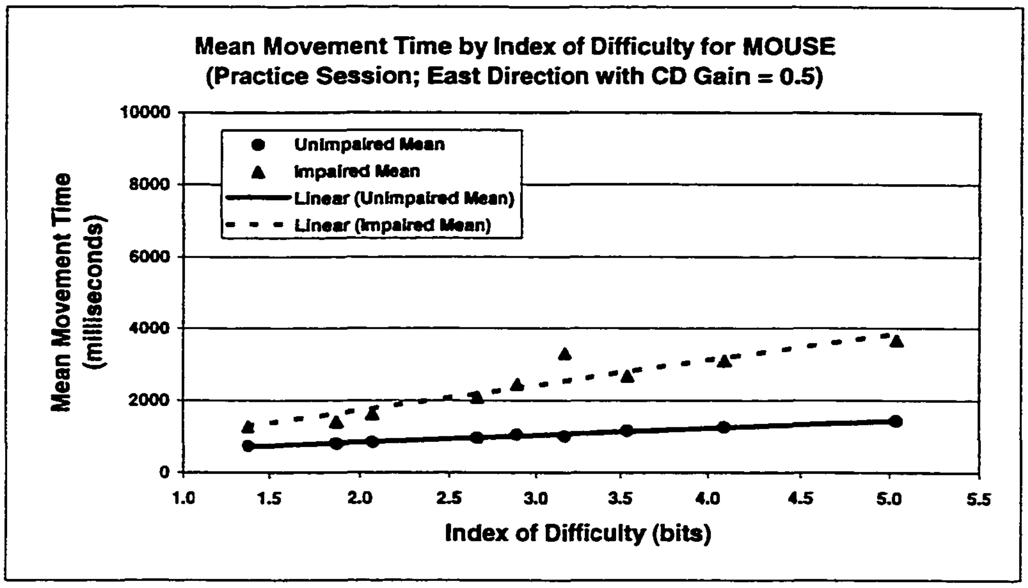
Mean Movement Time by Index of Difficulty for the Trackball during Main 2 with the 1.0 CD Gain.



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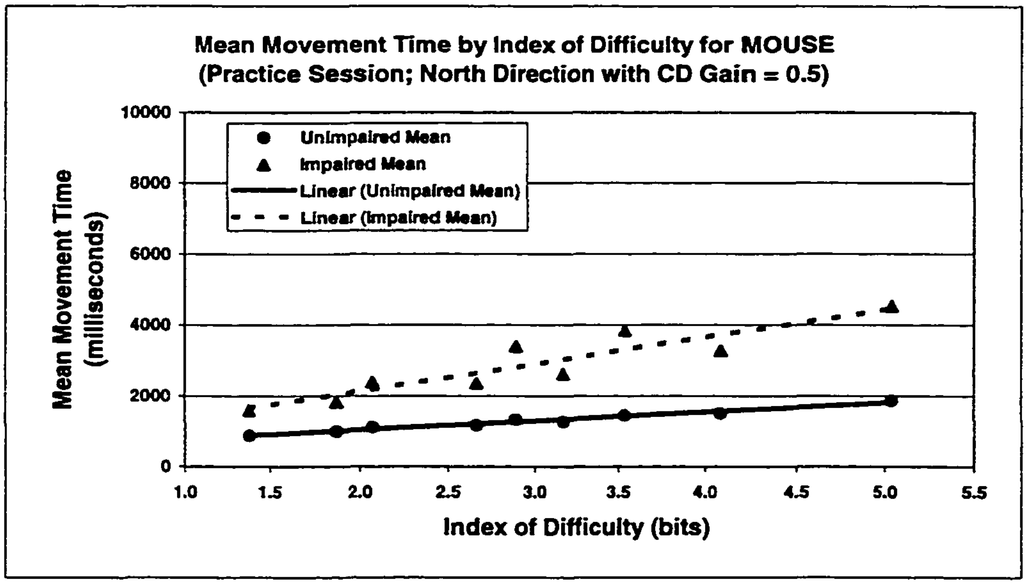
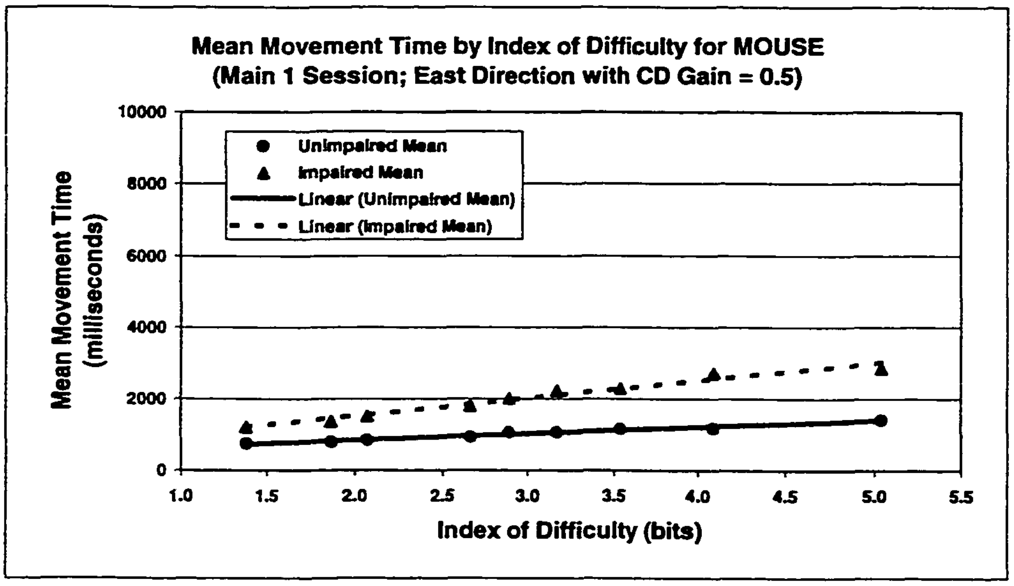


(b) North Direction

Mean Movement Time by Index of Difficulty for the Mouse during Practice with the 0.5 CD Gain.



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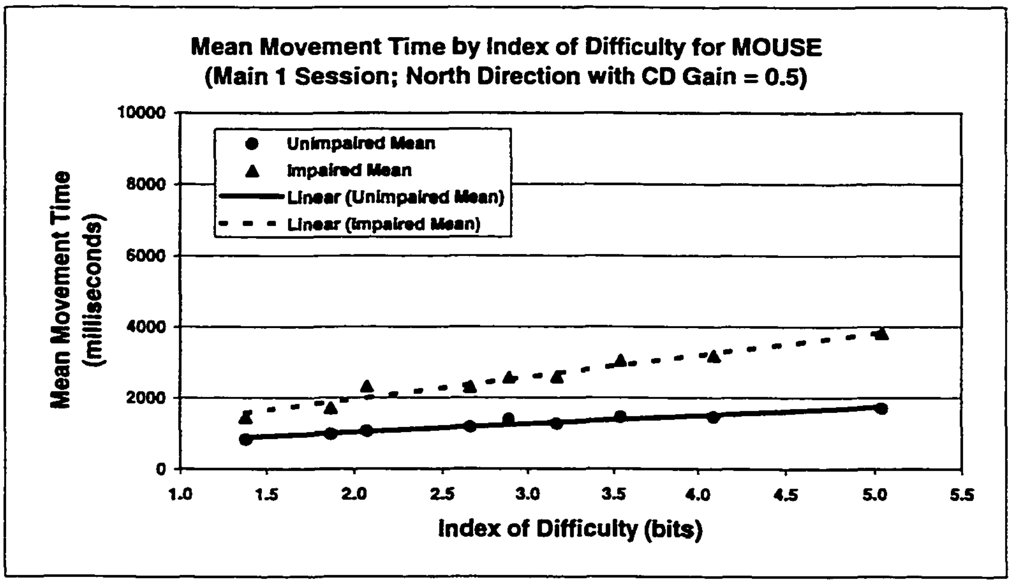
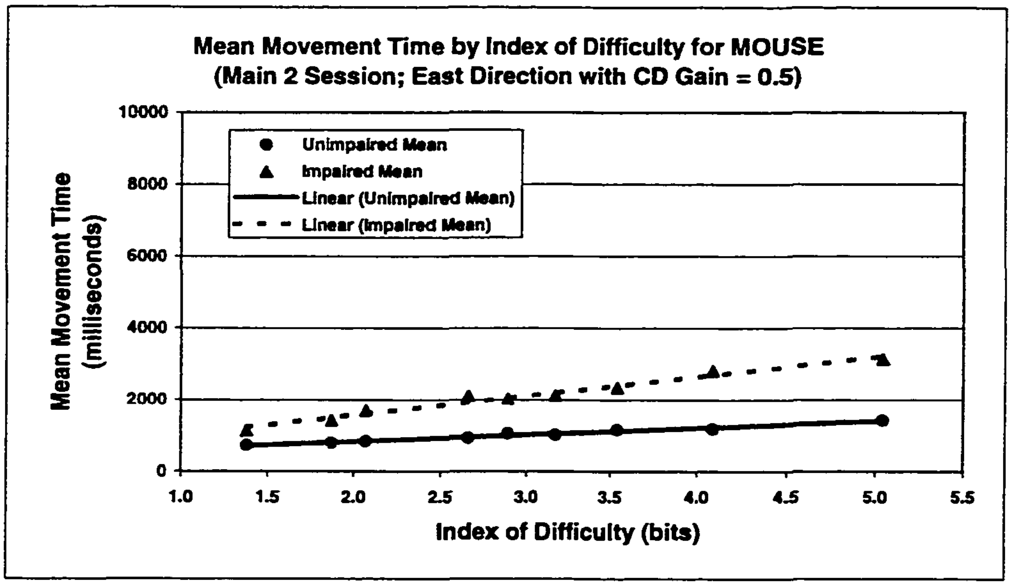
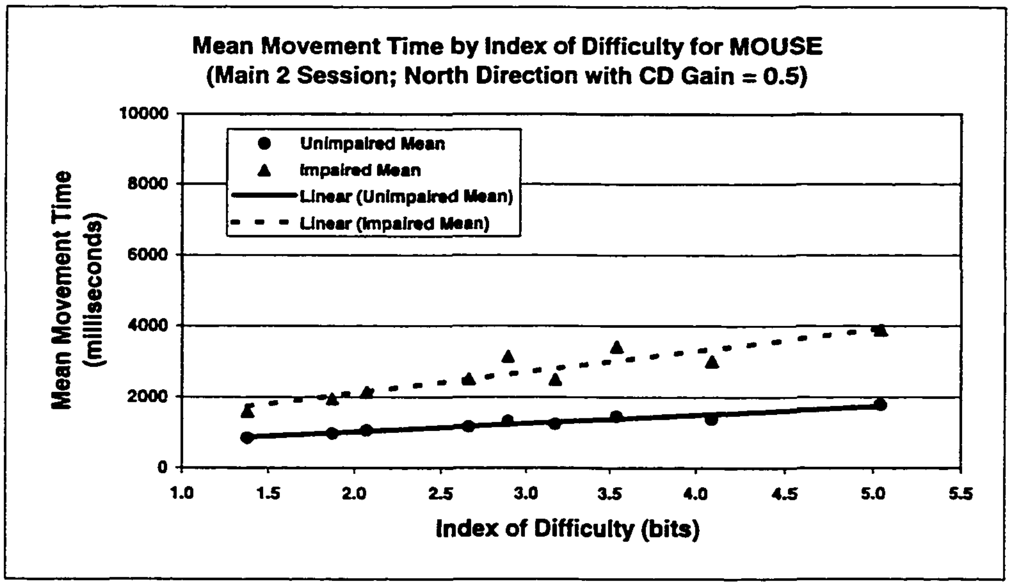


(b) North Direction

Mean Movement Time by Index of Difficulty for the Mouse during Main 1 with the 0.5 CD Gain.

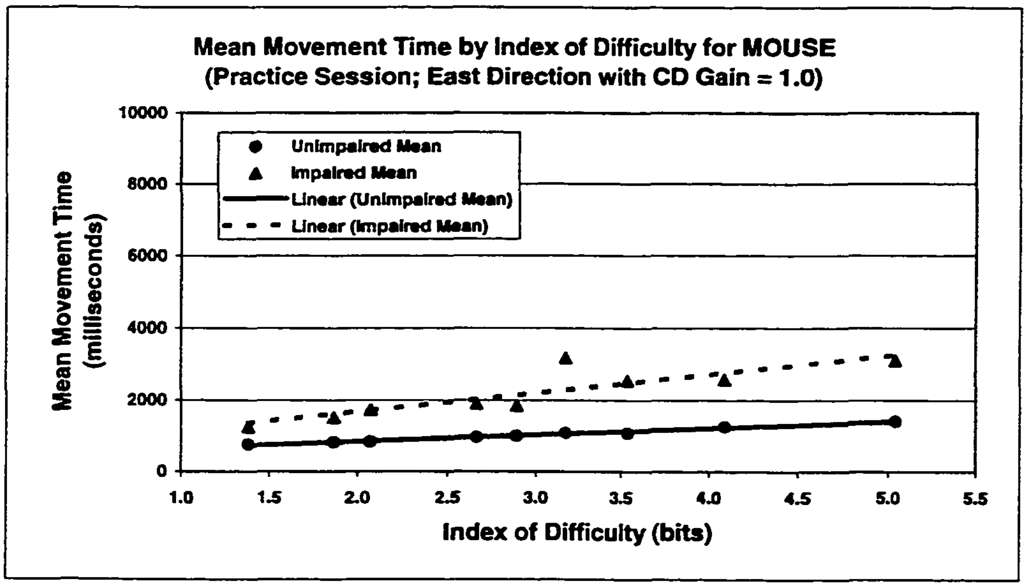


(a) East Direction

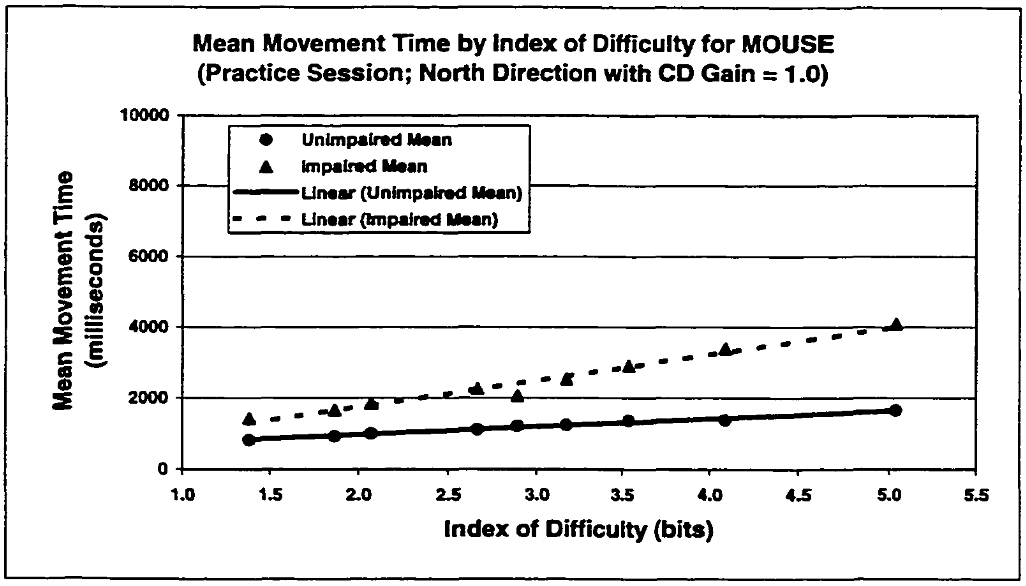


(b) North Direction

Mean Movement Time by Index of Difficulty for the Mouse during Main 2 with the 0.5 CD Gain.

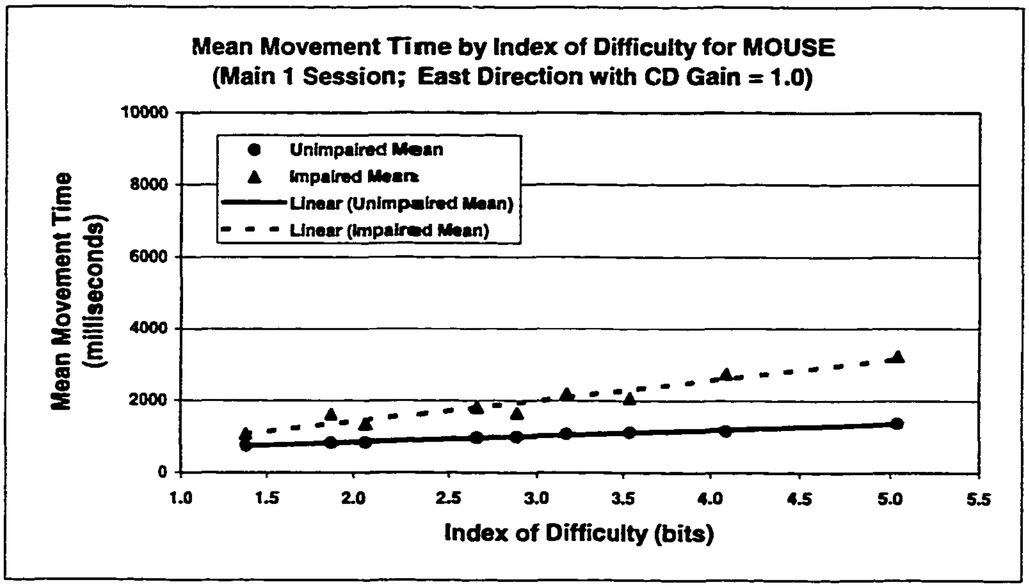


(a) East Direction

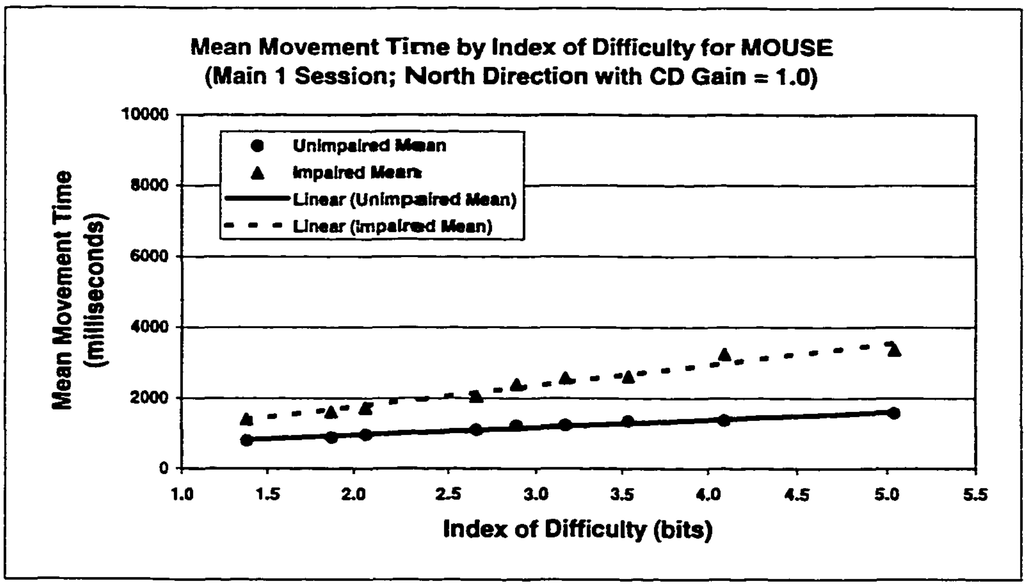


(b) North Direction

Mean Movement Time by Index of Difficulty for the Mouse during Practice with the 1.0 CD Gain.

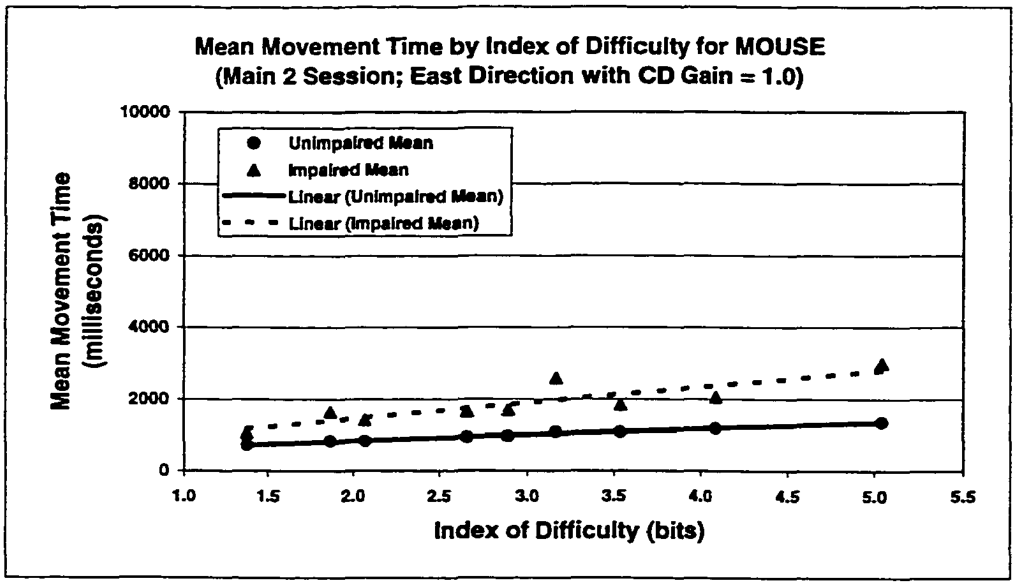


(a) East Direction

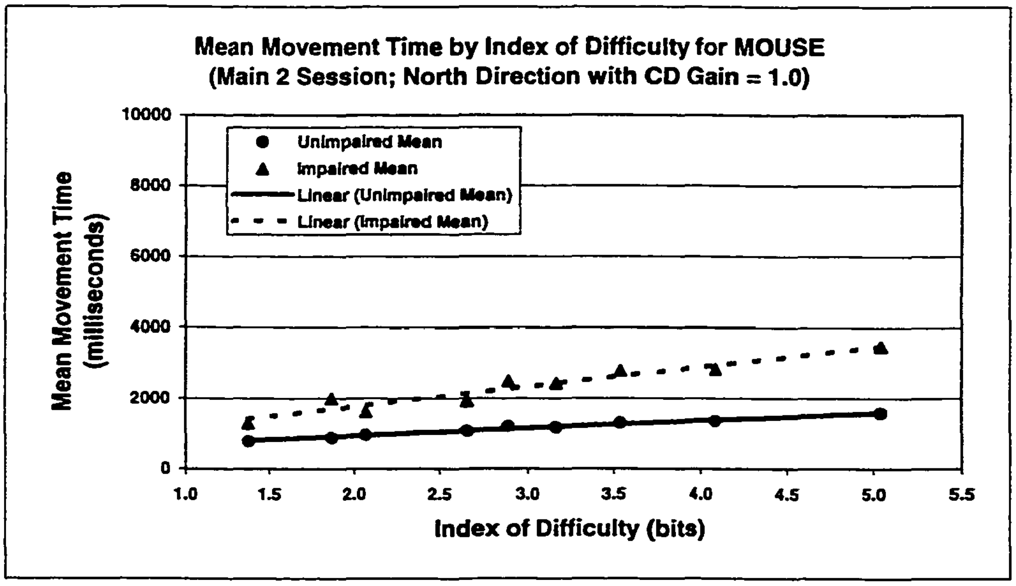


(b) North Direction

Mean Movement Time by Index of Difficulty for the Mouse during Main 1 with the 1.0 CD Gain.



(a) East Direction



(b) North Direction

Mean Movement Time by Index of Difficulty for the Mouse during Main 2 with the 1.0 CD Gain.

APPENDIX I

REGRESSION SUMMARY TABLES FOR MOVEMENT TIME AND INDEX OF PERFORMANCE

1.0 Joystick with 0.5 CD Gain

Direction	Session	Statistics	Unimpaired Group					Impaired Group				
			Slope	Intercept	R^2	IP	MidMT	Slope	Intercept	R^2	IP	MidMT
East	Practice	Mean	618.95	120.02	.6628	1.67	2106.83	1215.56	-205.74	.7004	1.12	3696.21
		Range	401.47	813.55	.3402	0.99	803.06	3696.09	7282.80	.4920	1.49	6918.40
		Standard Deviation	118.04	227.38	.1003	0.31	187.73	1056.21	1791.75	.1638	0.45	2111.54
	Main 1	Mean	593.01	171.12	.6464	1.73	2074.69	990.93	44.67	.6707	1.11	3225.55
		Range	460.81	717.36	.3225	1.05	791.17	813.78	2475.46	.4185	0.93	3994.19
		Standard Deviation	111.29	190.32	.0992	0.27	181.32	320.45	696.85	.1473	0.37	1268.02
	Main 2	Mean	576.30	196.27	.6114	1.77	2046.20	1188.42	-539.65	.7174	1.11	3275.17
		Range	374.25	670.99	.3701	0.96	552.58	3243.48	4641.96	.3505	1.39	6057.89
		Standard Deviation	87.50	153.28	.0864	0.23	142.03	931.75	1293.24	.1151	0.44	1722.73
North	Practice	Mean	1068.54	216.20	.4915	0.94	3646.20	1631.66	-64.21	.6074	0.69	5173.42
		Range	250.07	658.62	.1340	0.21	253.50	3040.01	3870.80	.4585	0.77	6535.20
		Standard Deviation	56.63	129.50	.0376	0.05	77.01	813.12	960.36	.1447	0.18	1808.43
	Main 1	Mean	1089.10	165.72	.5019	0.92	3661.74	1538.70	-78.38	.5769	0.71	4860.84
		Range	300.50	487.58	.2488	0.23	505.67	2117.90	4350.50	.5303	0.61	3792.31
		Standard Deviation	80.21	133.92	.0572	0.06	130.59	599.50	1047.69	.1505	0.17	1129.35
	Main 2	Mean	1056.00	242.63	.4814	0.95	3632.39	1596.16	-295.60	.5859	0.69	4828.09
		Range	184.09	599.82	.0822	0.16	419.83	2345.00	2849.27	.3181	0.60	4763.56
		Standard Deviation	47.33	131.17	.0221	0.04	90.42	657.79	804.67	.0946	0.17	1327.98
Southwest	Practice	Mean	1108.08	-72.17	.6429	0.92	3484.75					
		Range	587.91	1185.36	.3283	0.44	914.29					
		Standard Deviation	166.43	339.09	.0996	0.13	260.01					
	Main 1	Mean	1070.26	-65.50	.5996	0.95	3370.04					
		Range	686.65	1143.62	.3756	0.49	1150.61					
		Standard Deviation	157.23	261.82	.0915	0.12	259.24					
	Main 2	Mean	1038.32	-9.32	.5780	0.98	3323.69					
		Range	532.47	944.57	.3397	0.42	824.30					
		Standard Deviation	140.43	231.70	.0930	0.11	229.29					

2.0 Joystick with 1.0 CD Gain

Direction	Session	Statistics	Unimpaired Group					Impaired Group				
			Slope	Intercept	R^2	IP	MidMT	Slope	Intercept	R^2	IP	MidMT
East	Practice	Mean	511.14	22.47	.8010	2.19	1651.68	1180.36	-767.33	.7341	1.11	3021.63
		Range	1107.62	2141.18	.3240	2.94	1221.80	2287.66	2660.88	.4626	2.30	4932.86
		Standard Deviation	223.61	443.93	.0818	0.66	248.23	646.43	885.66	.1428	0.64	1425.77
	Main 1	Mean	446.50	165.70	.7805	2.51	1598.95	1214.30	-756.85	.7654	1.28	3141.06
		Range	726.51	1265.50	.5135	3.06	1139.86	3917.52	6052.80	.4440	2.44	7389.15
		Standard Deviation	170.16	316.52	.1460	0.82	256.16	1114.41	1619.79	.1317	0.72	2036.13
	Main 2	Mean	452.18	138.37	.8257	2.44	1589.87	1073.06	-570.34	.7005	1.24	2874.17
		Range	894.35	1907.70	.3204	3.00	1085.31	2063.15	2510.34	.4130	2.47	4449.03
		Standard Deviation	183.14	369.45	.0927	0.68	244.21	593.63	829.44	.1432	0.75	1283.93
North	Practice	Mean	635.53	183.81	.6007	1.61	2223.86	1339.44	-563.24	.6790	0.95	3736.37
		Range	347.44	781.67	.4143	0.79	470.46	3012.92	2970.41	.5102	1.25	6932.14
		Standard Deviation	104.55	218.13	.1107	0.25	147.54	855.50	924.61	.1717	0.43	1975.38
	Main 1	Mean	672.16	121.11	.6011	1.58	2265.40	1842.57	-1754.42	.7273	0.98	4160.24
		Range	962.50	1555.27	.4186	1.27	1252.90	9372.89	18536.28	.4742	1.40	12149.02
		Standard Deviation	214.31	374.57	.0997	0.32	277.06	2735.97	5352.16	.1478	0.43	3459.49
	Main 2	Mean	598.50	280.44	.5850	1.70	2201.63	1356.83	-433.48	.6770	1.02	3921.95
		Range	482.06	875.68	.3890	0.97	671.73	4355.79	2963.02	.6979	1.47	11231.27
		Standard Deviation	99.32	183.72	.0949	0.21	148.55	1229.47	904.33	.2129	0.42	3193.74
Southwest	Practice	Mean	841.03	-260.86	.7930	1.32	2438.84					
		Range	1293.15	1913.37	.2720	1.31	2256.54					
		Standard Deviation	321.10	517.61	.0885	0.38	558.76					
	Main 1	Mean	757.22	-108.89	.7451	1.45	2321.77					
		Range	954.00	1639.85	.4408	1.47	1680.09					
		Standard Deviation	260.79	450.91	.1244	0.43	430.91					
	Main 2	Mean	761.92	-115.38	.7717	1.46	2330.38					
		Range	954.47	1664.92	.3234	1.34	1769.72					
		Standard Deviation	290.17	489.11	.0854	0.40	492.21					

3.0 Trackball with 0.5 CD Gain

Direction	Session	Statistics	Unimpaired Group					Impaired Group				
			Slope	Intercept	R^2	IP	MidMT	Slope	Intercept	R^2	IP	MidMT
East	Practice	Mean	256.95	379.50	.8152	4.05	1204.31	675.19	105.38	.7643	1.95	2272.76
		Range	209.04	322.14	.3005	3.59	418.94	1026.09	1148.85	.4873	3.67	2209.58
		Standard Deviation	50.99	94.60	.0774	0.84	112.63	340.10	424.39	.1267	1.20	745.26
	Main 1	Mean	245.69	375.57	.7813	4.26	1164.24	718.22	8.10	.7776	1.95	2313.59
		Range	193.99	587.87	.3680	3.87	391.34	1032.64	1261.68	.4771	3.71	2850.26
		Standard Deviation	50.98	133.36	.0929	0.97	102.44	377.12	433.78	.1359	1.26	901.50
	Main 2	Mean	236.59	388.95	.7931	4.57	1148.41	704.26	33.11	.7120	1.83	2293.79
		Range	227.47	691.39	.4094	4.69	358.40	1132.16	1257.27	.5966	3.07	2564.23
		Standard Deviation	65.77	157.69	.1274	1.33	94.58	356.14	328.53	.1892	1.00	875.30
North	Practice	Mean	386.08	355.12	.8119	2.75	1594.44	1155.93	-123.68	.7854	1.08	3586.85
		Range	381.23	955.38	.2511	3.12	747.13	2149.87	2899.09	.2693	1.57	4430.36
		Standard Deviation	97.43	180.90	.0683	0.72	202.02	629.32	779.86	.0799	0.48	1409.52
	Main 1	Mean	378.00	324.93	.7956	2.76	1538.31	1050.37	-12.80	.7969	1.14	3358.89
		Range	304.25	643.80	.2989	2.51	594.92	1580.95	847.37	.5074	1.49	4622.59
		Standard Deviation	78.69	135.86	.0716	0.62	184.11	495.96	295.64	.1362	0.47	1402.90
	Main 2	Mean	351.61	357.64	.8022	2.99	1486.29	944.67	308.45	.7206	1.35	3340.83
		Range	391.65	900.34	.4196	3.00	666.25	1205.35	2007.74	.5958	1.64	4605.47
		Standard Deviation	84.44	184.01	.1076	0.69	179.49	487.76	679.15	.1747	0.64	1411.88
Southwest	Practice	Mean	416.42	301.19	.8045	2.46	1637.89					
		Range	247.42	517.30	.3121	1.35	611.68					
		Standard Deviation	70.71	130.99	.0810	0.39	151.35					
	Main 1	Mean	381.42	330.65	.7791	2.71	1555.00					
		Range	238.27	520.43	.2586	1.70	508.43					
		Standard Deviation	69.44	143.51	.0613	0.49	136.41					
	Main 2	Mean	351.66	393.28	.7703	2.94	1522.10					
		Range	286.37	707.62	.2674	2.51	520.30					
		Standard Deviation	65.09	168.38	.0627	0.56	126.57					

4.0 Trackball with 1.0 CD Gain

Direction	Session	Statistics	Unimpaired Group					Impaired Group				
			Slope	Intercept	R^2	IP	MidMT	Slope	Intercept	R^2	IP	MidMT
East	Practice	Mean	205.37	439.22	.7815	5.17	1098.46	682.98	128.79	.7328	2.06	2321.16
		Range	213.24	313.33	.4866	5.74	437.39	1046.06	1166.06	.4398	4.10	2424.85
		Standard Deviation	50.68	94.08	.1284	1.34	115.64	365.38	384.61	.1304	1.38	903.03
	Main 1	Mean	213.81	408.90	.8137	5.14	1095.23	712.91	-47.03	.7481	1.86	2241.40
		Range	242.89	690.64	.4610	5.54	406.24	1143.95	2035.79	.3404	2.58	2749.00
		Standard Deviation	66.83	155.65	.1174	1.63	104.88	414.93	591.83	.1043	0.92	924.41
	Main 2	Mean	219.67	401.31	.7843	4.94	1106.45	678.67	51.95	.7372	2.19	2230.48
		Range	263.01	785.17	.5199	5.60	324.73	1235.57	1897.76	.4088	3.39	2743.76
		Standard Deviation	65.85	171.54	.1121	1.45	93.32	467.40	568.39	.1376	1.25	1003.29
North	Practice	Mean	312.09	332.11	.8309	3.34	1333.93	980.86	-143.86	.7484	1.29	3004.71
		Range	291.81	679.72	.2812	2.78	533.59	1274.09	2305.84	.6308	2.07	2858.10
		Standard Deviation	66.77	153.18	.0787	0.68	131.40	457.49	671.96	.1995	0.69	1060.42
	Main 1	Mean	295.06	382.45	.8114	3.58	1329.61	886.19	85.49	.7583	1.45	2930.17
		Range	251.34	757.62	.4412	3.24	695.78	1607.36	2978.10	.4964	2.03	3252.60
		Standard Deviation	69.55	174.13	.1278	0.86	147.23	489.96	749.84	.1689	0.71	1092.15
	Main 2	Mean	293.94	359.59	.8379	3.56	1303.13	858.22	94.55	.7860	1.44	2849.42
		Range	269.06	536.40	.2969	3.27	608.80	1214.54	1811.62	.4729	2.12	2681.96
		Standard Deviation	63.48	120.89	.0964	0.81	144.44	399.82	482.39	.1489	0.69	1037.58
Southwest	Practice	Mean	300.56	382.68	.8456	3.57	1347.47					
		Range	314.70	1100.77	.6086	4.62	588.38					
		Standard Deviation	74.48	221.15	.1382	1.09	156.00					
	Main 1	Mean	304.04	374.81	.8482	3.39	1350.78					
		Range	205.65	531.41	.2690	2.51	454.02					
		Standard Deviation	53.91	143.65	.0729	0.61	118.55					
	Main 2	Mean	279.08	447.91	.8142	3.71	1343.77					
		Range	207.35	909.42	.3111	2.91	629.46					
		Standard Deviation	51.88	191.95	.1011	0.72	150.08					

5.0 Mouse with 0.5 CD Gain

Direction	Session	Statistics	Unimpaired Group					Impaired Group				
			Slope	Intercept	R^2	IP	MidMT	Slope	Intercept	R^2	IP	MidMT
East	Practice	Mean	195.32	451.57	.8059	5.30	1078.56	765.96	207.27	.6897	2.19	2666.02
		Range	165.35	395.36	.5469	4.09	344.07	1747.82	2404.20	.6934	5.05	4102.62
		Standard Deviation	37.70	99.86	.1297	0.98	81.47	587.66	718.20	.2208	1.59	1450.66
	Main 1	Mean	181.75	480.40	.7985	5.79	1063.81	517.92	500.12	.5843	3.38	2162.64
		Range	147.50	438.80	.4855	6.03	204.90	1059.75	1856.95	.7107	8.71	2081.82
		Standard Deviation	38.12	109.74	.1199	1.49	61.32	361.38	534.38	.2635	2.77	777.25
	Main 2	Mean	186.39	459.28	.7984	5.81	1057.60	526.42	487.23	.6860	2.60	2177.05
		Range	244.92	544.49	.4638	6.42	425.51	758.64	757.75	.4362	3.60	2230.28
		Standard Deviation	56.27	131.70	.1171	1.63	96.31	295.03	260.76	.1457	1.43	836.59
North	Practice	Mean	254.23	542.95	.7493	4.28	1359.03	832.17	594.76	.6625	1.57	3266.01
		Range	359.13	885.79	.5968	5.70	432.58	1476.72	367.55	.5185	3.17	4448.26
		Standard Deviation	78.90	198.63	.1369	1.25	117.82	431.66	117.42	.1652	0.91	1376.09
	Main 1	Mean	231.90	565.99	.7470	4.55	1310.40	709.15	649.44	.7003	2.11	2925.80
		Range	205.21	677.54	.5529	5.21	552.96	1647.67	1838.79	.4812	3.56	4460.16
		Standard Deviation	51.61	154.59	.1266	1.17	132.74	523.94	581.91	.1756	1.23	1351.76
	Main 2	Mean	240.69	532.13	.7520	4.49	1304.75	559.71	1049.80	.5586	2.80	2846.48
		Range	305.32	564.19	.4798	6.19	617.89	1192.38	1727.05	.8216	8.37	4114.29
		Standard Deviation	66.48	133.30	.1217	1.38	128.66	350.44	501.08	.2713	2.37	1275.69
Southwest	Practice	Mean	242.72	498.73	.8410	4.27	1277.87					
		Range	157.02	450.92	.4194	2.82	281.71					
		Standard Deviation	45.12	125.02	.1135	0.84	76.00					
	Main 1	Mean	227.67	489.15	.8296	4.53	1219.96					
		Range	167.19	460.99	.1740	2.99	304.37					
		Standard Deviation	41.71	108.62	.0497	0.78	72.87					
	Main 2	Mean	238.63	475.20	.8568	4.41	1241.21					
		Range	225.77	488.69	.2203	3.94	328.76					
		Standard Deviation	55.95	118.32	.0643	0.99	84.19					

6.0 Mouse with 1.0 CD Gain

Direction	Session	Statistics	Unimpaired Group					Impaired Group				
			Slope	Intercept	R^2	IP	MidMT	Slope	Intercept	R^2	IP	MidMT
East	Practice	Mean	184.10	477.14	.7999	5.67	1068.11	533.93	576.90	.6596	3.37	2290.82
		Range	132.45	391.75	.4710	3.93	283.03	1456.54	1443.89	.5868	7.62	3612.03
		Standard Deviation	40.18	102.25	.1074	1.19	79.97	447.99	464.42	.1613	2.49	1276.04
	Main 1	Mean	167.37	510.83	.7879	6.37	1048.08	579.51	232.64	.6908	3.10	2092.85
		Range	208.47	548.41	.3845	5.93	267.78	1395.58	1817.42	.4439	9.10	2662.39
		Standard Deviation	46.93	111.23	.1073	1.55	63.14	443.06	536.42	.1579	2.62	990.58
	Main 2	Mean	171.23	493.39	.7570	6.17	1043.03	433.36	570.57	.5905	3.35	1961.66
		Range	164.60	406.84	.5147	5.65	212.20	895.62	1866.63	.8255	5.15	2358.13
		Standard Deviation	41.55	105.39	.1548	1.47	63.13	331.94	455.25	.2764	1.61	869.71
North	Practice	Mean	223.37	523.84	.7818	4.72	1240.87	758.47	340.30	.6959	1.91	2774.98
		Range	240.59	511.48	.3917	5.02	319.93	1314.73	2859.10	.7983	3.07	3123.75
		Standard Deviation	53.38	138.76	.1216	1.13	97.95	479.59	794.19	.2103	1.14	1205.10
	Main 1	Mean	216.13	533.09	.8286	4.94	1226.85	666.28	497.71	.6492	2.03	2636.47
		Range	204.32	496.70	.3774	5.54	349.50	1379.05	3004.60	.6557	2.71	3359.47
		Standard Deviation	53.01	122.51	.1138	1.40	107.07	466.66	843.58	.1982	0.92	1121.18
	Main 2	Mean	213.51	515.82	.8584	4.86	1201.20	616.79	553.12	.6752	2.59	2533.01
		Range	170.84	507.28	.2766	3.84	311.91	1446.37	3015.10	.7393	7.41	3410.92
		Standard Deviation	41.90	121.66	.0649	0.95	80.85	415.59	809.84	.2472	2.10	1108.30
Southwest	Practice	Mean	211.95	491.87	.8276	4.95	1172.23					
		Range	196.82	409.03	.3742	4.37	340.84					
		Standard Deviation	47.76	103.04	.1037	1.12	87.31					
	Main 1	Mean	203.78	525.41	.7894	5.22	1179.56					
		Range	191.51	547.85	.4404	5.25	307.94					
		Standard Deviation	50.40	143.77	.1195	1.37	85.74					
	Main 2	Mean	233.04	421.34	.8515	4.50	1169.42					
		Range	207.84	537.51	.2443	4.12	320.45					
		Standard Deviation	53.85	128.64	.0696	0.96	76.61					