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Low vision, stimulus encoding and information processing: a characterization of performance of partially sighted users on computer-based tasks

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LOW VISION, STIMULUS ENCODING AND INFORMATION PROCESSING: A CHARACTERIZATION OF PERFORMANCE OF PARTIALLY SIGHTED USERS ON COMPUTER-BASED TASKS.

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To: Dean Gordon Hopkins
College of Engineering

This thesis, written by Max A. Dixon, and entitled LOW VISION, STIMULUS ENCODING AND INFORMATION PROCESSING: A CHARACTERIZTION OF PARTIALLY SIGHTED USERS ON COMPUTER-BASED TASKS, having been approved in respect to style and intellectual content, is referred to you for judgement.

We have read this thesis and recommend that it be approved.

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The thesis of Max A. Dixon is approved.

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College of Engineering

Dr. Richard L. Campbell
Dean of Graduate Studies

Florida International University, 1998

DEDICATION

This thesis is dedicated to my family and friends. Through your faith I received the strength to complete this challenge.

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"The journey of a thousand miles begins with the first step"

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ABSTRACT OF THE THESIS

LOW VISION, STIMULUS ENCODING AND INFORMATION PROCESSING: A CHARACTERIZATION OF PERFORMANCE OF PARTIALLY SIGHTED USERS ON COMPUTER-BASED TASKS

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This study focuses on the characterization of partially sighted users' performance within a graphical user interface environment. Participants, ranging in visual abilities from fully sighted (FSU) with no visual impairments to partially sighted (PSU) with limited visual abilities, participated in computer-based search and select tasks. It is shown that visual search strategies employed by both PSU and FSU within a graphical user interface can be described by Sternberg's (1969) Additive Factor Model. In addition, selection strategies, measured by mouse movement times, are linearly related and highly correlated to the Index of Difficulty as explained by Fitts' Law. This is the first study of its kind that links the physiology of partial vision to behaviors and strategies exhibited during psychomotor task performance. These results can enable system interface designers to effectively design and accommodate the wide range of visual capabilities of today's growing population of computer users.

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Introduction and Background Literature

Information processing theories enable researchers to understand and characterize user behaviors while performing psychomotor tasks. However, in order to understand the role of individual differences, a more comprehensive model of information processing needs to be employed. The complexity of designing universally acceptable screen displays stems from variations in visual abilities, cognitive processes, and demographics, as well as motivation from individual to individual. Cognitive theories and models have been developed and consolidated into guidelines and styleguides, but research has yet to develop a predictive assessment of an individual's ability to accept new or unfamiliar screen displays within the realm of Human-Computer Interactions (HCI).

This study will focus on the characterization of partially sighted users' performance within a graphical user interface (GUI) environment. To incorporate the wide range of visual abilities, participants will be recruited based upon their level of visual impairment ranging from fully sighted users (FSU) with no impairment to partially sighted users (PSU) with limited visual abilities. It is proposed that the reduced visual acuity and contrast sensitivity of PSU will influence the visual encoding stage of Sternberg's (1969) Additive Factor Model (AFM) such that the visual search time (RT) for PSU will be slower than FSU. Furthermore, enlarging the stimuli will facilitate easier recognition of the stimuli for PSU resulting in RT approaching that of FSU. Movement time (MT) for several combinations of stimuli enlargement and movement distance are expected to support Fitts' Law in that MT is linearly related and highly correlated to the Index of Difficulty (ID).

This is the first study of its kind that will link the physiology of partial vision to behaviors and strategies exhibited during psychomotor task performance. The results will enable system interface designers to accommodate the wide range of visual capabilities of computer users.

This research begins with an explanation of the physiological properties of vision. Next, the exploitation of the graphical user interface will be presented offering insight to the perceptual and cognitive processes within HCI. This will lead into detailed theories of information processing and how it is used as a tool for predicting performance. These theories will then be applied to an experimental setting. The statistical techniques that were utilized are described providing an explanation of the results. General comments summarizing the results follow.

The physiology of the human eye

Because performance is dependent upon the perception of information (Egan,1988), it is a primary concern to present information in a way that is easily assimilated by the human senses. In particular, the display of information using computers must accommodate the abilities and limitations of the human senses. Information generated by computers is generally presented through some form of visual media. Consequently, good display design must begin with an understanding of the basic principles of visual sensory processing.

Vision is a predominantly spatial system, providing immediate and precise information about the physical properties of the environment. Detection begins when energy, in the form of light, is absorbed and reflected by objects in our environment. The eyes serve as a mechanism through which projected or reflected light enters, and together with the brain, reconstruct the position, shape and motion of the objects we see around us. Along its path through the eye, light must traverse several media which will bend, twist, and refract the light before reaching the retina. There, light is transformed into neural signals and transmitted to the brain where the impulses are collected reforming the physical object in space (Proctor and Van Zandt, 1994). Conversely, during its journey through the "abnormal" eye, light from the image is refracted, bent, scattered or otherwise altered thus reflecting a degraded image upon the retina. The optical characteristics of the eye, however, are not the only determining factors of visual loss. There are other instances, in which the light passes through the eye normally but the image formed on the retina is distorted by the retina itself or by other parts of the visual nervous system (Kline & Scheiber, 1985). The following will describe in detail the vast network of physical and chemical properties involved in the visual processes.

Refraction

The human eye can be considered a complex collection of thin convex and concave lenses immersed in various solutions of differing densities. Using the principles of optics, one can develop mathematical models describing the image formed upon the retina. It is important to understand the optical nature of the human eye in order to fully comprehend the nature of loss in visual acuity caused by various degradation of the numerous anatomies of the eye.

The word refraction refers to the way light rays are focused. There are three basic elements that determine an eye's refractive characteristics - the shape of the cornea, the

power of the natural lens, and the length of the eyeball. When all of these elements are coordinated perfectly, light is focused directly on the retina and the person sees clearly. Unfortunately, many eyes develop imperfectly with these elements out of alignment. This misalignment results in the refractive problems of myopia (nearsightedness), hyperopia (farsightedness), and astigmatism. Presbyopia is a gradual loss of the ability to focus on near objects and is sometimes referred to as "old age vision".

Major Anatomic Features of the Eye

A schematic diagram of the major components of the human eye is shown in Figure 1. The human eye is sensitive to a small region of the electromagnetic spectrum, typically ranging from approximately 380 nm to 760 nm (Proctor and Van Zandt, 1994). As reflected light enters the eye, it is directed to the retina by the cornea and the lens. The iris lies between the cornea and the lens. The aperture created by the iris is called the pupil. The retina lies on the back wall of the eyeball and is comprised of many layers of photoreceptors.

Cornea

The cornea is the first refracting medium as light enters the eye. The cornea contains no blood vessels (avascular) which gives it its optical clarity (McIlwain, 1996). The cornea is a convex surface with a radius of about 8-mm. Surprisingly, the cornea accounts for approximately two-thirds of the focusing power of the eye (Kline & Schieber, 1985). If either the surface smoothness or the clarity of the cornea suffers, vision is distorted.

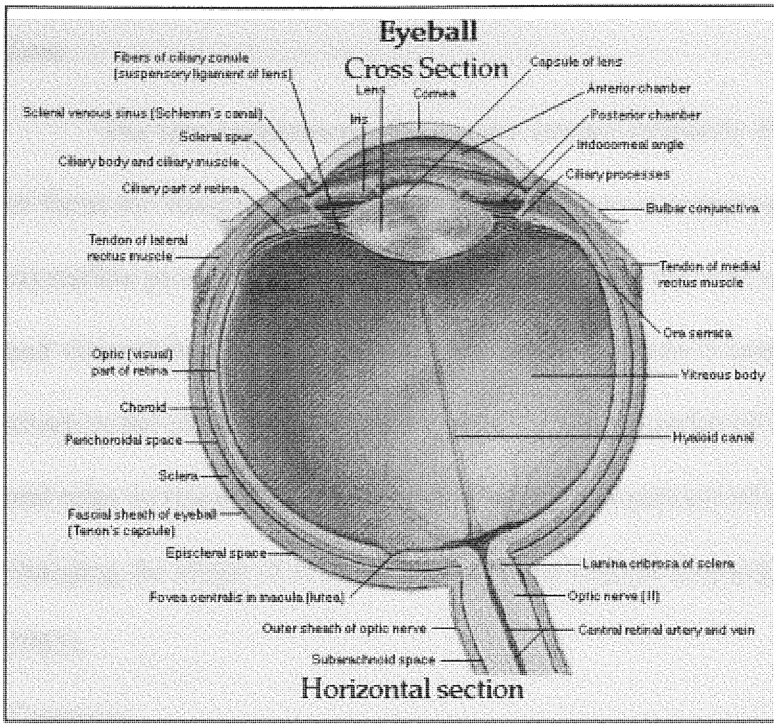


Figure 1: Horizontal section of the eyeball.

This smooth surface is composed of five layers of tissue. The outermost epithelium protects the eye from abrasion from foreign bodies and quickly regenerates new cells in the injured area. The epithelium lies upon Bowman's membrane. The thickest part of the cornea, the Stroma, is composed of collagen and scattered cells called keratocytes. Descemet's membrane and the endothelium form the outer boundary (Maurice, 1969).

Hereditary Corneal Dystrophy

Characterized by pathological deposits on the epithelium, endothelium, or Stroma, the only treatment of hereditary corneal dystrophy is the surgical removal and transplantation of a healthy cornea. Persons inflicted with this hereditary disease have blurred vision.

Lens

The lens supplements the cornea serving primarily for fine, dynamic adjustments of focus for varying viewing distances. The lens is composed of an avascular, clear, crystalline protein. It is therefore dependent upon the surrounding liquid of the aqueous and vitreous humor for nutrients. The bi-convex lens is suspended by zonule fibers that attach to the ciliary process (see Figure 1). The muscles of the ciliary process contract and relax in response to the fixated object. This process of accommodation results in changing the shape of the lens so as to keep objects focused on the retina (Clemente, 1985).

Cataracts

Like the cornea, the lens must be maintained in a dehydrated state in order to support transparency. A cataract results from opacification of the crystalline lens caused by the liquefaction of cortical cells. This leads to a progressive increase in the amount of insoluble proteins, which leads to hardening (sclerosis) and brownish discoloration (brunescence) of the lens. This loss in optical transparency produces poor image quality. Though, in most cases, it can be surgical replaced with an artificial lens.

Aqueous Humor and Interocular Pressure

The anterior chamber, filled with a clear liquid called the aqueous humor, is located between the cornea and the lens (see Figure 1). The role of the aqueous humor is to provide constant pressure inside the eyeball (normally about 15mm Hg) which is crucial for proper optical function (McIlwain, 1996). The aqueous humor is produced by the ciliary body and is secreted into the posterior chamber and circulates past the iris and the lens into the anterior chamber. Its flow continues through a tiny sponge-like tissue (the trabecular meshwork), draining into a capillary called sinus venous scleroe (canal of Schlemm) (Ali and Klyne, 1985).

Glaucoma

Impaired flow of the aqueous humor leads to elevated interocular pressure causing impingement of the nerve cells of the optic nerve and vessels of the retina and choroid. Prolonged compression can result in permanent visual loss (Ali and Klyne, 1985).

Vitreous Humor

Filling approximately four-fifths of the eyeball, the vitreous humor attaches itself to the retina maintaining the retina in position. Located between the lens and the retina, the vitreous humor is mainly comprised of water bound by collagen fibrils which gives it gel-like properties (Ali and Klyne, 1985).

Retinal Detachment

Shrinkage of the vitreous humor may cause detachment and tearing of the retina. A variety of clinical manifestations can occur from the tearing or detachment of the retina, such as photopsia (spontaneous occurrences of light flashes in the absence of an eternal stimulus); gross distortion of the visual image; blurred vision; and most often, ephemeral, or moving opacities in the vitreous humor ("floaters") (Kline and Scheiber, 1995).

Retina

In a normal eye, images are focused on the retina located on the back wall of the eye. Here, the image is transformed into neural impulses and transmitted by the optic nerve to the brain. Given the complex nature of this neural network, a closer examination of its intricacies is essential.

The retina can be seen as a complex link of photoreceptors and neural networks stratified into alternate nuclear and synaptic layers (see Figure 2). The posterior layer, closest to the sclera, is the photopigment epithelium comprised of the two types of photoreceptors, rods and cones. This is the only visually sensitive region of the eye. Light must pass through almost the entire thickness of the retina before being detected by the rods and cones (Ali and Klyne, 1985).

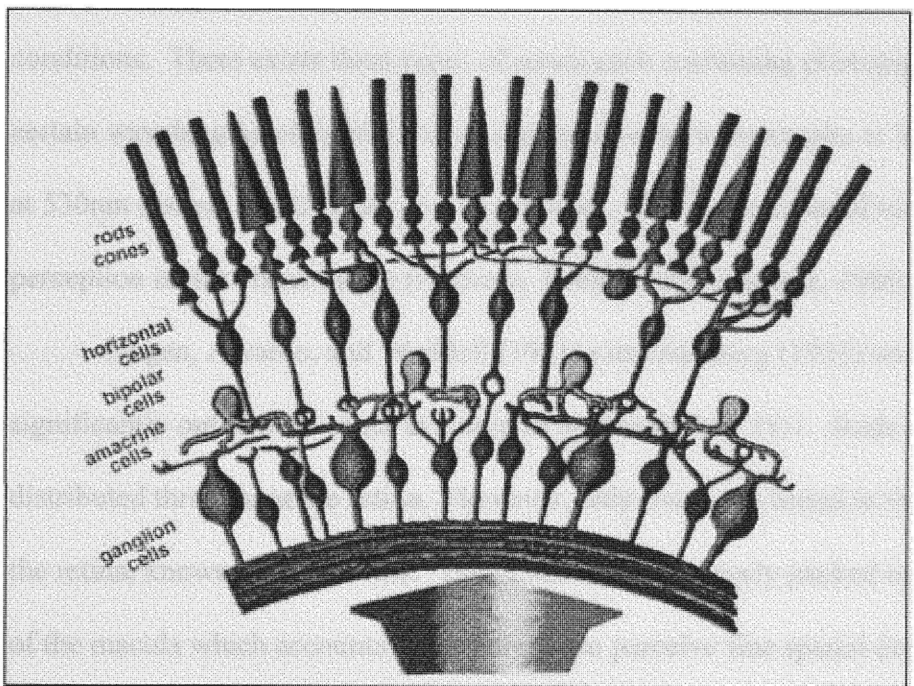


Figure 2: Plan of retinal neurons.

These photoreceptors extend into the outer nuclear layer and proceed to the outer plexiform layer where they make contact with bipolar and horizontal cells. The somata of the bipolar and horizontal cells share the inner nuclear layer with amacrine, interplexiform and Muller cells. Synaptic interactions of the bipolar, amacrine, and ganglion cells take place in the inner plexiform layer. Ganglion cells dominate the ganglion cell layer with their axons proceeding to the optic nerve. These layers of synapses and cell bodies are separated from the vitreous by a thin membrane (McIlwain, 1996).

The rods and cones, named after the shapes of their outer segments, are responsible for absorbing photons of light energy through photopigments located in their outer segments. Rod photopigments are sensitive to wavelengths of light around 495 nm (blue-green light). Rods are highly sensitive and are used for vision under dark or dim conditions. There exists three types of cones each containing photopigments sensitive to certain wavelengths of light: L-cones are sensitive to wavelengths at 560 (red), M-cones at 530nm (green) and S-cones at 420nm (blue). This is the basis of trichromatic color perception in our visual image (Nathans, Thomas, and Hogness, 1986).

Hogan, Alvardo, and Weddell (1971) cite Osterberg (1935) who found that rods significantly outnumber cones at a ratio of approximately 19:1. Rods and cones are distributed throughout the retina. However, only cones are found in the central region of the retina, known as the macula. The cones become densely packed in the foveal region of the macula which accounts for the ability to perceive fine spatial detail. The area of the optic nerve, known as the blind spot or foveola, is photoreceptor free (Hogan et al, 1971).

Diseases of the retina

The retina has two main functions: converting an optical image into neural signals and abstracting certain features of the plethora of neural signals and sending them to the brain by way of the optic nerve for processing. Under normal conditions, the refracting media of the eye (cornea, lens, iris, etc.) will produce a sharp image on the retina. However, if the retina is deficient in any of its main functions, visual perception is diminished. There exist numerous pathologies of the retina that are too extensive to list. However, a brief discussion of the most common will be presented.

Retinitis Pigmentosa

An inherited disease, retinitis pigmentosa (RP) is characterized by a degeneration of the photoreceptors of the retina. RP, which is characterized by poor night vision and constricted peripheral vision, first affects the rods. Gradually the disease begins to destroy the cones resulting in central vision loss.

Retinal Edema

This is a condition in which the capillaries of the retina bleed. If left untreated, permanent vision loss can occur. Some causes of retinal edema are diabetes and hypertension.

Color Blindness

Defective color vision is characterized by the congenital absence or defect of the photopigments in the cones in the retina. One result is an inability to discriminate hues, determined by a combination of the red, green, and blue photopigments. Absence of cones also reduces ones ability to discriminate spatial details. Poor night and peripheral vision is a result of the absence or defect in rod photopigments.

Visual Nature of Human-Computer Interfaces

Advances in the computational power of personal computers have led to an increased use of graphics. Compared to their crude predecessors, today's pictorial representations provide astonishingly sharp details and vivid colors to the "normal" eye. The use of graphics has been exploited for representing quantitative, numerical and pictorial information. Moreover, graphical symbols, or icons have become mainstream in the graphical user interface (GUI) environment of today's computing systems. The use of icons in interactive interfaces serves as a means through which users can initiate higher level actions and concepts without the use of complex syntax. Furthermore, icons continually represent the objects of interest, as well as provide quick reversible actions with immediate feedback (Schneiderman, 1998). Icon selection and activation requires the use of a pointing device. The most frequently used pointing device is the mouse. However, iconic functions can also be invoked through the keyboard input of function keys and cursor movement keys. Other forms of input devices include touchscreen, joystick, trackball, and light pen. However, the usefulness of a pointing device depends on its application. Foley et al (1984) describe six types of interaction tasks.

1. *Select:* The user chooses from a set of items (i.e. menu selection).
2. *Position:* The user chooses a point in a one-, two-, or three- dimensional space (i.e. dragging an icon or creating a drawing).
3. *Orient:* The user chooses a direction in a one-, two-, or three- dimensional space (i.e. rotate a symbol).
4. *Path:* The user rapidly performs a series of position and orient operations (i.e. draw a curved line).

5. *Quantify:* The user specifies a numeric value (i.e. select a page number in an electronic document)
6. *Text:* The user enters, moves, and edits text in a two- dimensional space (i.e. indicate the location of an insertion, deletion, or change in an electronic document).

Completion of these tasks requires complex interactions of the visual and tactile senses. The use of indirect input devices such as a mouse requires the operator to possess keen psychomotor skills. Such is the case when performing direct manipulation tasks.

<u>Direct manipulation tasks</u>

Eason et al (1991) characterized direct manipulation as a "visual interface which emphasizes eye-hand coordination skills as a prime requisite for successful and efficient interaction" (p. 116). It is apparent that direct manipulation is attractive because its use often results in faster performance, fewer errors, easier learning, and user satisfaction (Buxton, 1985). Physical, spatial, or visual representations also appear to be easier to retain and manipulate than textual or numeric representations (Arnheim, 1972). Although providing an effective means of human computer interaction, there are inherent limitations in the design of computer-generated displays (Farrell, 1991).

First, the user must understand the information presented in order to react appropriately. The constraint implied is that the user possesses sufficient experience to relate the icon to its function. A user may incorrectly interpret the metaphor represented by the icon portraying its meaning one way when its actual function is different. Or, icons may not be obvious to the user and therefore confusing to interpret. Creation of meaningful, analogous and metaphoric icons continues to challenge designers of GUI systems.

Secondly, the information presented to the user is limited by the available technology of the output device. There exist on the market today various technologies for displays. Of these, the most popular is the cathode ray tube (CRT). Other mediums of displays include light emitted diode (LED), liquid crystal display (LCD), and plasma displays. A CRT is an electronic tube lined with a phosphorous material arranged in an array that glows when it is struck by a stream of electrons. Electron guns, located at the back of the monitor scan the phosphor coated CRT beginning at the top sweeping left to right, continuing down one line at a time until it reaches the bottom before repeating the process. The intensity of the electron beam at each dot is what controls the color and brightness of each pixel on the screen. The surface of the CRT only glows for a small fraction of a second before beginning to fade. This means that the monitor must redraw the picture many times per second to avoid having the screen flicker as it begins to fade and then is renewed. This rapid redrawing is called "refreshing" the screen. However, one can reduce the probability that a display will flicker by increasing the refresh rate, decreasing the display luminance, decreasing the display size or using a phosphor with a shorter decay time. These various parameters to reduce flicker allow a wide variety of the user population to make the appropriate adjustments to perceive a continuous illuminated source (Farrell, 1991). Furthermore, enhancements in liquid crystal flat panel displays have provided an affordable alternative to display computer-generated images and text without any flicker.

Finally, one must understand the limitations of the human as the recipient of the information. Given that visual displays are the dominant medium for human computer interactions, losses in the visual sense reduce the ability to perceive graphical and textual information. No matter how well the interface is developed or the quality of the visual medium of presentation, reduced visual capability results in poor perceived image quality.

Dimensions of human vision affecting interaction with computers

The eyes' resolving power spans the temporal, spatial and chromatic dimensions (Snyder, 1988). In the realm of human computer interactions, the issue of spatial discrimination has been mostly resolved with the advent of improved visual display technology. Hence, a comprehensive determination of one's ability to perceive the state of a computer system lies in the discrimination of light, space, and color. This is the foundation upon which this research lies.

There exist parameters of the visual field for which current hardware facilities do not provide sufficient flexibility in accommodating visually impaired users. These lie in the spatial domain characterized by acuity and contrast sensitivity. Acuity is defined as the minimum visual angle for a detail to be resolved and depends strongly on the illumination of the stimulus. Visual angle is a measure of image size perceived by the retina (Proctor and Van Zandt, 1994). There are several measures of acuity. The most typical is identification acuity that is traditionally measured by a Snellen eye chart consisting of rows of progressively smaller letters. This technique is useful only for determining one's general acuity level. Ferris, Kassoff, Brisnick, and Bailey (1982) identified shortcomings of using the Snellen and similar charts when quantifying changes in acuity over time. They propose the Bailey-Lovie chart, which provides an accurate assessment of visual acuity that facilitates quantitative data analysis.

Acuity is a measure of contrast sensitivity defined by the upper limit for detecting fine detail at high contrast. Therefore, a more accurate prediction of acuity is by means of the contrast sensitivity function (CSF). The CSF is a measure of the ability to detect objects of different sizes and contrasts (Czaja, 1988). A CSF is typically obtained by measuring an observer's contrast detection threshold for a number of different grating patterns at different spatial frequencies. The contrast detection threshold is the lowest contrast at which a pattern can be seen. Sensitivity is the reciprocal of the threshold (Snyder, 1988). The Pelli-Robson chart (Pellie, Robson and Wilkins, 1988) which consists of letter charts composed of varying contrasts can obtain one's contrast sensitivity function.

Vision field refers to the ability to perceive a stimulus that lies outside of the central foveal vision. One's visual field can be ascertained utilizing the Goldman projection perimetry technique (Kline and Schieber, 1985). This involves detecting a light source in the peripheral field while fixated on an object straight-ahead.

Besides the ability to distinguish objects from their backgrounds, another important aspect of vision is its ability to discern wavelengths of light. Today's CRT technology provides users with a rainbow of colors that have been extensively used by GUI designers. Chromatic pattern identification can be clinically assessed using the Farnsworth D-15 color vision test.

Relevant Literature on Human Information Processing

The performance of computer-based tasks are psychomotor in nature, hence theories of human information processing are applicable. Many theorists have examined the nature of human information processing (Egath, Jondies, Wall, 1972; Neisser, Novick, & Lazar, 1963; Sternberg, 1969). It is widely agreed that tasks can be subdivided according to how they affect specific components of information processing. This approach analyzes the task components in terms of the demands they place upon the perceptual, cognitive and psychomotor processes.

Information processing begins with the onset of a stimulus (i.e. a computer interface depicting an icon representing the print function). This graphical representation is detected, discriminated, and identified by our eyes (perception). Once information has been extracted from the display, processes begin to produce a decision based upon the goal or goals of the task. In this case, the user wants to print the current document. During this process, the user retrieves stored memory such as information retained for short periods of time, short-term memory (STM) or previously learned information, long term memory (LTM). Comparisons are made with the displayed information and decisions are formulated (cognition). A response is then executed resulting, in this case, in a tactile maneuver of moving a mouse and selecting an icon representing the function to print the document (psychomotor).

Sternberg's Additive Factors Model

Sternberg (1969) proposed a theory that the sequence of task components in events requiring recall of information from short-term memory occur in succession. In this instance, not until one process is fully completed, does the next process begin. Furthermore, Sternberg suggests that processing stages are additive such that response latency is the sum of the latencies of discrete processing stages (figure 3). According to Sternberg, a stage is "...one of a series of successive processes that operates on an input to produce an output, and contributes an additive component of the RT [reaction time]." (p. 282). It is assumed that each stage is independent of all others such that the duration of one stage does not directly affect the duration of other stages. Stages are influenced only by their input (information transferred from the previous stage) and factors affecting that stage. A factor is an external influence such that its effect is measured by a change in mean RT.

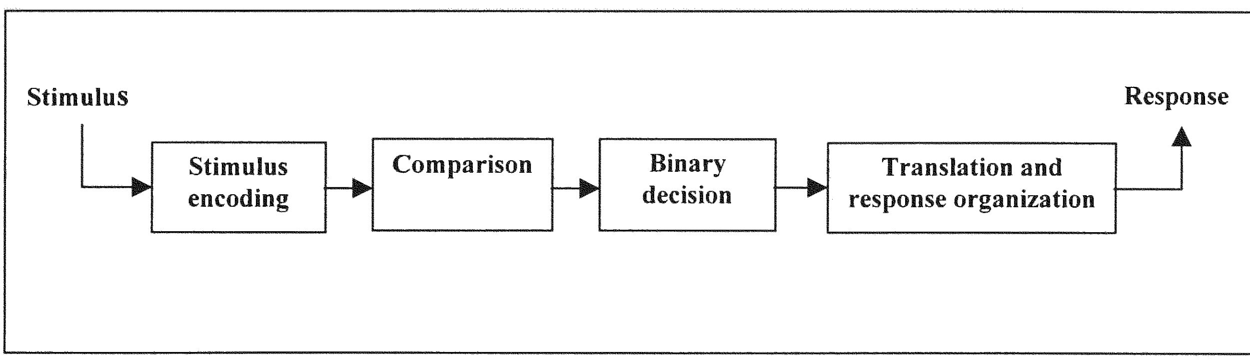


Figure 3: Sternberg's additive factors model.

Under the stage model, when two factors influence different stages of processing, their combined effects on reaction time are additive. Each factor increases or decreases the duration of a stage of processing and the change in the duration of the stage influenced by each factor is simply added to or subtracted from the total reaction time.

On the other hand, when two factors influence the same stage of information processing, the change in the duration of that stage can indicate an interaction between the effects of the two factors. Also, the total time required to make the response will be increased or decreased as a function of this interactive effect on the duration of a single processing stage. The influences based upon these assumptions of Sternberg's additive factors model are:

1. If factors have additive effects on mean reaction time (MRT), the factors influence different processing stages
2. If factors have interactive effects on MRT, the factors influence at least one stage in common.

The duration of the mental processes (RT) in Sternberg's additive factors model can be expressed by the linear relationship:

$$RT = a + bx. \quad \text{(Equation 1)}$$

According to Sternberg, the slope, b, of this function is the representation of the mean time to compare the physical stimuli with the perceived stimuli in memory during the comparison stage. The y-intercept, a, is a measure of the mean time of the events that occur before (serial encoding) and after (translation and response organization) the serial comparison stage, while x is defined as the set size.

Degradations of stimuli have been shown to increase MRT (Sternberg, 1967). These experiments involved fully sighted individuals subjected to stimuli (the numbers 0-9) that were superimposed with a checkerboard pattern. The results of this study indicated that reducing the quality of an object did not affect the manner in which we cognitively process information. Instead, this effect influences the stage prior, the stimulus encoding stage, which was evident in Sternberg's (1967) experiment by a change only in the y-intercept of Equation 1.

Similar experiments have been performed using graphical representations. Dickman and Meyer (1988) reported using a test stimuli of randomly generated complex geometric figures. Participants were asked to compare a pair of figures and determine if they were similar. Similarly, Exposito and Andres-Pueyo (1997) produced a display generated by an array of simple symbols on a computer monitor. Results from both studies produced linear reaction time functions in the form of Equation 1. Though these experiments did not directly study the effects of poor image quality on RT, these results indicate that Sternberg's paradigm holds true for more complex stimuli rather than textual or numerical representations. It would be of interest, especially for software developers and designers, to extend the information processing model proposed by Sternberg so that it is useful for practical applications such as the use of graphical representations typical in today's computer desktop environment.

Fitts-like motor movements

The need for a reliable predictive model of motor movement in computer input tasks are stronger today than ever before. Icons and bit-mapped graphical displays fill the typical GUI desktop that is gaining in popularity over menus and command lines. As interactions with today's computer interfaces become more "direct", models of human psychomotor behavior are extending into HCI. By means of a mouse, discrete psychomotor movements carry out this direct manipulation of icons located on the interface. A typical movement involves moving the cursor from one point on the screen to an icon of a certain size on another part of the screen. These movements have been shown to conform to Fitts' Law (Card, English, and Burr, 1978; Card, Moran, and Newell, 1983; Epps, 1986). Fitts studied the relationship in aiming movements between movement time and the distance to the target (A) and the target's width (W) (Fitts, 1954; Fitts and Peterson, 1964). This relationship showed that movement time (MT) was linearly related to the index of difficulty (ID) which he described as $\log_2(2A/W)$. This law has been shown to be a robust, highly cited, and widely adopted model for predicting movement time of the human motor system.

Keele (1968) further described the MT-ID relationship. Keele proposed that as the target is approached, a series of aiming adjustments are made until the target is finally acquired. These corrections are the result of visual comparisons between the end of the limb and the target area. Keele's model suggests that the amount of time spent near the target is disproportional to the initial ballistic movement. The duration of the visual error corrections that are made close to the target have been shown to last between 190-260 ms (Keele and Posner, 1968).

Wallace and Newell (1983) evaluated Keele's model. In their experiment, visual feedback was manipulated for fully sighted participants while performing a selection task using a stylus to tap a target of a set size and distance. Half of the tasks were performed with no light thus eliminating any visual guidance. The other half was performed under illuminated conditions. Their results showed significant interaction between MT and vision only above an ID level of 3.58. They concluded that vision does not play a role in target selection at lower ID levels.

However, Wallace and Newell (1983) did not account for dark adaptation of the rod and cone photoreceptors. During dimly lighted (scotopic) conditions, rods are most sensitive to light. Under lighted (photopic) conditions, the cones are most sensitive to light. In Wallace and Newell's research, each trial began in an illuminated (photopic) condition, resulting in initial saturation of most cone and some rod photopigments. As these photopigments regenerate, sensitivity to light progressively improves. However, rods take longer to regenerate than cones due to their larger surface area. On half of the trials, the light was extinguished after the stylus was moved from the home position. This produced a scotopic condition resulting in the activation of rod photopigments. At that point, rod sensitivity levels were low. Because it takes approximately 60 seconds for rods to regenerate, the threshold levels for target perception were higher. The insignificant results below the 3.58 ID level reported by Wallace and Newell could be the result of this latency.

This examination of visual feedback during psychomotor responses is better investigated in a more realistic setting. Distorting the perception of the stimuli is an alternative approach to altering the stimuli directly (illuminated vs. dark conditions). One method to test Wallace and Newell's (1983) hypothesis is to use participants who are partially sighted. This could provide evidence that as the ID increases the need for vision increases.

Hypothesis Formulation

This study will couple theoretical aspects of psychomotor task performance within a realistic task environment. These theories, applied to the field of human computer interaction, will provide a fundamental basis upon which computer interface designers can better utilize the computational power of today's computing systems. Specifically, this study proposes to explore two robust and widely cited theories of experimental psychology to investigate and characterize behaviors exhibited by partially sighted users while performing tasks within a computer-based task domain. First, Sternberg's Additive Factors Model will investigate the effect of a user's visual profile defined by visual acuity, contrast sensitivity, field of view and color perception on visual search time in a GUI environment under experimentally enhanced conditions of enlargement and contrast. Fitts Law will explore the time to position a cursor with a mouse considering a user's visual profile defined by visual acuity, contrast sensitivity, field of view and color perception. Knowledge of visual search and position time will provide a holistic view to characterizing human behaviors and strategies in a GUI environment. An examination of these behaviors will be investigated by the following hypotheses assessed under four conditions.

Condition 1: Assessment of task performance in a standard desktop environment

Under standard conditions, the GUI desktop provides a powerful and efficient means to execute complex syntax and commands yet provides a challenge for the partially sighted user. In order to gain an understanding of the differences in performance with partially sighted and fully sighted users, a baseline assessment will be made utilizing Sternberg's Additive Factors Model and Fitts Law.

Hypotheses 1-4

1) In a standard desktop environment, set size and reaction time will be related linearly regardless of the degree of one's visual impairment.
2) In a standard desktop environment, the reaction time (RT) for partially sighted users (PSU) and fully sighted users (FSU) will be significantly different given the same interface which will be indicated by differences in the y- intercept of the set size - reaction time line.
3) In a standard desktop environment, movement distance (A), object size (W) and movement time (MT) will be described by Fitts Law regardless of the degree of one's visual impairment.
4) In a standard desktop environment, the movement time (MT) for partially sighted users (PSU) and fully sighted users (FSU) are significantly different given the same interface.
    a) The slope of the movement distance, object size and MT line will be significantly greater for PSU compared to FSU.

Condition 2: Assessment of task performance in an enlarged environment

Current screen enlargement using software available today allows only discrete adjustments. However, an individual's visual acuity does not follow the same discrete changes. It is proposed that there exists a magnification related to one's visual acuity such that an interface enlarged by this factor will enable the user to perform in a manner equal to someone who is fully sighted. Therefore, regardless of one's visual ability, there exists an enhanced interface design utilizing magnification that will maximize performance.

Hypotheses 5-8

5) In an enlarged desktop environment, set size and reaction time will be related linearly regardless of the degree of one's visual impairment.
   a) The slope of the set size-reaction time (SS-RT) line will not be significantly greater for PSU compared to FSU.
   b) The intercept of the SS-RT line will not be significantly greater for PSU compared to FSU.
6) In an enlarged desktop environment, the reaction time (RT) for partially sighted users (PSU) and fully sighted users (FSU) will not be significantly different given the same interface.
7) In a enlarged desktop environment, movement distance (A), object size (W) and movement time (MT) will be described by Fitts Law regardless of the degree of one's visual impairment.
   a) The slope of the object distance, object size and MT line will not be significantly greater for PSU compared to FSU.
   b) The intercept of the object distance, object size and MT will not be significantly greater for PSU compared to FSU.
8) In an enlarged desktop environment, the movement time (MT) for partially sighted users (PSU) and fully sighted users (FSU) are not significantly different given the same interface.

Condition 3: Assessment of task performance in an environment with enhanced contrast

Regardless of one's visual ability, there exists an enhanced interface design utilizing improved contrast that will maximize performance.

Hypotheses 9-12

9) In a contrast-enhanced desktop environment, set size and reaction time will be related linearly regardless of the degree of one's visual impairment.
    a) The slope of the set size-reaction time line will not be significantly greater for PSU compared to FSU.
    b) The intercept of the SS-RT line will not be significantly greater for PSU compared to FSU.
10) In a contrast-enhanced desktop environment, the reaction time (RT) for partially sighted users (PSU) and fully sighted users (FSU) are not significantly different given the same interface.
11) In a contrast-enhanced desktop environment, object distance, object size and MT will relate linearly regardless of the degree of one's visual impairment.
    a) The slope of the object distance, object size and MT line will not be significantly greater for PSU compared to FSU.
    b) The intercept of the object distance, object size and MT will not be significantly greater for PSU compared to FSU.

12) In a contrast-enhanced desktop environment, the movement time (MT) for partially sighted users (PSU) and fully sighted users (FSU) are not significantly different given the same interface.

Condition 4: Assessment of task performance in a magnified environment and with enhanced contrast

Regardless of one's visual ability, there exists an enhanced interface design utilizing improved contrast and magnification that will maximize performance.

Hypotheses 13-16

13) In an enlarged desktop environment with enhanced contrast, set size and reaction time will relate linearly regardless of the degree of one's visual impairment.
    a) The slope of the set size-reaction time (SS-RT) line will not be significantly greater for PSU compared to FSU.
    b) The intercept of the SS-RT line will not be significantly greater for PSU compared to FSU.
14) In an enlarged desktop environment with enhanced contrast, the reaction time (RT) for partially sighted users (PSU) and fully sighted users (FSU) are not significantly different given the same interface.
15) In an enlarged desktop environment with enhanced contrast, object distance, object size and MT will relate linearly regardless of the degree of one's visual impairment.
    a) The slope of the object distance, object size and MT line will not be significantly greater for PSU compared to FSU.

b) The intercept of the object distance, object size and MT will not be significantly greater for PSU compared to FSU.

16) In an enlarged desktop environment with enhanced contrast, the movement time (MT) for partially sighted users (PSU) and fully sighted users (FSU) are not significantly different given the same interface.

Methodology

Participants

To express the differences along the full range of vision, participants were selected from two pools: persons who have been diagnosed with an uncorrectable ocular disease (PSU) and persons who possess no known uncorrectable ocular diseases and who have fully correctable vision (FSU). PSU participants were identified with assistance from the Computer Systems Coordinator at the Miami Lighthouse for the Blind in Miami, Florida. Thus, all PSU participants were prescreened and known to possess knowledge of the utility of computers to perform tasks. In addition to their ocular status, information was also gathered from the PSU participants concerning level of computer experience, age and gender. The ten FSU participants were approximately experience-, age- and gender-matched to the PSU participants so that valid comparisons could be made between the two groups. Table 1 expresses the similarities between the two groups of participants.

Participants performed the tasks with the assistance of corrective eyewear (glasses, contacts, field glasses) if necessary, to allow experimentation under best-corrected vision. PSU were provided with an assessment of their vision at the Low Vision

Clinic at the Bascom-Palmer Eye Institute (BPEI) located in Miami, Florida, to ensure that the experimenters had knowledge of their current visual status. As an incentive to participate, PSU were provided this assessment free of charge, a $300 value. Participants were not paid for their participation. Table 2 describes the four clinical assessments that were made on each PSU.

Table 1: Comparison of PSU to FSU

Partially Sighted Users				Fully Sighted Users			
Participant #	Age	Gender	Computer experience (yrs)	Computer experience (yrs)	Gender	Age	Participant #
29	29	F	8	10	F	31	3
54	75	F	3	1	F	70	59
44	35	F	3	9	F	37	69
63	23	F	6	10	F	23	67
33	28	F	10	6	F	28	71
49	47	F	11	7	F	47	82
56	30	M	3	5	M	28	73
65	26	F	4	2	F	25	75
26	32	M	0.25	0.5	M	31	77
30	38	M	0.25	1	M	38	79

Table 2: Visual parameter testing techniques

Visual Parameter	Technique
Acuity	Bailey-Lovie acuity chart
Contrast Sensitivity	Pelli-Robson chart
Field of View	Esterman projection perimetry technique (binocular) Humphrey Visual Field-SITA 60 (monocular)
Color Perception	Farnsworth D-15 color vision test

Experimental Tasks and Environment

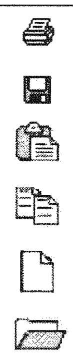
A computer interface was used to test the ability of the participants to correctly identify and select icons common in a Microsoft® Windows environment. The apparatus consisted of an IBM compatible PII/266 running under a Microsoft Windows NT 4.0® environment. An interface was designed with Microsoft® Visual Basic® 5.0 using a timer capable of measurements to one-hundredth of a second. A total of six (6) icons were employed throughout the experiments (see Table 3). These icons were chosen because studies have shown that they are the most identifiable to Microsoft® Word 7.0® users (Sears, Jacko, Brewer, and Robelo, 1998).

Table 3: Icons used in experiments

Iconic representation	Function
	Print
	Paste
	Save
	Copy
	New
	Open

The following is a storyboard description of the interface employed in this experiment. The user was presented with the target presentation screen (see Appendix A) that displayed a visual instruction that read "Select the Following Icon". Accompanying this instruction was the iconic representation of one of the six functions shown in Table 3. The target icon was randomly chosen from one of the six icons described above and displayed on the target presentation screen. The interface then generated the stimulus presentation screen (see Appendix B) that displayed a set of two to six icons, which were also randomly chosen from the icon set described. On each trial the size of the icons varied in size from 9.2 to 58.3 mm (see Table 4). The size of the icons are representative of the size of the letters on the Bailey-Lovie acuity chart. For example, an acuity level of 20/100 is represented by letters 29.19 mm wide on the Bailey-Lovie chart. The color of the background upon which the icons were presented was also manipulated. Five colors: black, white, blue, red, and green were employed and were chosen based on the fact that they are primary colors. All colors were presented at the fully saturated level.

Table 4: Interface characteristics

Icons	Set Size	Icon size (mm)	Corresponding Acuity Level	Background colors
	2	9.2	20/32	Black
	3	14.6	20/50	White
	4	23.2	20/80	Red
	5	36.8	20/125	Green
	6	58.3	20/200	Blue

A timer was necessary to record various events throughout each trial. Within each trial, the following times were recorded:

Event	Description
1	Onset of stimulus interface (time 0)
2	Mouse click to indicate target identification
3	Mouse leaves the home position
4	Mouse enters icon target area
5	Mouse click indicating selection

The distance from the center of the home position to the center of the target icon was identified for each trial. The home position was located at the bottom center of the screen with an outside diameter of 58.3 mm and an inner diameter of 38.3 mm. The outside diameter was filled with a 60% gray tone and the inner diameter was completely filled black. The distance from the center of the home position to the bottom of the bottom row of icons was 90 mm for every trial. The icons were arranged in a 3 x 2 matrix. The space between icons was the same distance as the size of the icons used. This configuration allows all icons to be visible to the user on every trial when using a 21" monitor (see Figure 4). See Appendix B for an example screen.

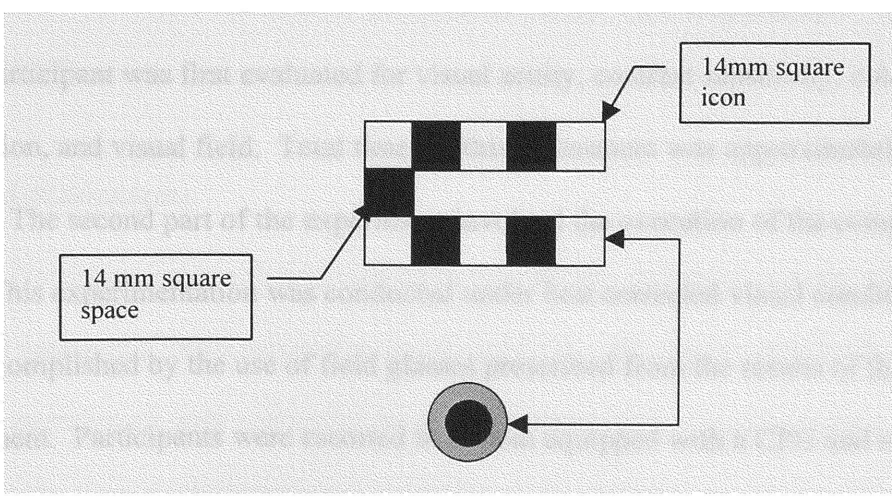


Figure 4: Arrangement of interface icons.

Experimental Design

A 5 x 5 x 5 repeated measures design was utilized to test the hypotheses of this study. Five set sizes of icons, five background colors, and five icon sizes were examined yielding 125 conditions. Each condition was repeated two times resulting in a total of 250 trials per participant. Replication of conditions was necessary for statistical purposes to account for variability within each condition. The dependent variables in the experiment were reaction time, and movement time. The independent variables were set size, background color, icon size, distance from the center of the home position to the center of the target icon, and participants' visual profiles. Other demographics that were collected were years of computer experience, age, and gender.

Procedure

The study was conducted in two parts. In the first part, partially sighted participants' vision was assessed at the Bascom-Palmer Eye Institute, Low Vision Clinic. Each participant was first evaluated for visual acuity, contrast sensitivity, color perception, and visual field. Total time for this assessment was approximately three hours. The second part of the experiment involved the execution of the computer-based tasks. This experimentation was conducted under best corrected visual conditions which was accomplished by the use of field glasses prescribed from the results of the low vision assessment. Participants were escorted to a room equipped with a CPU and monitor. Illumination levels were low during the initial stages, to allow for dark adaptation of the eyes, while the experimenter gathered demographic information about the participant. The lights were then extinguished in the room so that the only source of illumination came from the monitor. The participants then positioned themselves such that the distance from the monitor to their eyes was 20 inches. The mouse was the only input device used by the participants. The first fifty trials were used as practice, which allowed the participants to become familiar with using a mouse. The results of these trials were recorded but were not used in the statistical analyses. Upon completion of the practice trials, the participant rested for 5 minutes before beginning the actual experimentation and data collection. Participants were given the opportunity to discontinue the experiment at any time if they desired. Conditions were blocked by background color. Background color blocks were randomly ordered. After the completion of one color block, participants were given a 5-minute break but were not allowed to leave the room. The estimated duration of the computer-based evaluation was two hours. The same procedure was used for the FSU as was used with the PSU, with the exception that the FSU did not receive clinical visual assessments.

RESULTS

Clinical Assessments

The following is a description of the procedures utilized in scoring visual acuity, contrast sensitivity, color perception and visual field. All assessments for the partially sighted participants were conducted by an ophthalmologist. Upon completion of an optical refraction, participants were tested for acuity, contrast sensitivity, and color perception. Lighting conditions were controlled for each test. Using a Bailey-Lovie chart, located at 4 meters from the eyes of the participant, participants read the letters, beginning from the top row, reading from left to right, and proceeded down until they could no longer decipher the letter. The number of letters correctly identified on each row was recorded. When more than two letters on any given row were incorrectly identified, that row of letters was considered to be the best visual angle that can be perceived. Each row was marked with an equivalent Snellen ratio. This is the reported visual acuity for that participant. The test was first performed on the left eye and then repeated using a chart with different letters for the right eye.

Contrast sensitivity was measured using a Pelli-Robson chart at one meter. As with the Bailey-Lovie chart, participants read letters beginning at the top row, and read from left to right, proceeding down until no other letters could be correctly identified. The contrast sensitivity score was the sum of the correctly identified letters. As before, the left eye was tested first, followed by the right eye, using a chart with different letters.

The Farnsworth D-15 color examination required the participant to arrange a series of fifteen colored blocks in order from darkest to lightest. Each successive colored block was different than the previous, extending through the color spectrum. Each block was numbered. Upon completion of the trial, the number of the block was recorded and the participant was asked to repeat the test. Based upon the participant's ordering of the blocks, their vision could be categorized at normal, protan (red blindness), deutan (green blindness), tritan (blue blindness), color confusion, or normal with minor error.

Visual fields, both binocularly and monocularly, were tested using the Esterman projection perimetry technique (Kline and Schieber, 1985). The Esterman method provides a proficiency score that indicates the portion of the visual field present. The test requires the participant to sit in front of monitor. While the participants looked straight ahead, tiny lights were flashed at various angles away from the central focal point. The participant indicated if the light was perceived by pressing a button. The total duration of the visual field test was approximately 30 minutes. The results of assessments for the PSU participants as well as the self-reported profile scores for the FSU participants are shown in Table 5.

Table 5: Visual profile measurements for PSU and FSU, VFQ near vision scores for PSU, and diagnosis of PSU

	Ss #	Acuity (L)	Acuity (R)	Contrast Sensitivity (L)	Contrast Sensitivity (R)	Visual Field	Color Perception	VFQ Near Vision	Diagnosis
PSU	26	32	50	36	32	15	4	57.14	RP
	29	200	160	32	36	100	5	46.43	Albinism
	30	0	200	0	17	27	2	28.57	Optic Nerve damage
	33	250	200	18	18	13	3	28.57	RP
	44	160	250	32	27	93	5	64.29	High myopia
	49	160	80	32	35	90	5	62.50	cataract
	54	320	250	21	24	71	3	7.14	AMD
	56	50	64	24	15	1	4	28.57	RP
	63	126	160	32	28	100	4	85.71	Congenital achromotopsia
	65	126	126	29	30	100	4	62.50	Congenital achromotopsia
FSU	3	20	20	48	48	100	5		
	59	25	25	48	48	100	5		
	67	20	20	48	48	100	5		
	69	30	30	48	48	100	5		
	71	20	20	48	48	100	5		
	73	30	30	48	48	100	5		
	75	25	25	48	48	100	5		
	77	25	25	48	48	100	5		
	79	25	25	48	48	100	5		
	82	20	20	48	48	100	5		

Analytical Analyses of Results

The aims of this research are to explain sources of variations, as well as explain any sources of consistency in performance produced by declined vision measured across various physical and social factors. For these reasons, a general linear model (GLM) was used that allowed a summary of the wide variety of research outcomes. Analysis of the data was performed using the statistical analysis program, SPSS-PC, version 8.0.

A repeated measures analysis of variance (ANOVA) was employed with one between subjects factor, sight (PSU and FSU), and three within subjects factors, set size, icon size and background color. Each of the within-subjects factors had five levels. Such a design reduces inter-subject variability that otherwise would have resulted in a large error term. Also, factorial ANOVAs require fewer participants than does a simple one-way ANOVA while maintaining the same degree of power (Howell, 1992). However, repeated measures analysis of variance requires not only the usual assumptions of normality and homogeneity of variances, but also must also consider the effects of any losses in sphericity. Therefore, adjustments in the degrees of freedom were made using Greenhouse-Geisser (Howell, 1992).

The effect of a factor is defined as the change in response (RT or MT) produced by a change in the level of the factor. An Analysis of Variance (ANOVA), with adjustments to degrees of freedom using Greenhouse-Geisser, was utilized to determine the effects of the independent variables on RT and MT. When the differences in responses between the levels of one factor are not the same at all levels of the other factors, an interaction between the factors is said to occur. This analysis allows interpretation not only of the effects of each variable individually (main effect) but also any interactive effects that may have occurred between them.

ANOVAs, however, only provide an indication that not all the means are equal. As a result, further analysis of the differences among sets of means is warranted. Hence, post hoc comparisons using pairwise comparisons of means were conducted using Least Significant Differences (LSD) *t*-test.

Given the vast differences from individual to individual, variability in visual capabilities will be expected between PSU and FSU. Attempting to control for this variability, the performance measures, RT and MT, were adjusted by removing the effects of the visual profile parameters of acuity, contrast sensitivity, field of view, and color perception measured for each participant using the analysis of covariance (ANCOVA). This method will be used to analyze Hypotheses 6, 8, 10, 12, 14 and 16. Further attempts to reduce the error term, ε, were made by selecting FSU with the same gender and similar age and level of computer experience as the PSU. In doing so, the ANCOVA model, incorporating these demographics, may reduce differences in the treatment effects. It should be noted that using this approach increases the probability of committing a Type I error across the experiment as a whole (Howell, 1992).

In examining the paradigms described by Sternberg and Fitts, the data were analyzed to express the degree of the relationship between the independent variables and the time to criterion (RT and MT). Data were regressed and correlations between the independent variables and the time to criterion (RT and MT) were determined. All significant values were tested at $\alpha = .05$.

The following discussion of the results will be divided into two sections. The first section will present the results corresponding to the dependent variable, RT. The second section will present the results corresponding to MT. Within each section, results of the ANOVA model will be discussed first, followed by the results of the ANCOVA model, and ending with the results of the regression analysis.

Reaction Time

Initial performance data were analyzed to assess the between subject variable, vision (PSU vs. FSU), which indicated a significant effect due to vision ($F=8.57$, $p \leq .009$). The effects of icon size, set size and background color will be described separately in terms of their influence on RT.

Icon Size

The mean RT data is shown in Table 6. Adjusting the degrees of freedom using Greenhouse-Geisser, ANOVA revealed a significant main effect of icon size, ($F=9.31$, $p \leq .001$). A significant two-way interaction between icon size and vision was also evident, ($F=7.36$, $p \leq .003$.) A post hoc comparison of means for all participants (PSU and FSU) using LSD showed pairwise comparisons of RT were significantly different between all sizes of icons except between 1 and 2 and between 4 and 5. For a summary of these differences and corresponding p-values, see Table 7. When comparing mean RT data for the PSU alone, all levels of icon size were significantly different from each other. There were no significant differences between pairs of means for FSU (see Table 8).

Table 6: Mean reaction times (in ms) for PSU and FSU for each icon size

	Icon Size				
Vision	**1** (9.2 mm)	**2** (14.6 mm)	**3** (23.2 mm)	**4** (36.8 mm)	**5** (58.3 mm)
PSU	322	264	215	189	166
FSU	64	60	58	58	54
Overall (PSU and FSU)	193	162	136	123	110

Table 7: Pairwise comparisons of mean reaction times using LSD t-test across all participants (PSU and FSU) for each icon size, with and without adjustments for covariates

Icon Size (mm)	Compared with icon size (mm)	p-value	p-value after covariate adjustment
1	2	.091	.054
	3	.005*	.001*
	4	.003*	.001*
	5	.002*	.001*
2	1	.091	.054
	3	.014*	.002*
	4	.012*	.002*
	5	.013*	.005*
3	1	.005*	.001*
	2	.014*	.002*
	4	.020*	.010*
	5	.019*	.015*
4	1	.003*	.001*
	2	.012*	.002*
	3	.020*	.010*
	5	.062	.062
5	1	.002*	.001*
	2	.013*	.005*
	3	.019*	.015*
	4	.062	.062

Table 8: Pairwise comparisons of mean reaction times using LSD t-test of icon sizes for each group of participants, PSU and FSU

Sight	Icon Size	Icon Size	p-value	Sight	Icon Size	Icon Size	p-value
PSU	1	2	.031*	FSU	1	2	.860
		3	.001*			3	.804
		4	.001*			4	.818
		5	.001*			5	.750
	2	1	.031*		2	1	.860
		3	.001*			3	.892
		4	.001*			4	.913
		5	.001*			5	.823
	3	1	.001*		3	1	.804
		2	.001*			2	.892
		4	.001*			4	.964
		5	.001*			5	.775
	4	1	.001*		4	1	.818
		2	.001*			2	.913
		3	.001*			3	.964
		5	.026*			5	.693
	5	1	.001*		5	1	.750
		2	.001*			2	.823
		3	.001*			3	.775
		4	.026*			4	.693

Set Size

Mean RT data for set size is shown in Table 9. ANOVA showed a main effect of set size, ($F=5.54$, $p \leq .006$) across all participants, PSU and FSU. There were no interactions with set size that were significant. Table 10 details the results of the pairwise comparisons. Post hoc pairwise comparisons without adjustments for covariates revealed significant differences in mean RT between set size of 2 with 4, 5, and 6. Also set size of 6 was significantly different in mean RT from set sizes of 2, 3, and 4 but not with 5.

Table 9: Mean reaction times (in ms) across all participants for each set size

	Set Size				
	2	3	4	5	6
Overall	132	137	149	149	157

Table 10: Pairwise comparisons of mean reaction times using LSD t-test across all participants (PSU and FSU) for each set size, with and without adjustments for covariates

Set Size	Compared to Set Size	p-value	p-value after covariate adjustment
2	3	0.418	.320
	4	0.015*	.010*
	5	0.012*	.004*
	6	0.003*	.002*
3	2	0.418	.320
	4	0.132	.101
	5	0.075	.072
	6	0.026*	.013*
4	2	0.015*	.010*
	3	0.132	.101
	5	0.939	.853
	6	0.017*	.022*
5	2	0.012*	.004*
	3	0.075	.072
	4	0.939	.853
	6	0.065	.017*
6	2	0.003*	.002*
	3	0.026*	.013*
	4	0.017*	.022*
	5	0.065	.017*

Background Color

ANOVA indicated that there were no differences in mean reaction time across all participants under any of the five background color combinations ($F=.32$, $p\leq .852$).

There was also no interactive effect between background color and vision ($F=.15$, $p \leq .959$).

ANCOVA

A repeated measures ANCOVA of RT on vision, set size, background color and icon size was performed with the visual profile measurements of acuity, contrast sensitivity, visual field and color perception as covariates. The between subjects effect of vision was still significant after covariate adjustments ($F= 5.18$, $p\leq .001$). The covariates of contrast sensitivity ($F= 19.47$, $p\leq .001$), visual field ($F= 14.49$, $p\leq .002$) and color perception ($F= 17.14$, $p\leq .001$) were significant in predicting RT. Acuity was only marginally significant ($F= 3.07$, $p\leq .103$). Therefore, a second ANCOVA was performed omitting acuity as a covariate. After this analysis, the effect of vision was no longer significant ($F=3.83$, $p\leq .069$). However, the three covariates remained significant, contrast sensitivity ($F=14.55$, $p\leq .002$), visual field ($F=10.05$, $p\leq .006$), and color perception ($F=14.02$, $p\leq .002$).

Icon Size

Mean RT data after covariate adjustment is shown in Figure 5. The effects of icon size ($F=7.88$, $p\leq .001$) and the two-way interaction of vision with icon size ($F=12.05$, $p\leq .001$) remained significant after the covariate adjustment. The two-way interaction indicates that there exist differences in mean reaction time between PSU and FSU on at least two levels of icon size. Given this information, there is no direct indication to support Hypothesis 6 which states that PSU and FSU will perform equally as well under differing levels of icon sizes. However, further analysis using post hoc pairwise comparisons using LSD (adjusting for covariates) were examined and are presented in conjunction with the ANOVA results in Table 7. Pairwise comparisons of icon size revealed comparable results to the results of the pairwise comparisons without the covariate adjustments.

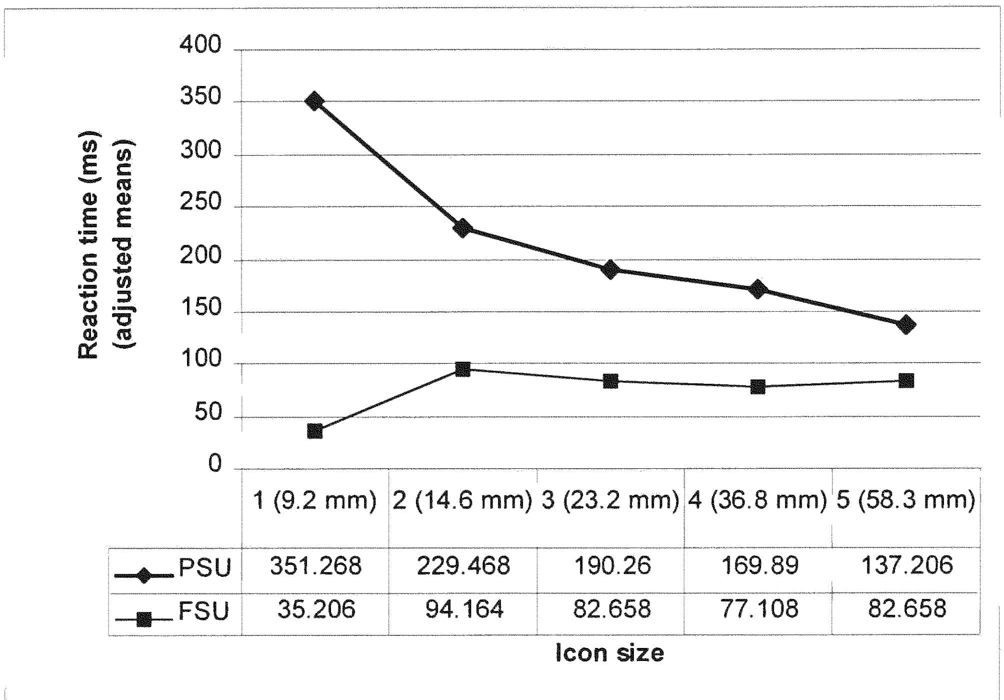


Figure 5: Mean reaction time vs. icon size (after covariate adjustment)

Set Size

The main effect of set size failed to indicate any differences (F=1.15, p≤ .331) in mean reaction time after covariate adjustment. However, after covariate adjustment, set size by vision (F=3.50, p≤ .043) and icon size by set size (F= 3.05, p≤ .029) were significant in indicating differences in mean reaction times.

Comparing the adjusted mean RT across all participants for the five levels of set size also indicated results comparable to the results of the pairwise comparisons without the covariate adjustments with one exception, the mean RT for set size 5 and 6 are significantly different when adjusting for the covariates (see Table 10).

Background Color

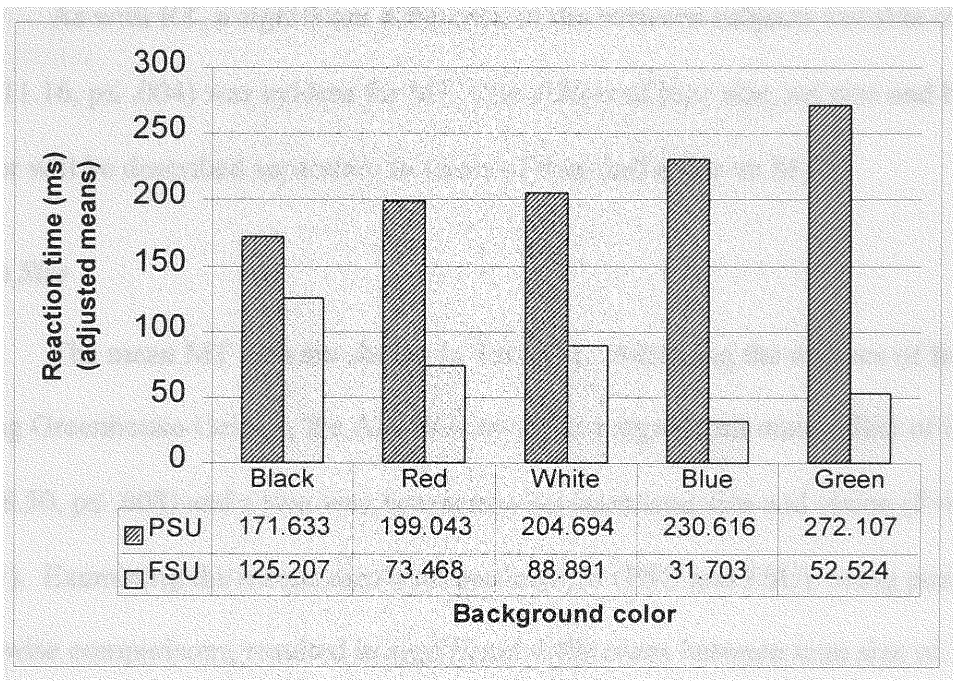


Figure 6: Mean reaction time vs. background color (after covariate adjustment)

Mean reaction time data after covariate adjustment is displayed in Figure 6. Several two-way interactions and a three-way interaction became significant: background color by vision ($F=5.12$, $p\leq .017$), background color by icon size ($F=4.43$, $p\leq .018$), and background color by set size by vision ($F=3.12$, $p\leq .028$). The interaction between background color and vision suggests that at least one pair of mean RTs for background color and vision differ from the rest. Therefore, PSU and FSU do behave differently under different enhanced contrast conditions, therefore not supporting Hypothesis 10. There were no differences in mean performance under enlarged conditions with enhanced contrast, after covariate adjustment, between PSU and FSU ($F=2.30$, $p \leq .114$) which supported Hypothesis 14.

Movement Time

As with RT, a significant difference in the between subjects variable of vision ($F=11.16$, $p \leq .004$) was evident for MT. The effects of icon size, set size and background color will be described separately in terms of their influence on MT.

Icon Size

The mean MT data are shown in Table 11. Adjusting the degrees of freedom using Greenhouse-Geisser, the ANOVA revealed a significant main effect of icon size, ($F=8.50$, $p \leq .008$) and a two-way interaction between icon size and vision ($F=6.10$, $p \leq .021$). Examining the means across all participants (PSU and FSU), using post hoc pairwise comparisons, resulted in significant differences between icon size of 1 with 2, 3, 4, and 5. Also, icon size of 2 was significantly different than 3, 4 and 5. Table 12 describes these differences and the levels of significance. The same differences were obtained when evaluating the means separately over PSU alone (see Table 13). However, comparing means among FSU indicated no differences.

Table 11: Mean movement times (in ms) for PSU and FSU for each icon size

Vision	Icon Size				
	1 (9.2 mm)	2 (14.6 mm)	3 (23.2 mm)	4 (36.8 mm)	5 (58.3 mm)
PSU	438	260	219	224	208
FSU	112	101	97	91	91
Overall	275	181	158	158	150

Table 12: Pairwise comparisons of mean movement times using LSD t-test across all participants (PSU and FSU) for each icon size, with and without adjustments for covariates

Icon Size	Icon Size	p-value	p-value after covariate adjustment
1	2	.013*	.001*
	3	.007*	.001*
	4	.007*	.001*
	5	.001*	.001*
2	1	.013*	.001*
	3	.001*	.001*
	4	.006*	.001*
	5	.005*	.001*
3	1	.007*	.001*
	2	.001*	.001*
	4	.967	.968
	5	.187	.049
4	1	.007*	.001*
	2	.006*	.003*
	3	.967	.968
	5	.293	.135
5	1	.010*	.001*
	2	.005*	.001*
	3	.187	.049
	4	.293	.135

Table 13: Pairwise comparisons of mean movement times using LSD t-test of icon sizes for each group of participants, PSU and FSU

Vision	Icon Size	Icon Size	p-value	Vision	Icon Size	Icon Size	p-value
PSU	1	2	.002*	FSU	1	2	.837
		3	.001*			3	.796
		4	.001*			4	.711
		5	.001*			5	.737
	2	1	.002*		2	1	.837
		3	.001*			3	.612
		4	.003*			4	.323
		5	.002*			5	.449
	3	1	.001*		3	1	.796
		2	.001*			2	.612
		4	.579			4	.540
		5	.249			5	.466
	4	1	.001*		4	1	.711
		2	.003*			2	.323
		3	.579			3	.540
		5	.150			5	.979
	5	1	.001*		5	1	.737
		2	.002*			2	.449
		3	.249			3	.466
		4	.150			4	.979

Set Size

Table 14 shows the mean MT data. The ANOVA revealed a main effect of set size ($F=5.34$, $p \leq .005$) and a two-way interaction between set size and vision ($F=3.29$, $p \leq .037$). Post hoc pairwise comparison of means across all participants (PSU and FSU), shown in Table 15, indicated significant differences between set size of 2 with 3, 4, 5, and 6. No other differences were evident. When comparing means within PSU, differences were obtained between set size of 2 with 3, 4, 5, and 6 (see Table 16). Also, mean MT was significantly different between set sizes 5 and 6. There were no differences between mean MT for any pairs of set sizes for FSU.

Table 14: Mean movement times (in ms) for PSU and FSU for each set size

	Set Size				
Vision	**2**	**3**	**4**	**5**	**6**
PSU	237.58	272.928	272.998	272.714	292.376
FSU	95.036	95.418	99.332	100.338	102.128
Overall (PSU and FSU)	166.308	184.173	186.165	186.526	197.252

Table 15: Pairwise comparisons of mean movement times using LSD t-test across all participants (PSU and FSU) for each set size

Set Size	Set Size	p-value
2	3	.015*
	4	.001*
	5	.004*
	6	.008*
3	2	.015*
	4	.727
	5	.696
	6	.095
4	2	.010*
	3	.727
	5	.948
	6	.141
5	2	.004*
	3	.696
	4	.948
	6	.067
6	2	.008*
	3	.095
	4	.141
	5	.067

Table 16: Pairwise comparison of mean movement times using LSD t-test of set size for each group of participants, PSU and FSU

Sight	Set Size	Set Size	p-value	Sight	Set Size	Set Size	p-value
PSU	2	3	0.001*	FSU	2	3	0.968
		4	0.002*			4	0.665
		5	0.001*			5	0.544
		6	0.001*			6	0.632
	3	2	0.001*		3	2	0.968
		4	0.993			4	0.628
		5	0.980			5	0.565
		6	0.800			6	0.530
	4	2	0.002*		4	2	0.665
		3	0.993			3	0.628
		5	0.971			5	0.897
		6	0.073			6	0.787
	5	2	0.001*		5	2	0.544
		3	0.980			3	0.565
		4	0.971			4	0.897
		6	0.021*			6	0.820
	6	2	0.001*		6	2	0.632
		3	0.080			3	0.530
		4	0.073			4	0.787
		5	0.021*			5	0.820

Background Color

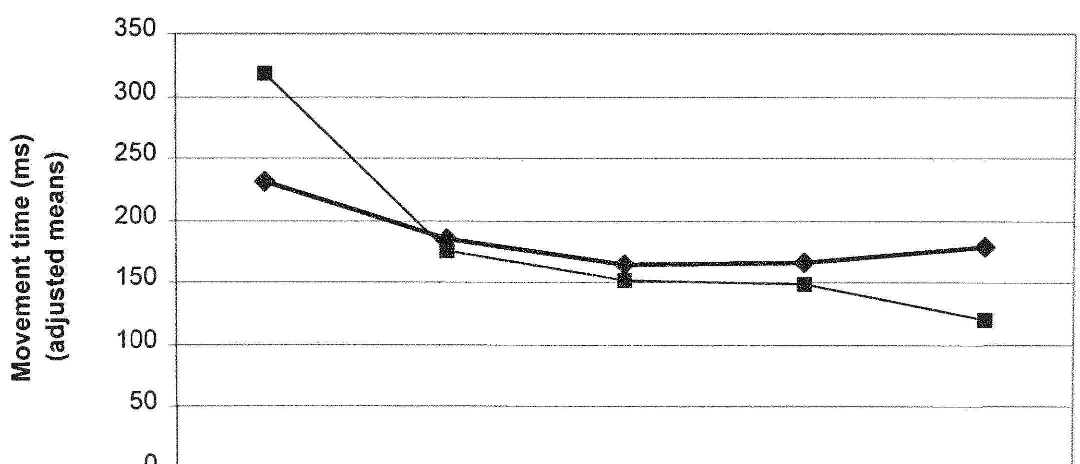
The main effect of color ($F= 1.54$, $p \leq .200$) and the two-way interaction between background color and vision ($F= .81$, $p \leq .520$) were not significant in the ANOVA.

ANCOVA

Similar to RT, a repeated measure ANCOVA on MT was performed. However, acuity was the only covariate that was significant. After executing the second ANCOVA with acuity as the only covariate, acuity remained as a significant covariate in predicting MT ($F=11.41$, $p \leq .004$).

Icon Size

Mean reaction time data after covariate adjustment is shown in Figure 7 below. After covariate adjustment, icon size remained marginally significant ($F=4.08$, $p \leq .053$). The two-way interaction between icon size and vision was no longer significant ($F=1.99$, $p \leq .174$). After adjusting for vision using ANCOVA, there is an indication that PSU and FSU movement time performances are not different within a GUI environment utilizing enlarged icons (see Hypothesis 8). Further, combining the effects of background color and icon size failed to produce any significant differences in performance between PSU and FSU ($F= 1.53$, $p \leq .220$) (see Hypothesis 16).



	1 (9.2 mm)	2 (14.6 mm)	3 (23.2 mm)	4 (36.8 mm)	5 (58.3 mm)
PSU	231.43	185.046	164.358	165.914	178.983
FSU	318.552	175.986	151.442	149.29	119.847

Icon size

Figure 7: Mean movement time vs. icon size (after covariate adjustment).

Post hoc pairwise comparison, detailed in Table 12, of the adjusted means for icon size revealed comparable results to the results of the pairwise comparisons without the covariate adjustments.

Set Size

Set size failed to indicate any influence on MT across all participants (F= 1.04, p≤ .377). There were no interactive effects between set size and vision (F= .47, p≤ .677).

Background Color

Mean movement time data after covariate adjustment is shown in Figure 8 below. There is also not enough evidence to suggest that background color (F= 1.33, p≤ .223) is a strong effect to produce differences in performance between PSU and FSU (see Hypothesis 12). Adjusting for acuity, a strong predictor of vision (F=11.41, p≤ .004), could be the reason why these interactions were no longer significant.

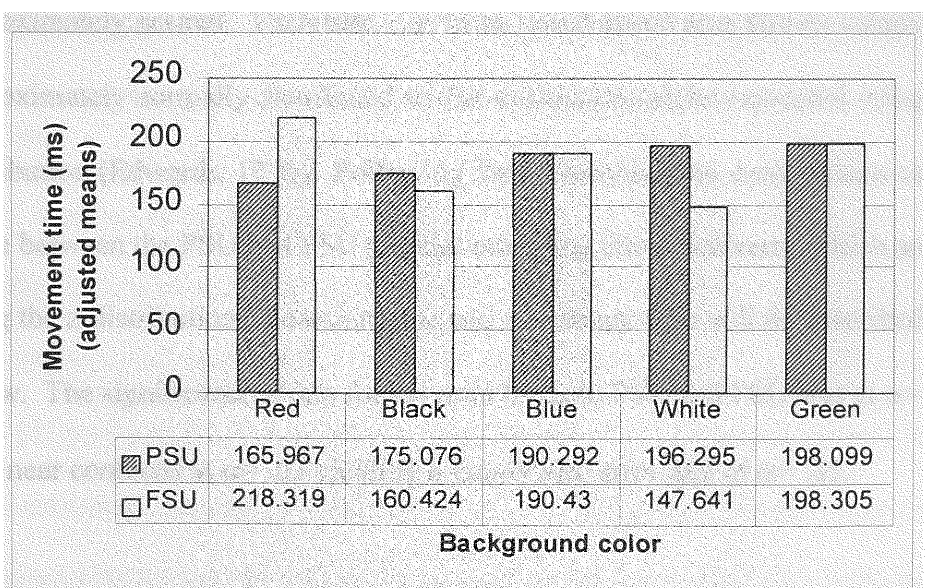


Figure 8: Mean movement time vs. background color (after covariate adjustment)

Regression Analysis

It is of interest to determine if certain treatment and response variables are correlated, as is the case with Sternberg's paradigm and Fitts' Law. In other words, as the stimuli change (set size, ID), does the time to criterion also change? And if so, does it increase at a constant rate? Furthermore, to what extent do PSU differ from FSU? These questions can be answered through regression analysis.

First, it is important to determine if PSU (and FSU), as a population, behave equally. By hypothesizing that b_0 and b_1 (y-intercept and slope, respectively) vary significantly from participant to participant (with the intent of failing to reject the null hypothesis that they are equal), a formal examination can proceed. One could use a weighted analysis in a MANOVA, however, since there is only one predictor variable (set size), analysis of the correlation coefficient, r, can be used instead. But in cases when $\rho \neq 0$ (population correlation coefficient estimated by r), the distribution of r is not approximately normal. Therefore, r must be transformed such that its values are approximately normally distributed so that evaluation can be expressed using the χ^2 distribution (Edwards, 1976). Following these examinations, comparisons can then be made between the PSU and FSU populations using linear contrasts, which are compared using the z-distribution. Reaction time and movement time will be described separately below. The significance levels for the tests for both PSU and FSU was at $\alpha = .01$ and for the linear contrasts at $\alpha = .03$ yielding a familywise error rate of $\alpha = .05$.

Reaction Time

Correlations were determined for each participant using set size and RT and are summarized in Table 17 below. It should be noted that several participants' performance were well defined by the set size-RT relationship. Measuring across the conditions of background color and icon size, three out of ten PSU and three out of ten FSU performances of RT to set size were significant at an $\alpha = .1$. Upon evaluating each group, there was enough evidence to indicate that at least one pair of correlation coefficients differed within the PSU group ($\chi^2 = 1203.12$; $p \leq .01$). This indicates that, as a group, PSU, performed differently. This was due to the large variability in performance between each participant in the PSU group. However, similar results were indicated by FSU ($\chi^2 = 1761.54$; $p \leq .001$).

Further analysis is warranted to describe the effects that icon size and background color play on RT. Similar analysis was performed as above, the results of which are described below.

Icon Size

Regression analysis measuring across all five levels of background colors provided information regarding the set size reaction time performance of all participants using the five different icon sizes. These results are shown in Table 18 below. Both PSU and FSU performed as hypothesized when subjected to various icon sizes (see Hypothesis 5). Furthermore, analysis between the PSU and FSU groups did not suggest any differences between groups thus supporting Hypothesis 5a) and 5b) which states that the slope and the y-intercept of the set size-RT line would not be significantly greater for PSU than for FSU (see Table 19).

Table 17: Summary of correlation between RT and set size for each participant (n=5000)

Vision	Partici-pant #		Coefficients	p value	r	Vision	Partici-pant #		Coefficients	p value	r
PSU	26	b0	370.696	.001		FSU	3	b0	44.092	.001	
		b1	-0.42	.877	-0.096			b1	1.194	.171	0.719
	29	b0	60.408	.075			59	b0	60.732	.005	
		b1	14.494	.072*	0.844			b1	14.864	.004*	0.976
	30	b0	157.24	.002			67	b0	43.032	.001	
		b1	23.678	.009*	0.962			b1	1.608	.070*	0.847
	33	b0	301.432	.011			69	b0	56.596	.001	
		b1	13.952	.355	0.533			b1	0.642	.533	0.376
	44	b0	111.564	.019			71	b0	62.62	.001	
		b1	3.554	.575	0.341			b1	-1.124	.142	-0.753
	49	b0	71.92	.088			73	b0	54.188	.001	
		b1	17.012	.087	0.823			b1	2.162	.068*	0.85
	54	b0	544.984	.002			75	b0	38.248	.019	
		b1	26.936	.129	0.769			b1	3.712	.153	0.739
	56	b0	206.64	.002			77	b0	48.984	.006	
		b1	-5.582	.355	-0.533			b1	-0.066	.971	-0.023
	63	b0	42.916	.003			79	b0	50.092	.001	
		b1	2.772	.082*	0.829			b1	-0.104	.816	-0.145
	65	b0	42.6	.031			82	b0	33.092	.001	
		b1	4.224	.202	0.685			b1	0.916	.209	0.677

Table 18: Comparisons of the set size-RT relationship for all participants for each of the five levels of icon sizes

Icon Size	Correlation Coefficient	*t*- statistic	p-value
1	.062	1.964	.050*
2	.039	1.223	.222
3	.056	1.781	.075
4	.063	2.006	.045*
5	-.016	-.516	.606

Table 19: Comparisons of the set size-reaction relationship between PSU and FSU for each of the five levels of icon size

Icon Size	z-statistic	p-value
1	-0.386	0.704
2	0.964	0.337
3	1.170	0.242
4	0.501	0.617
5	-1.090	0.271

Background Color

For the five levels of background color, correlation coefficients were calculated across each participant and levels of icon sizes and are presented in Table 20 below. Enhancing the contrast of the icons through the use of the background colors of white or red appeared to provide a setting such that users' performance would be linearly related to set size. It was predicted that contrast enhancement would result in this linear relationship (see Hypothesis 9). Performance between both groups was expected to not be different in the enhanced GUI environment, which was evident by the results given in Table 21 below (see Hypotheses 9 a) and 9 b)).

Table 20: Comparisons of the set size-RT relationship for all participants for each of the five levels of background colors

Background Color	Correlation Coefficient	*t*-statistic	p-value
Black	.051	1.604	.109
White	.056	1.763	.078*
Red	.069	2.179	.030*
Green	.001	.022	.982
Blue	.050	1.593	.112

Table 21: Comparisons of the set size-RT relationship between PSU and FSU for each of the five levels of background color

Background color	z-statistic	p-value
Black	0.202	0.841
White	0.452	0.653
Red	0.806	0.424
Green	-1.410	0.159
Blue	0.739	0.459

Icon Size/Background Color

Finally, assessments were ascertained regarding performance in a magnified environment using enhanced contrasts. Again, the set size-reaction time relationships were calculated using correlations indicating a linear relationship ($r=.043$, $t=3.069$, $p\leq .002$) thus supporting Hypothesis 13. Differences in performance between the two participant groups were evident ($z=3.140$, $p\leq .003$) which did not support Hypotheses 13 a) and 13 b), yet yielded an interesting significant finding.

Movement Time

Data were correlated per participant using ID and MT and are summarized in Table 23 below. ID was calculated by the following equation:

$$ID = \log_2((A+W)/W);$$

A= distance from the center of the start position to the center of the icon

W= width of the target icon

As with RT, the z-transformation indicated that there was enough evidence to indicate that at least two of the six correlation coefficients differed, thus rejecting the null hypothesis that all PSU behaved equally ($\chi^2 = 24.55$, $p \leq .001$). The same was true for FSU ($\chi^2 = 37.14$, $p \leq .001$). Also, the mean movement time was again more highly correlated with ID for PSU than for FSU. This is evident by noting that the data was well defined by a linear function for nine of the ten PSU and seven of the ten FSU as shown in Table 22 below.

Table 22: Summary of correlation between MT and ID for each participant (n=5000)

Vision	Parti-cipant #		Coeffi-cients	p-value	r	Vision	Parti-cipant #		Coeffi-cients	p-value	r
PSU	26	b0	171.931	.001		FSU	3	b0	46.22	.001	
		b1	81.646	.001*	.211			b1	25.105	.001*	.383
	29	b0	-43.981	.314			59	b0	61.1	.252	
		b1	201.646	.001*	.324			b1	128.583	.003*	.187
	30	b0	-111.182	.290			67	b0	58.414	.001	
		b1	394.948	.001*	.263			b1	9.697	.048*	.125
	33	b0	139.736	.247			69	b0	87.299	.001	
		b1	286.429	.002*	.196			b1	10.354	.041*	.130
	44	b0	71.822	.044			71	b0	60.202	.001	
		b1	122.407	.001*	.27			b1	10.379	.212	.079
	49	b0	98.061	.001			73	b0	79.411	.001	
		b1	52.293	.001*	.238			b1	8.491	.144	.093
	54	b0	-604.774	.001			75	b0	61.741	.001	
		b1	900.198	.001*	.491			b1	16.863	.024*	.142
	56	b0	193.542	.001			77	b0	61.376	.001	
		b1	8.379	.715	.023			b1	15.511	.243	.074
	63	b0	43.794	.063			79	b0	88.148	.001	
		b1	76.082	.001*	.248			b1	16.209	.001*	.261
	65	b0	17.451	.276			82	b0	51.385	.001	
		b1	66.611	.001*	.323			b1	25.795	.001*	.253

Icon Size

Regression analysis was performed to determine if enlarging the target stimuli resulted in linear relationships between ID and MT. It was predicted that users' performance could be described linearly as a function of MT and ID, which was evident at icon size of 36.8 mm (icon size 4) ($r=.090$, $t=2.855$, $p \leq .004$). There were no significant differences in the linear function between PSU and FSU at an enlargement of 58.3 mm (icon size 5) ($z = -3.21$, $p \leq .012$). This suggests that at enlargements of 58.3 mm, PSU performed no differently than FSU.

Background Color

Performance under enhanced contrast conditions does not appear to provide any significant differences in users' performance (see Table 23) resulting in well fitted ID-MT lines at every level of background color. These results supported the hypothesis that contrast enhanced desktop environments would yield linear relationships between ID and MT, regardless of the degree of one's visual impairment.

There were no significant differences in the linear functions between PSU and FSU under the white and green contrast conditions (see Table 24 below).

Table 23: Comparisons of the ID-MT relationship for all participants for each of the five levels of background colors

Background Color	Correlation Coefficient	*t*-statistic	p-value
Black	.208	6.729	.001*
White	.101	3.205	.001*
Red	.170	5.446	.001*
Green	.154	4.936	.001*
Blue	.157	5.024	.001*

Table 24: Comparisons of the ID-MT relationship between PSU and FSU for each of the five levels of background color

Background color	z-statistic	p-value
Black	1.801	0.072*
White	0.041	0.968
Red	1.962	0.050*
Green	0.471	0.638
Blue	2.674	0.008*

Icon Size/ Background Color

Under the combined enhancements of icon enlargement and contrast enhancement, the ID-MT relationship was well fitted ($R=.156$, $t=11.138$, $p\leq .001$). Furthermore, across all levels of icon size and background colors, PSU performance did not approach that of the FSU as indicated by the differences in the slope of the line ($z= 3.020$, $p\leq .003$).

Discussion and Conclusion

General Discussions

The visual abilities of the participants in this study varied considerably. Due to this large variability as well as the small number of participants, caution should be heeded when interpreting these results. However, trends in performance were evident for certain visual profiles. These will be discussed in the following sections.

By using ANCOVA, any variability associated with losses in vision was removed and differences in performance between PSU and FSU were re-examined. However, the results of the ANCOVA only indicate that differences exist. Further analysis with post hoc pairwise comparisons was used to determine under what conditions these differences were evident. This technique used to analyze the data allowed us to examine a variety of variables and their effects on user performance.

Furthermore, this research studied the application of two experimental psychology theories to the domain of human-computer interaction. Sternberg's paradigm and Fitts' Law were examined within a graphical user interface (GUI) environment under four conditions:

- a standard desktop environment using the default icon size of 9.2 mm with a white background,
- an enlarged desktop environment with icons ranging in size from 9.2 mm to 56.8 mm,
- a desktop environment with five levels of contrast provided by the use of five background colors, and
- a hybrid environment utilizing both enlargement and contrast enhancement.

The experimental manipulations of two variables, enlargement and contrast, each with five levels yielded 24 different enhanced interfaces. Both Sternberg's paradigm and Fitts' Law describe linear relationships between two factors, latency in response and a controlled variable. A discussion of the results of the analysis for each of the four conditions follows.

<u>Assessment of task performance in a standard desktop environment</u>

Refer to Table 25 for a summary of the results of this section. The standard desktop condition was defined as having icons 9.2 mm in size displayed against a white background. An increase in the number of icons present on the screen showed an increase in visual search time. This was apparent when analyzing across all participants, regardless of their visual impairment. Performance differences were also shown in movement time. Though these findings were to be expected, it was necessary to study the performance of users in a standard desktop environment in order to establish a baseline from which to compare.

Assessment of task performance in an enlarged environment

Refer to Table 26 for a summary of the results of this section. From Figure 5, it can be seen that as the size of the icon increases, the time to visually search the targets decreases for PSU. Moreover, once the variability due to vision was removed using ANCOVA, PSU and FSU do not perform significantly differently with icons that are 36.8 mm and 58.3 mm wide. These results appear to indicate that increasing the dimension of the target stimuli enhances the ability for PSU to properly identify objects within a GUI. There also appears to be a convergence of performance in movement time between PSU and FSU as the size of the icon increases (see Figure 7). No significant differences in mean movement between PSU and FSU were evident for icons of size 23.2, 36.8, and 58.3 mm.

Assessment of task performance in an environment with enhanced contrast

Refer to Table 27 for a summary of the results of this section. During identification tasks, PSU performed best with black and red backgrounds and the slowest with green and blue. This could be explained by the fact that five of the ten PSU participants had disorders of the rod photoreceptors of the retina. The rods are sensitive to the high frequency colors of green and blue, hence the poor performance associated with these colors.

Furthermore, it appears that color plays a significant role in accommodating users with declined vision in performing selection tasks. Significantly parallel RT-set size lines at all levels of background colors confirmed this result. Similarly, overall users' performances on selection tasks were well described by a linear relationship between ID and MT at all levels of background color. Again, black and red background colors tended to enable PSU to perform the best while selecting icons. This trend in red and black backgrounds is of interest and warrants further investigation.

Assessment of task performance in a magnified environment with enhanced contrast

Refer to Table 28 for a summary of the results of this section. After removing the effects of vision using ANCOVA, the combined use of color and magnification (icon size) supported the prediction that PSU and FSU performance on selection and identification tasks do not differ and can be described by Sternberg's paradigm and Fitts' Law respectively. However, the reader is cautioned on generalizing these results. Due to the small sample size, the few number of trials, as well as the inherent weakness of the ANCOVA makes these results difficult to interpret. However, it would be of great interest to dissect these results further to determine best performance using enlargement combined with contrast enhancement. Further research to include more participants and more trials per participant is needed to make these generalizations possible.

Table 25: Summary of the assessment of task performance in a standard desktop environment

#	Hypotheses statement	Statistic	p-value	Supported
1	In a standard desktop environment, set size and reaction time will be related linearly regardless of the degree of one's visual impairment.	r=.858, t=2.897 (n=200)	.062	Marginally supported
2	In a standard desktop environment, the reaction time (RT) for partially sighted users (PSU) and fully sighted users (FSU) will be significantly different given the same interface which will be indicated by differences in the y- intercept of the set size - reaction time line.	z=-0.592	.549	Not supported
3	In a standard desktop environment, movement distance (A), object size (W) and movement time (MT) will be described by Fitts Law regardless of the degree of one's visual impairment.	r=.178, t=1.268 (n=200)	.210	Not supported
4	In a standard desktop environment, the movement time (MT) for partially sighted users (PSU) and fully sighted users (FSU) are significantly different given the same interface.	PSU mean 258.184 FSU mean 235.626	p> .05	Not supported
4 a)	The slope of the movement distance, object size and MT line will be significantly greater for PSU compared to FSU.	z=-1.421	.1556	Not supported

Table 26: Summary of the assessment of task performance in an enlarged environment

#	Hypotheses statement		Statistic	p-value	Supported
5	In an enlarged desktop environment, set size and reaction time will be related linearly regardless of the degree of one's visual impairment.	Icon size 1	r=.062, t=1.964	.050	Supported
		Icon size 2	r= .039, t=1.223	.222	Not supported
		Icon size 3	r= .056, t=1.781	.075	Not supported
		Icon size 4	r= .063, t=2.006	.045	Supported
		Icon size 5	r= -.016, t= -.516	.606	Not supported
5 a)	The slope of the set size-reaction time (SS-RT) line will not be significantly greater for PSU compared to FSU.	Icon size 1	z=-.386	.704	Supported
		Icon size 2	z= .964	.337	Supported
		Icon size 3	z= 1.170	.242	Supported
		Icon size 4	z= .501	.617	Supported
		Icon size 5	z= -1.090	.271	Supported
5 b)	The intercept of the SS-RT line will not be significantly greater for PSU compared to FSU.	Same as 5a)			
6	In an enlarged desktop environment, the reaction time (RT) for partially sighted users (PSU) and fully sighted users (FSU) will not be significantly different given the same interface.		Icon Size By Vision ANCOVA: F=12.05	.001	Not supported
7	In a enlarged desktop environment, movement distance (A), object size (W) and movement time (MT) will be described by Fitts Law regardless of the degree of one's visual impairment.	Icon size 1	r=-.041, t=-1.301	.193	Not supported
		Icon size 2	r= .014, t=.431	.667	Not supported
		Icon size 3	r= .043, t=1.364	.173	Not supported
		Icon size 4	r=.090, t=2.855	.004	Supported
		Icon size 5	r=.032, t=1.003	.316	Not supported
7 a)	The slope of the object distance, object size and MT line will not be significantly greater for PSU compared to FSU.	Icon size 1	z= -.858	.395	Supported
		Icon size 2	z= -.900	.368	Supported
		Icon size 3	z= -.972	.332	Supported
		Icon size 4	z= -1.105	.312	Supported
		Icon size 5	z= -3.207	.012	Not supported
7 b)	The intercept of the object distance, object size and MT will not be significantly greater for PSU compared to FSU.	Same as 7a)			
8	In an enlarged desktop environment, the movement time (MT) for partially sighted users (PSU) and fully sighted users (FSU) are not significantly different given the same interface.		Icon Size By Vision ANCOVA F= 1.99	.174	Supported

Table 27: Summary of the assessment of task performance in an environment with enhanced contrast

#	Hypotheses statement		Statistic	p-value	Supported
9	In a contrast-enhanced desktop environment, set size and reaction time will be related linearly regardless of the degree of one's visual impairment.	Color 1	r=.051, t=1.604	.109	Not supported
		Color 2	r=.056, t=1.763	.078	Supported
		Color 3	r=.069, t=2.179	.030	Supported
		Color 4	r=.001, t=.022	.982	Not supported
		Color 5	r=.050, t=1.593	.112	Not supported
9 a)	The slope of the set size-reaction time line will not be significantly greater for PSU compared to FSU.	Color 1	z= .202	.841	Supported
		Color 2	z= ..452	.653	Supported
		Color 3	z= ..806	.424	Supported
		Color 4	z= .-1.410	.159	Supported
		Color 5	z= .739	.459.	Supported
9 b)	The intercept of the SS-RT line will not be significantly greater for PSU compared to FSU.	Same as 9 b)			
10	In a contrast-enhanced desktop environment, the reaction time (RT) for partially sighted users (PSU) and fully sighted users (FSU) are not significantly different given the same interface.		Color By Vision ANCOVA F= 5.12	.017	Not supported
11	In a contrast-enhanced desktop environment, object distance, object size and MT will relate linearly regardless of the degree of one's visual impairment.	Color 1	r=.208, t=6.729	.001	Supported
		Color 2	r=.101, t=3.205	.001	Supported
		Color 3	r=.170, t=5.446	.001	Supported
		Color 4	r=.154, 4.936	.001	Supported
		Color 5	r=.157, t= 5.024	.001	Supported
11 a)	The slope of the object distance, object size and MT line will not be significantly greater for PSU compared to FSU.	Color 1	z=1.801	.072	Not supported
		Color 2	z=.041	.968	Supported
		Color 3	z=1.962	.050	Not supported
		Color 4	z=.471	.638	Supported
		Color 5	z=2.674	.008	Not supported
11 b)	The intercept of the object distance, object size and MT will not be significantly greater for PSU compared to FSU.	Same as 11b)			
12	In a contrast-enhanced desktop environment, the movement time (MT) for partially sighted users (PSU) and fully sighted users (FSU) are not significantly different given the same interface.		Color By Vision ANCOVA F= 1.33	.223	Supported

Table 28: Summary of the assessment of task performance in a magnified environment with enhanced contrast

#	Hypotheses statement		Statistic	p-value	Supported
13	In an enlarged desktop environment with enhanced contrast, set size and reaction time will relate linearly regardless of the degree of one's visual impairment.		r=.043, t=3.069	.002	Supported
13 a)	The slope of the set size-reaction time (SS-RT) line will not be significantly greater for PSU compared to FSU.		z= 3.140	.003	Not Supported
13 b)	The intercept of the SS-RT line will not be significantly greater for PSU compared to FSU.		same as 13a)		
14	In an enlarged desktop environment with enhanced contrast, the reaction time (RT) for partially sighted users (PSU) and fully sighted users (FSU) are not significantly different given the same interface.		Color By Icon Size By Vision ANCOVA F= 2.30	.114	Supported
15	In an enlarged desktop environment with enhanced contrast, object distance, object size and MT will relate linearly regardless of the degree of one's visual impairment.		r=.156, t=11.138	.001	Supported
15 a)	The slope of the object distance, object size and MT line will not be significantly greater for PSU compared to FSU.		z= 3.020	.003	Not supported
15 b)	The intercept of the object distance, object size and MT will not be significantly greater for PSU compared to FSU.		same as 15a)		
16	In an enlarged desktop environment with enhanced contrast, the movement time (MT) for partially sighted users (PSU) and fully sighted users (FSU) are not significantly different given the same interface.		Color By Icon Size By Vision ANCOVA F= 1.53	.220	Supported

Conclusions

Theories of information processing and psychomotor movement have been used to model many aspects of human behavior. These predictive mechanisms ultimately allow engineers and designers to develop products that are more easily accepted by their intended users. Computer usage today is growing at an alarming rate. Because of this, an opportunity exists for theories of human behavior to be also examined in this new environment that is changing the way in which we work.

Many of the interfaces provided by the new software available today has moved from using complex syntax and long strings of commands to the favored WIMP (Window, Icon, Menu, Pointing device) interface. The icon allows users the flexibility of quick and easy application of actions with a simple mouse click. This process implies that the user must search through a series of icons and make comparisons with a memorized set of icons until the appropriate one is located.

Previous studies have measured the mental processes involved in the recognition of characters (i.e. letters of the alphabet, numbers) and geometric figures. The results of these studies tended to follow the memory-scanning model presented by Sternberg (1967). In his Additive Factors Model, Sternberg proposed that information processing could be divided into stages. This method provided an indication of how many stages exist and the duration of each stage. Since information transfer with computers is predominately visual in nature, visual perception of the computer interface would be the first stage within the information-processing model involved in computer tasks. Utilizing Sternberg's Additive Factors Model, the duration of the mental processes involved in the visual perception of bitmapped stimuli such as those encountered in a GUI environment can be determined.

Furthering Sternberg's Additive Factors Model to instances of declinations in the human visual system was of interest in this study. Given the mental processes involved in information transfer, one would expect increased latencies only in the visual perceptual stage of the information-processing model for individuals with declined vision. Evidence was found in this study to support this. Further findings of this study conclude that under certain conditions, the memory scanning techniques of computer users can be predicted with Sternberg's Additive Factors Model. Furthermore, the visual system does not affect any of the other stages within the information-processing model other than the perceptual stage. Parallel RT-set size lines within certain conditions indicated this. These findings are useful to future research in extending the theory set forth by Sternberg into the realm of human-computer interaction.

Fitts' Law is a reliable means of predicting human motor movement. This model has proven to be robust in a variety of studies within kinematics, human factors and human-computer interaction (HCI). Previous adaptations of Fitt's Law in HCI have shown that motor movements using a mouse to select textual information can be described by the linear relationship between the index of difficulty and movement time. This study has furthered previous research by utilizing current applications of the graphical user interface. Bitmapped metaphoric representations of actions depicted by icons were used as targets within this study. The index of difficulty, defined as a function of the distance to the icon and the width of the icon, was shown to be a strong predictor of the time it takes to physically select the icon using a mouse. This model of psychomotor movements is applicable, as the results show, for both fully and partially sighted individuals.

Individual differences significantly affect the way we work, socialize or otherwise perform daily life activities. Given their popularity, computers have begun to touch the lives of not only the researcher at large universities but also consumers at home and at the office. Due to this information revolution, design emphasis, originally given to the physical hardware and programming aspects of computer design, has shifted toward the psychological standpoint of including individual differences in the design of computing systems. However, the design of today's computer interfaces has neglected to take into consideration the reduced capabilities of those users with low vision. Low vision, defined as an uncorrectable reduction in the visual processes due to disease or deformation of the eye, affects over 3 million Americans. It is apparent that more emphasis should be devoted to the development of interface standards by which system interface designers can accommodate the wide range of capabilities of the low vision computer user.

Suggestions for future research

The differences in performance in identification and selection tasks could be accounted for by the large variability in visual impairments in the PSU group. For example, for PSU, visual field scores ranged from 1% to 100%, with a mean of 61% and standard deviation of 42%. Furthermore, the small number of participants limits the robustness of the results. Selecting participants of similar visual profiles or increasing the number of participants regardless of their visual profile would result in a more powerful statistical analysis and greater generalizability of the results.

Further research linking color blindness to performance in a GUI environment is also warranted. Specifically, expanding the concept that one's inability to discern higher wavelengths of light caused by the reduced sensitivity of the retinal rods results in poorer performance when subjected to those wavelengths of light.

The ANCOVA results analyzing reaction time indicated interactions with set size. Further investigation of these interactions could include using set sizes comparable to that of a typical computer desktop.

The results of this research provide a characterization of human abilities and behaviors within the computer domain. These tools are valuable for computer system interface designers. Their use can reduce the need of conducting comparative experiments between design alternatives thereby providing efficient development of user-friendly interfaces, both for fully sighted and partially sighted users alike.

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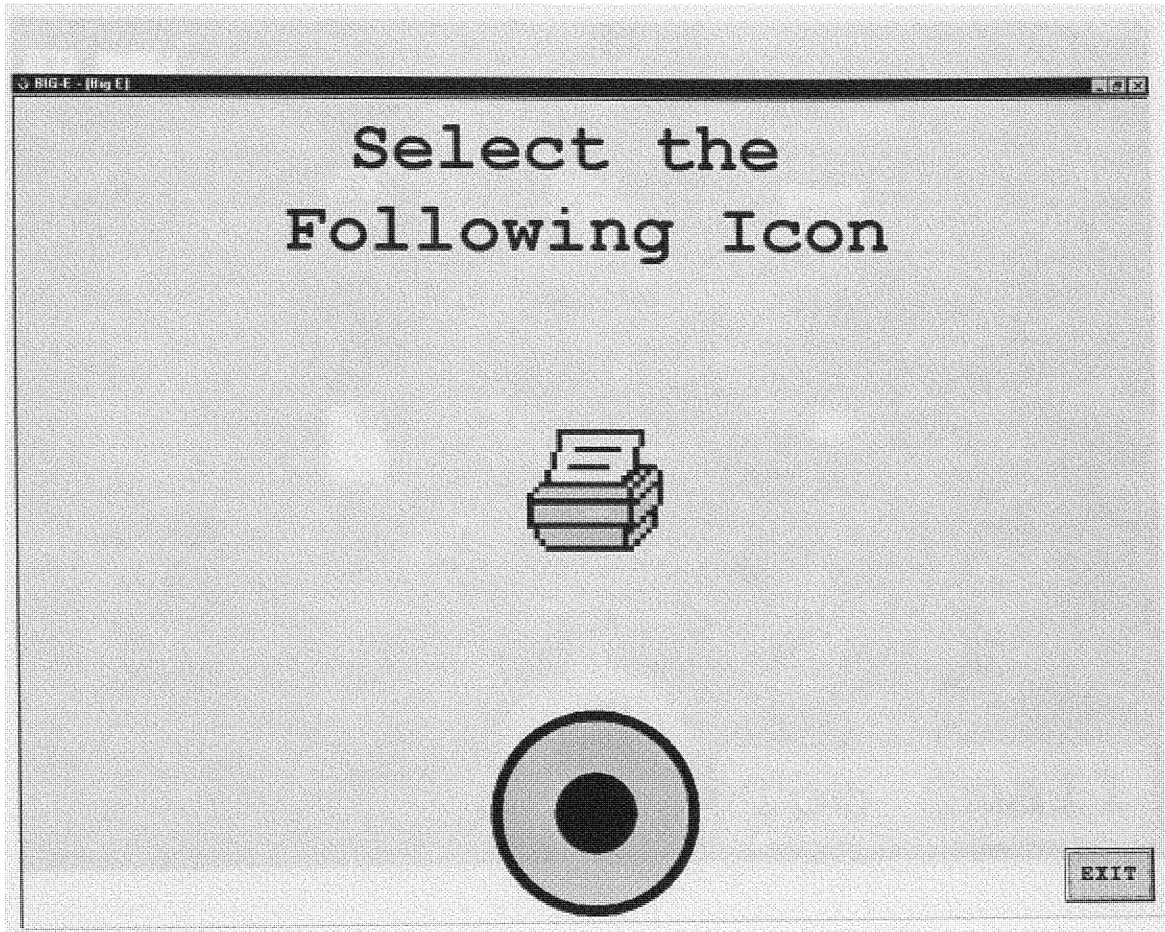
APPENDICES

Appendix A: Target presentation screen.



Appendix B: Stimulus presentation screen