THE EFFECT OF TARGET COLOR AND CONTRAST

ON MOVEMENT TIME IN AIMED MOVEMENT TASKS

A Thesis

Presented to

The Faculty of the Department of

Human Factors and Ergonomics

San Jose State University

In Partial Fulfillment

Of the Requirements for the Degree

Master of Science

by

Robert Murphy

December 2005

APPROVED FOR THE GRADUATE PROGRAM IN
HUMAN FACTORS / ERGONOMICS

Dr. Kevin Jordan, Chair
Professor, Department of Psychology

Dr. Lou Freund, Member
Professor, Department of Industrial & Systems Engineering

Dr. Abbas Moallem, Member
Oracle Corporation

APPROVED FOR THE UNIVERSITY

ABSTRACT

THE EFFECT OF TARGET COLOR AND CONTRAST ON MOVEMENT TIME IN AIMED MOVEMENT TASKS

By Robert Murphy

Through interactions with various devices and software, aimed movement tasks are common occurrences. Understanding the effect of interface elements or targets in aimed movements will assist in optimizing performance within these interfaces. This study addresses the potential effect of color and contrast of targets on performance in aimed movement tasks through a pointing and clicking task on the computer. Target size, color, contrast, and movement direction were analyzed, measuring any effect on movement time and errors. Size had an effect on movement time, as predicted by Fitts' law, and a similar effect on errors, with a decrease in performance as size decreased. Color had no significant effect on movement time or errors. High contrast targets were hit faster than low contrast targets, as size decreased. High contrast targets also resulted in more errors, as size decreased. Direction had an effect on movement time, with faster movements to the left.

ACKNOWLEDGMENTS

I would like to express my gratitude to all the people who have assisted me in this project. To my thesis chair and committee members, providing support, direction, and encouragement which kept me focused and provided confidence in completing this project. To my classmates, whose support and interest helped fuel my motivation and perseverance. To my family, for their tolerance and patience, while I pursued this endeavor.

CONTENTS

LIST OF FIGURES AND TABLES

Introduction

Since the development of the graphic user interface, human computer interaction has become much more than simple text entries. Aimed movements, or pointing and clicking at icons, menu items, tabs and command buttons, are all common methods of interacting with computer software. In addition, the emergence of the internet has introduced a variety of new interactive interfaces. Any text, graphic, or segment of either displayed on a web page can be used as a "hot spot," or an interactive element, intended to be clicked on.

In addition to computer use, aimed movement tasks are encountered throughout the day. From using an automated teller machine, to using any number of different styles of telephones, to controls on equipment and machinery, aimed movement tasks are ubiquitous. Some of these movement tasks are critical, requiring fast and accurate responses, such as controls on medical equipment, emergency shut-down buttons, or entering a security code in alarm systems. Other movements may simply require accuracy, such as using an automatic teller machine, adjusting computer system settings, or using a remote control.

Everyday, one encounters a variety of interactive elements, of different shapes, sizes, colors and positions, on a variety of interfaces, requiring different levels of efficiency. Whether it is using a computer in the workplace, or using a personal handheld music player, efficiency of performance in these human-machine interactions is important.

Optimizing performance of interfaces has taken into consideration, the size, position and color of elements. Relative size can affect search tasks (Wolfe, 1996), and larger targets can be hit with more accuracy than smaller targets (Fitts, 1954). Position also can play more than one role in performance, where distance to targeted elements (Fitts, 1954) and position in relation to other elements (Chapanis, 1959) can affect performance. Color can also be effective in search tasks (Christ, 1975) and in recognition or purpose of elements (Galitz, 2002).

Understanding how these variables interact with the human cognitive, perceptual and motor control systems are essential for optimizing performance. Some interactions have been found and analyzed, but a particular possible interaction, the effect of color and contrast of targeted elements in aimed movement tasks, does not appear to have been considered at this point.

Because of the human motor control system's reliance on perception (Woodworth, 1899; Fitts, 1954; Jeannerod, 1990; MacKenzie, 1991), might these additional factors, color and contrast, have an effect on performance? If so, guidelines or recommendations for color usage and contrast levels of targets could be forthcoming.

Literature Review

Speed-Accuracy Tradeoff

Robert S. Woodworth was one of the earliest researchers studying voluntary aimed movements and is often credited as the founder of research in the speed-accuracy tradeoff concept in movement (Plamondon & Alimi, 1997; Meyer, Smith, Kornblum, Abrams & Wright, 1990).

Unique at the time, Woodworth (1899), studied the behavior of movement, analyzing voluntary movements as intended and executed, not as simply perceived. His inspiration came from observing construction worker's ability in swinging hammers to break bricks with a high level of accuracy, and the ability of the human vocal cord to achieve perfect tones. Using the task of drawing a line in time to a metronome, Woodworth studied the relationship between duration, amplitude and velocity of movement, and their effects on accuracy.

Two phases of movements were proposed. The first, *initial adjustment*, is the initial directional ballistic movement of a limb. *Current control* is the second phase, executing finer adjustments or corrective movements, using sensory feedback to adjust for any errors produced during the initial adjustment phase (Woodworth, 1899).

Woodworth (1899) reported that the first phase of movement, initial adjustment, can be accurate up to certain speeds; beyond that, accuracy of movement comes from the second phase, current control. As speed increases, movement time decreases, prohibiting the finer adjustments of the current control phase, resulting in less accurate performance.

In turn, decreasing speed and increasing movement time, allows for the finer adjustments in the current control phase, resulting in more accurate performance.

The role of the two different phases of movements in accuracy has since been researched, with some results placing emphasis on the initial adjustment phase, and other results placing emphasis on current control phase (Meyer et al., 1990).

Fitts' Law

One of the next major steps in motor control research was in 1954, when Paul Fitts wanted to provide a theoretical model to account for the capacity of the human motor system and to help explain the variety of results reported in previous motor control literature. Many studies cited and most studies to that date examined speed and amplitude of movement, with little attention to accuracy. Fitts returned to Woodworth's research (Woodworth, 1899), examining the relationship between speed, amplitude, and accuracy (Fitts, 1954).

Fitts' research involved tasks of rapid aimed movements, analyzing the effect of amplitude and acceptable variability or accuracy on movement time for specific tasks. Both the distance from starting point to the target, and the width of the target (determining accuracy) were varied, while subjects were encouraged to emphasize accuracy over speed (Fitts, 1954).

Fitts' interests were in the capacity, as opposed to the behavior, of the human motor system. He was able to analyze capacity separately from behavior by using highly learned tasks in a controlled environment, relying on visual and proprioceptive feedback. The tasks employed for this experiment were reciprocal stylus tapping tests, transferring of discs (washers) from pin to pin, and transferring of pins from hole to hole (Fitts, 1954).

Results found that as distance increased, movement time increased, and as target width increased, movement time decreased (Fitts, 1954).

Formulation of Fitts' Law: Measuring the Capacity of the Human Motor System

Fitts considered the human motor system analogous to a communications channel, transmitting information about movement, and defined the system's information capacity as the ability to consistently execute a particular movement. As options of movements for a response increase, so does the information capacity of that response. Thus, variability associated with a response can determine the information capacity of that response (Fitts, 1954).

To measure capacity of the human motor system, Fitts utilized Shannon's Theorem 17 (Shannon, 1948), which describes an upper limit of data transmission, in bits/second, with a low level of errors. This formula measures the capacity of a communications channel (C) with bandwidth (W, in hertz), of a limited power or signal (P) in the presence of white noise (N):

$$C = W \log [(P + N) / N] \quad \text{or} \quad C = W \log [(P / N) + 1] \tag{1}$$

Fitts applied movements and their variability to this theorem, determining distance of movement equivalent to signal, and width of target equivalent to noise. Utilizing a variation on Shannon's theorem, Fitts produced an index of task difficulty (ID), measured in bits of information. This index of difficulty represents the amount of information contained in a movement with a particular distance and target size, and is defined as:

$$ID = \log_2 (2A / W) \tag{2}$$

where A = amplitude (distance) and W = width of target (Fitts, 1954).

After plotting movement times against index of difficulty values for a particular task, Fitts found movement times (MT) could be estimated with the following formula:

$$MT = a + b \log_2 (2A / W) \quad \text{or} \quad MT = a + b\, ID \tag{3}$$

where a is the y intercept and b is the slope of the line (Fitts, 1954; Fitts & Peterson, 1964; MacKenzie 1995).

To take into account additional variables affecting movements for a particular task, Fitts (1954) proposed an index of performance (IP) value which is calculated using movement times and index of difficulty values for that task. The index of performance can be defined as:

$$IP = ID / MT \text{ (bits/sec).} \tag{4}$$

A linear relationship was found between movement times and index of difficulty values, so a common index of performance can be defined for the task as a whole, and would be relatively constant for that task with any given ratio of amplitude and width (Fitts, 1954). So, the same task, varying target distance and target width, could be studied under varying conditions or with different equipment, thus each variation of condition or equipment would produce a unique and comparable index of performance value.

In addition, movement times can also be predicted for tasks of a particular index of difficulty and index of performance:

$$MT = ID / IP. \tag{5}$$

This logarithmic trade-off relation Fitts presented, between the target distance divided by target width, and the average movement time, has been documented and supported with minor variations. However, Fitts' theoretical explanation of this trade-off phenomenon is not universally accepted. More recent theories of control of movement accuracy have emerged, some of which utilize the two phases of movements initially proposed by Woodward (Meyer et al., 1990; Plamondon & Alimi, 1997).

Revisions to Fitts' Index of Difficulty Formula

Analyzing Fitts' original data, Welford (1968) observed that some of the plotted data does fit a straight line, suggesting Fitts' formula is basically correct, but noted that the data at the low end of the scale (MT<.25 sec, ID<3 bits) does not fit that line. To improve data calculations, Welford proposed the following index of difficulty formula:

$$ID = \log_2 [(A / W) + .5]. \qquad (6)$$

Welford (1968) also proposed, to more accurately represent variability in movement, width (W) should be calculated using a percentage of the distribution of hits, instead of the physical target width, and that movement time should include time on target, not just time between targets. Using these updated methods and calculations, Welford was able to produce a better fit when plotting both Fitts' original data, and his own experimental results.

In applying Fitts' Law as a predictor of movement time in human computer interfaces, MacKenzie (1995) proposed refinements to formulas and measurement methods used in Fitts' Law. To calculate the index of difficulty, Fitts deviated from Shannon's original formula. Welford (1968) proposed an index of difficulty formula, closer to Shannon's original formula, but MacKenzie proposed an index of difficulty formula using Shannon's original logarithmic function (Equation 1):

$$ID = \log2 [(A / W) + 1]. \quad (7)$$

This formula provides yet a better fit with data, and will avoid negative index of difficulty values if $A < 1/2 W$ (MacKenzie, 1995).

Fitts measured the width of the target along the axis of motion, and did not consider the height of the target, thus these experiments were conducted using one-dimensional movements towards a target. MacKenzie (1995) experimented with two-dimensional tasks, varying target height, width, and angle of approach. A problem encountered with two-dimensional tasks is defining the target width; a rectangular target will have different widths depending on the angle of approach. MacKenzie found the optimal solution to this dilemma was to use the smaller of either width or height, no matter the angle of approach.

MacKenzie (1995) also recommended Welford's adjustment of width to accurately represent error or variability. This would apply if the error rate differs from 4%, meaning if greater or fewer than 2% of the hits land outside each side of the target.

This more recent version of the index of difficulty formula presented by MacKenzie has been the preferred formula, even by Welford himself (Plamondon & Alimi, 1997).

Applications of Fitts' Law

Fitts' Law has been confirmed and utilized in a broad range of experiments, over a number of years, as a comparative measurement of movement times and a model of motor control.

Kerr (1973) used Fitts' Law to compare the effect of an underwater environment and a land environment on movement time in a reciprocal tapping test. Langolf and Hancock (1974), measured motor control performance using Fitts' Law on tasks viewed at various levels of magnification under a microscope.

Fitts' speculation of different limbs having different levels of information capacity was supported by Langolf, Chaffin, and Foulke (1976), who analyzed movement times on various finger, wrist, and arm motions over a wide range of amplitudes.

Card, English and Burr (1978), were the first to conduct a theoretical evaluation of human computer interaction utilizing Fitts' Law, evaluating the performance of four computer text selection devices, mouse, joystick, step keys, and text keys. Results indicated the mouse control was the optimally performing device and Fitts' Law can be applied as a predictive model of mouse control in human computer interaction.

Wallace, Newell, and Wade (1978) found Fitts' Law to be a reliable predictor of movement time with preschool children performing the task of placing pins in target holes. Variations of Fitts' Law were used by Hoffman (1991) while developing a steering law to model trajectory based HCI movements, such as navigating nested menus and drawing curves.

Mottet, Guiard, Ferrand and Bootsma (2001) found Fitts' Law to hold in both one and two handed pointing tasks, where the pointer, the target, or both were manipulated. Accot and Zhai (2002) used Fitts' Law to evaluate pointing tasks and goal crossing tasks (passing over the target), establishing the foundation for goal-crossing based computer interfaces.

Fitts' Law has also been incorporated into ISO standards, specifically ISO 9241-9, *Ergonomic Requirements for Office Work with Visual Display Terminals, Part 9 Non-keyboard Input Device Requirements*. ISO 9241-9 provides methods to evaluate performance, comfort, and effort of computer input devices. Procedures for performance evaluations use Fitts' Law, creating a measure of Throughput (equivalent to Fitts' index of performance), for device comparison (Douglas, Kirkpatrick, & MacKenzie, 1999; Albinsson & Zhai, 2003).

Optimizing Performance in the Graphic User Interface

In addition to target size and distance from movement starting position, target position and penetrability of target edges can have an effect on GUI performance.

Movements to targets positioned perpendicular to starting position, either horizontally or vertically, were found to be faster than diagonal movements using a joystick (Card et al., 1978) or a mouse (Whisenand & Emurian, 1995). Specifically, Whisend and Emurian found horizontal movements the most efficient, followed by vertical or diagonal downward movements, with vertical or diagonal upward movements being the least efficient.

Positioning targets at the perimeter of the active screen restricts cursor movement beyond the physical dimension of the target, creating an impenetrable border or edge on the target. This condition allows users to rely on the initial ballistic movement to a target, because the movement cannot overshoot the target position. This is, in effect, equivalent to movements towards larger targets, without the space requirements of larger targets. As predicted, edge positioned targets were selected faster than non-edge positioned targets (Walker, Smelcer & Nilsen, 1991).

Ferris, Jones, and Anders (2002) examined this concept with the addition of distance to target, height of target, and angle of approach to target. They found edge-positioned targets were selected faster than targets positioned one pixel from the edge, supporting previous findings. In addition, as distance to target increased and as height of target decreased, movement time increased. The starting position of 90º to the target (horizontal movements to the right), was found to have the fastest movement time, with time increasing as starting positions moved incrementally lower, to 10º to the target.

The Human Visual Perception System

The human visual perception system plays an important role in aimed movement tasks. The ability to perceive an object or target has obvious benefits to one's ability in hitting the target. The reliance of accuracy in aimed movements on the visual perception system necessitates understanding how targets or objects are visually perceived.

Our visual perception comes from the stimulus of visual light, a small band of electromagnetic energy, which is reflected off or emitted from objects, then passes through the eye, stimulating visual receptors in the retina, located in the back of the eye (Goldstein, 2002).

There are two types of visual receptors, rods and cones. These contain light sensitive chemicals that produce electrical signals that travel through a network of neurons, to optical nerves, reaching the lateral geniculate nucleus located in the thalamus section of the brain (Goldstein, 2002).

Rods and cones differ in shape, distribution, and sensitivity or functionality. Rods and cones are named after their respective physical shapes, rods are cylindrical and cones are conical. Both rods and cones are distributed throughout the retina, except for the fovea, a spot on the retina located in one's line of sight or center of focus, which contains only cones. Rods are more sensitive to lower levels of light and lower wavelengths of colors (blue-green), while cones are sensitive to a wider range of wavelengths of color, and provide better detailed vision (Goldstein, 2002).

Cones contain one of three types of pigment, each sensitive to a different range of wavelengths of colors. These are referred to as short wavelength (S) cones, medium wavelength (M) cones, and long wavelength (L) cones, with approximate peak wavelength sensitivities of 419, 531 and 581 respectively (Goldstein, 2002).

Cones, or their respective pigments, are frequently referred to by their peak color sensitivity. S, M and L cones are known as the blue, green and red cones, even though their individual sensitivity covers a range of colors with some overlap. The L cone specifically, actually peaks closer to a yellow than a red (Murch, 1984). The S cone's range of sensitivity has the least amount of overlap with M and L cone's ranges of sensitivity, while M and L cone's ranges of sensitivity overlap considerably.

L and M cones are found in the retina and make up the fovea area of the retina (Goldstein, 2002; Shevell, 2003). Even though the ratio of L and M cones can vary among individuals, this ratio seems to have little effect on color appearance (Shevell 2003) or luminosity contrast (Gunther, 2002). A highly symmetrical or balanced ratio does result in higher chromatic contrast sensitivity (Gunther, 2002).

S cones account for about 7% of the cones, are absent from the fovea, and are sparsely distributed in the retina. Due to their low density and uneven distribution, S cone resolution is 1/4 to 1/6 of M and L cone resolution, and an under sampling of some colors will occur, resulting in chromatic aliasing. These shortcomings of the S cones appear to be compensated for by chromatic aberration and a possible chromatic interpolation system in the brain (Shevell, 2003).

Due to the uneven distribution of individual color-sensitive cones in the retina, blues and yellows are easier to detect in the peripheral vision than greens and reds, and the lack of S cones in the fovea, can result in a "blue-blindness," during attempts to fixate on small blue objects (Murch, 1984).

Color and Luminance in Graphic User Interfaces

The use of color in user interfaces is commonplace today. In addition to esthetic properties, effective color use can provide many benefits to user interfaces. Varying color or contrast of interface elements has been shown to be effective in highlighting objects and can assist in discrimination of objects, improving performance in search and identification tasks (Brown, 1991; Van Orden, Divita, and Shim, 1993; Bauer, Jolicoeur & Cowan, 1996).

The use of color in displays, as opposed to achromatic displays, can improve performance in both search and identification tasks. Realistic color representation in displays was found to reduce search times, and memory of target color is retained longer than memory of various target shape attributes (Christ, 1975).

Redundant color use on objects can help identify common elements. Visual grouping can be achieved using unique colors that help join similar elements or help separate distinct elements. Color can also be used to indicate status of information, or invoke calls to action (Galitz, 2002).

The efficiency of blue links on web pages has been questioned, due to the uneven distribution of blue sensitive cones in the retina. Despite this potential deficiency, blue links were found to be more effective than red links in both visual and interactive search tasks on web pages, although this result could be influenced by participant's previous experience with the similar interface style used on the internet (Pearson & van Schaik, 2003).

The reading abilities of people with normal vision were found to have a high tolerance to luminosity contrast between text and background. Legge, Rubin and Luebker (1987) found a 50% decrease in reading performance while contrast levels decreased from 100% to 10%. Below 10% contrast levels though, there was a much more significant decrease in reading performance. In addition, reading performance with smaller characters was found to be more affected by contrast than performance with larger characters.

Color and Luminance in Prehension Tasks and Size Perception

Prehension movements can be broken into two components: transportation, the reaching movement of the limb to the stimulus, and manipulation control, the grasping mechanism. These components are organized independently, but executed in parallel (Jeannerod, 1990). Each component relies on different stimulus properties to control movement accuracy. Transportation relies on extrinsic object properties, such as distance, direction and velocity, while manipulation control relies on intrinsic object properties, such as size, shape and color (Jeannerod, 1990; Gentillucci, Benuzzi, Bertolani & Gangitano, 2001).

In accordance with the influencing object properties, target color was found to affect grasp, and not reach, where red objects were estimated to be larger than green objects (Gentillucci, et al., 2001).

This finding also follows research on the influence of color and luminance on perceived size of objects. It was found that the "warmer" colored objects, using reds and yellows appeared larger than the "cooler" colored objects, using blues and greens. The less saturated, lighter colored objects, also appeared larger than their counterpart. (Gundlach & Macoubrey, 1931; Wallis, 1935; Tedford, Bergquist & Flynn 1977).

The resulting effect of lighter objects appearing larger may be attributed to the contrast between the object and background. When presented on a gray background, the darker or more saturated objects appeared more pronounced, while the borders of the lighter objects, producing lower contrast, appeared less pronounced, possibly creating the illusion of a larger object (Tedford et al., 1977).

The Role of Vision in Aimed Movements

The importance of vision in aimed movement tasks has been known and considered for years. Fitts (1954) specifically points out the motor control system under evaluation in his research includes both visual and proprioceptive feedback.

In analyzing the role of visual feedback in controlling movement accuracy, movements greater than 200 ms were found to rely on visual feedback, while faster ballistic movements less than 200 ms did not (MacKenzie, 1991).

Regarding the two phases of movement initially proposed by Woodworth, the more complex current control phase is considered a closed-loop movement, relying on sensory feedback for corrective adjustments (Woodworth, 1899; Meyer et al., 1990).

As an alternative to the slower visuomotor feedback loop, Jeannerod (1990) presents a more proactive control of movement, through both visual and proprioceptive senses beginning prior to the initial movement.

In a study varying the presence or absence of visual information of the initial static hand position and eliminating visual feedback during movement, it was shown the initial visual position sense of the hand increased accuracy of movement. This indicates that proprioception alone is inadequate for accurate movements, and a visual map matched to a proprioceptive map improves accuracy of movements (Jeannerod, 1990).

Foveation of target appears to allow improved encoding of hand position prior to movement, in turn improving movement accuracy. As foveation time increased, allowing increased encoding of initial hand position, movement accuracy improved, even without visual feedback after movement began. When hand movement preceded target foveation, or when the target disappeared, eliminating foveation, accuracy decreased (Jeannerod, 1990).

These findings indicate Fitts' Law may not be dependent on traverse distance between hand and target, but rather eye to hand coordination, between initial hand position and target, where visual information is needed at initiation and throughout movement for optimal performance (Jeannerod, 1990).

In tracking the motion of the eye during aimed movements tasks, a spatial and temporal correlation was found between point of gaze and hand motion (Helson, Elliot, Starkes & Ricker, 1998). During these tasks, point of gaze patterns followed the same pattern of the hand's movements, both of which followed the two phases of movement as proposed by Woodworth (1899). Typically there was a large initial movement that undershot the target, followed by additional smaller corrective movements to reach the target.

Project Overview

Extensive research has been cited covering many aspects of motor control, perception, and color usage in graphic user interfaces. Individually, these topics are not lacking in volume of research, but possibly more important than individual considerations, are the interactions between these topics. A limited amount of research was found covering some interactions, but no research was found dealing specifically with the interaction between target color or target contrast and motor control in aimed movement tasks.

A few noted findings have similarities with, or deal with, common aspects of the topic at hand, and may provide direction of research or give support to the possibility of finding an effect in this specific interaction.

As object color was found to affect the grasping phase in prehension movements (Gentillucci, et al., 2001), the current control phase in aimed movements may also be affected by intrinsic object properties, specifically target color or contrast. A potential underlying cause for the grasping errors, the effect of color and contrast on perceived object size (Gentillucci, et al.), may affect the perceived size of targets in aimed movements, interfering with the accuracy of the refined movements in the current control phase of movement.

If foveation of targets assists in performance of aimed movement tasks, and eliminating foveation decreases performance of aimed movements (Jeannerod, 1990), then aimed movements towards targets that are more difficult to focus or fixate on, may result in a decrease in performance, as compared to movements towards targets that are easier to focus or fixate on.

A potential deficiency in the visual system to focus and fixate on small blue objects was cited (Murch, 1984). Despite the results of the search tasks using blue links, which could have been influenced by previous experience (Pearson & van Schaik, 2003), this potential deficiency may impede one's ability to focus or fixate on small blue or light blue targets, decreasing performance in aimed movements towards these targets.

Beyond target recognition in search and detection tasks, aimed movement tasks require a concentrated effort of focusing on targets. As a similar effort is required in character recognition, the same factors affecting reading may affect aimed movement tasks. A 50% decrease in reading performance was found when text contrast decreased from 100% to 10%, and a more significant decrease in reading performance was found with contrasts below 10% (Legge et al., 1987). Assuming contrast is as important in target recognition as in character recognition, a decrease in contrast may have an effect on aimed movement tasks.

Fitts' Law has been found to be an effective tool as both a predictor of movement time, given empirical data from aimed movement tasks, and as a comparative mechanism, in evaluating performance of aimed movement tasks performed using different equipment or under different conditions. Fitts' Law has also been found to apply to tasks performed in both the physical world, and on the computer, making it a useful evaluation tool for this topic.

Problem Statement

The purpose of this study is to determine the effect of color of target, and contrast between target and background on movement times in aimed movement tasks.

Hypotheses

H_0 1. There will be no difference in movement times for different colored targets.

H_0 2. There will be no difference in movement times as the contrast between target and background decreases.

H_1 2. Movement times in aimed movement tasks will increase as the contrast between target and background decreases.

H_0 3. There will be no difference in movement times as the contrast between target and background decreases, and the size of the target decreases.

H_1 3. An interaction between target size and target contrast is expected, with a greater increase in movement times towards smaller low contrast targets than towards larger low contrast targets.

Applying Fitts' Law

Results will be analyzed using Fitts' law to confirm this experiment as an accurate representation of performance in aimed movement tasks. Further application of Fitts' law will be used to compare performance within any factor found to have a significant effect on movement time.

Delimitations

1. Participants will be students at San Jose State University.
2. Participants will have a minimum of two years computer experience.
3. Participants will have normal vision, they will not be color blind, and will be free of field of vision or peripheral vision limitations.
4. Participants will not have any upper limb motor control limitations or disabilities, and be able to maneuver a computer mouse and use a computer keyboard.
5. All participants will be provided the same instructions and allowed the same amount of task rehearsal.
6. All participants will perform the tasks on the same equipment, using the same equipment settings, in the same environmental conditions.
7. Participants should not be under the influence of excessive stimulants, sedatives, or any recreational drug (moderate coffee or tea consumption prior to the experiment will be accepted).

Limitations

1. Participant's motivation in performance.
2. Participant's posture, arm position and method of grasping and maneuvering a computer mouse.
3. Participant's intake of non-disclosed stimulant or sedative prior to the experimental session.

Method

To determine the potential effect of color and contrast on performance in aimed movement tasks, a pointing and clicking task on a computer was used in this experiment. Independent variables manipulated were target size, target color, target contrast, and direction of movement. Dependent variables measured were movement time and errors.

Four square target sizes were used, 8, 16, 32, and 64 pixels, with approximate screen dimensions of 2, 4, 8, and 16 mm. These sizes are based on and extrapolated from the recommended icon sizes of 16x16 or 32x32 pixels (Galitz, 2002), and are the same target widths used by MacKenzie (1991).

Square targets were used, to simulate icons and buttons used on computer interfaces. This also avoided the need to consider the effect between target width and height, in calculating the index of difficulty values used in analysis.

Targets were composed of four different colors, black, red, green and blue. Each color was set at two levels of contrast, high and low, and was presented on a white background. Color and contrast combinations were created by programmatically setting RGB display values of the targets (see Appendix A).

The two levels of contrast were established using equal levels of RGB, producing gray values of approximately 90% black (high contrast) and 10% black (low contrast). These also served as the black target color values.

High contrast values (dark colors) for each red, green and blue were produced by beginning with 0% values of all colors (black), and adding the respective color until a luminosity equivalent to the established high contrast gray value was achieved.

Low contrast values (light colors) for each red, green and blue were produced by beginning with 100% values of all colors (white), and reducing the two other colors until a luminosity equivalent to the established high contrast gray value was achieved.

A 1º photographic spot light meter was used to compare luminosity of each level of contrast for each color displayed on the monitor, to generate targets of equal luminance.

Two directions of movement were used, diagonally to the upper right, and diagonally to the upper left (approximately 50° diagonals). These diagonal movements should produce the highest movement times (Whisenand & Emurian, 1995), possibly making any measurable effect more apparent (Drury, 1995). One distance of movement was for used for data collection, 552 pixels, an approximately screen distance of 17 cm.

To decrease rehearsal effects, ten distracter trials were randomly introduced into each experimental session. These trials were shorter distances, approximately 150 pixels, and in different directions, horizontally right and left, vertically upwards. These ten additional trails were excluded from data analysis.

Participants

Thirty seven San Jose State University students (28 women and 9 men) participated in this experiment. Approximately half the participants received class credit for participating; the others received no credit or compensation. All were between the ages of 19 to 40, were right handed, had normal vision (corrective lenses accepted) and were free of any upper limb disability. Desktop computer experience ranged from 5 to 16 years. One participant's data (male) was removed from analysis, due to their inability to complete the color vision test (described later), resulting in 36 participants for initial analysis.

Apparatus

A Sony VAIO desktop computer running Windows XP Home Edition was used for this experiment. The system processor was a Pentium 4 at 2 GHz, with 736 MB of ram. The monitor was a 19 inch (48 cm) Dell flat panel display, with system settings at 32 bit color, resolution of 1280 x 1024, and a refresh rate of 60 Hz. The monitor settings (color, contrast, brightness), were all set to default levels.

The mouse was a Microsoft optical mouse. The mouse speed was set at the midpoint of the scale, the pointer was a normal arrow, and all pointer options (e.g. enhanced pointer position) were turned off. A 20x23 cm felt mouse pad was used.

The light meter was a Honeywell Pentax 1° spot light meter. Room lighting was provided by fluorescent ceiling lights.

A Java applet was created as the application to conduct this experiment on, running within Windows Internet Explorer v.6.0. The display consisted of three elements. The first element, the *starting box,* was a 32x32 pixel outline of a square (screen dimensions of approximately 8x8 mm), consistently located at the lower center of the display. To avoid potential errors of participants missing the starting box, the active area of the box was extended 8 pixels beyond the border of the box. The second element was the *target*, which varied in color, contrast, size and position. At the beginning of the session and between each trial, a 64x64 pixel outline of a square would appear for 1 second, as a *cue*, indicating the position of the target for that trial (see Appendix B).

The time between the click on the starting box and the click on the target was recorded on the computer, along with the trial number. Errors (target misses) were also recorded for each trial. An error click did not stop the time; recording time continued until the target was actually hit, allowing potential accumulation of errors for each trial.

Procedure

Participants sat at a table, approximately 50 cm from the monitor. Before beginning the experiment, qualifying questions were asked, documenting participant's age, approximate years of desktop computer use, confirming the absence of any upper limb disabilities and asking if participants were under the influence of sedative or stimulant other than caffeine. A color vision test was administered, asking participant to read the numbers from an Ishihara plate (see Appendix C).

Participants were then asked to read the task instructions (see Appendix D). Clarification of instructions was provided, if requested. The task for the participants was to click on the starting box, then move the mouse and click on the target as fast as possible, while maintaining accuracy. A trial was completed when the participant clicked on the target, at which point the target disappeared, and a cue re-appeared, indicating the beginning of the next trial and the position of the next target. A warm-up consisting of 10 to 12 trials was provided to each participant.

Following the warm-up, each participant conducted 5 sessions of 74 randomly presented trials. The 74 trials consisted of 64 experimental trials and 10 distracter trials. The experimental trials were composed from four target sizes, four target colors, two levels of target contrast and two directions of movement. Each session lasted approximately 3 to 4 minutes. A break of approximately 1 minute was provided between each session.

Results

Data Analysis

All statistical analysis was conducted using MINITAB Statistical Software, release 14.20 for Windows. Data compiled from 36 participants conducting 5 repetitions of 64 combinations of levels of four factors, resulted in 11,520 data points. Descriptive statistics of the raw data are displayed in Appendix E.

Adjustment of Data

A one-way ANOVA and a Tukey Pairwise Comparison test at 95% confidence interval were run on the factor repetition to determine any rehearsal or learning effect. Significant differences in movement times between repetitions were found, $F(4, 11{,}515) = 29.02$, $p < .000$. Tukey's test revealed a rehearsal effect between repetition one and all other repetitions. The rehearsal effect was reduced by eliminating data from the first repetition.

Outliers were analyzed using a boxplot graph. To avoid excessive data manipulation and retain potentially valid data, a 4x interquartile range was used to identify outliers, instead of the default 3x interquartile range. These were identified for each level of size, color and contrast, and adjusted to the means of those levels of factors for the respective participant. This resulted in an adjustment of approximately 0.9% of the data (see Appendix G).

Initial error analysis was conducted using a bar graph, displaying the count of errors for each participant. This revealed excessive error counts for participants 9, 18, 29 and 36, each of whom had errors in more than 15% of the trials and each accounted for more than

5% of the overall errors. These four sets of participant's data were removed from the data (see Appendix H).

The effect of errors on movement time was avoided by adjusting the movement time on trials with errors to the means of those levels of factors for the respective participant. This allowed analysis of movement time to be distinct from analysis of errors and provides more accurate representation and prediction of the potential of the human motor control system. Adjusting for errors also allowed accurate representation of the target size used in applying Fitts' model, avoiding the necessity of calculating target width based on the distribution of errors and hits. This required an adjustment of 758 data points.

The final adjusted data was composed of 32 participants, 4 repetitions and 64 levels of factors, resulting in 8192 data points. Descriptive statistics of this data are available in Appendix F. This adjusted data set was used in all subsequent analysis.

Modeling Fitts' Law

To validate this experiment as an accurate model to analyze and predict performance in aimed movement tasks, results were analyzed to determine how well they fit Fitts' law.

Applying Fitts' law requires the calculation of an index of difficulty (ID) value, based on distance to, and size of target. ID values were calculated based on three different formulas provided by Fitts (1954), Welford (1968) and MacKenzie (1995), and are displayed in Table 1. ID values for this analysis were based on MacKenzie's formula.

Table 1

Index of difficulty values calculated from four different target sizes.

Size	A	W	Fitts $Log_2(2A/W)$	Welford $Log_2(A/W + .5)$	MacKenzie $Log_2(A/W + 1)$
1	552	64	4.11	3.19	3.27
2	552	32	5.11	4.15	4.19
3	552	16	6.11	5.13	5.15
4	552	8	7.11	6.12	6.13

Note. A = amplitude or distance (pixels); W=target width (pixels).

The trend of Fitts' model is apparent in the regression analysis of the overall task (see Figure 1), with MT increasing as index of difficulty value increases. The relation between MT and ID is statistically significant, $F(1, 2) = 178.04$, $p = .006$, with $R^2(adj) = 98.3\%$.

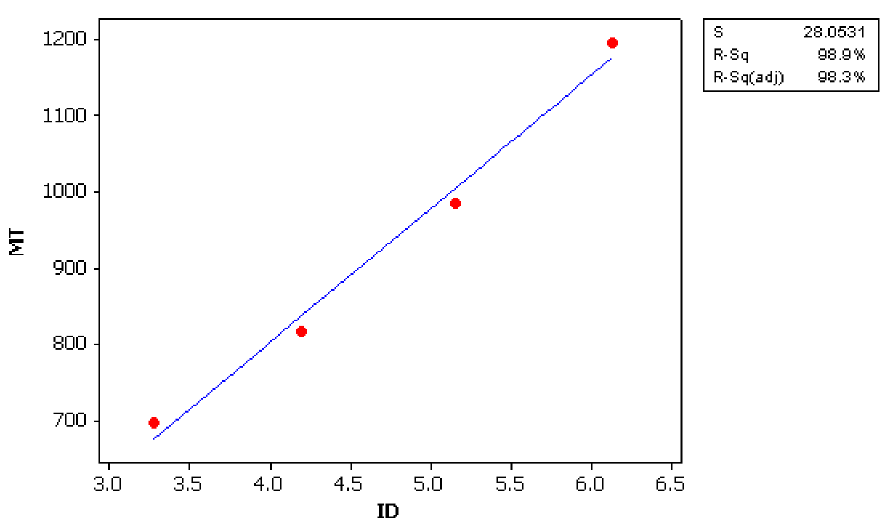


Figure 1. Regression analysis of mean movement time versus index of difficulty. Index of difficulty values calculated using MacKenzie's formula. $R^2 = 98.9\%$; R^2 (adj) = 98.3%; MT = 101.8 + 175.5 ID.

Movement Time

The dependent variable movement time (MT) was analyzed using a 32 (participants) x 4 (sizes) x 4 (colors) x 2 (contrasts) x 2 (directions) within subject analysis of variance (ANOVA), collapsed across repetition.

A significant main effect of size was found, $F(3, 6144) = 747.13$, $p < .000$. This effect of size upon MT is apparent in Figure 2, with mean MT increasing from 696.1 to 816.4 to 986.4 to 1196.5 ms for each increase in size.

To test the first hypothesis, the effect of color on movement times, the main effect of color was analyzed and not found to be statistically significant $F(3, 6144) = .01$, $p = .999$.

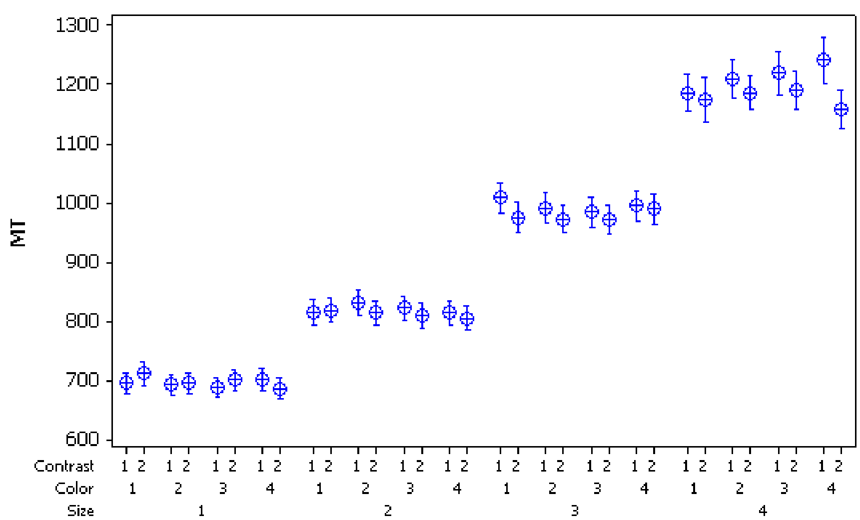


Figure 2. Interval plot of movement time versus target size, color and contrast. Sizes 1-4: large to small targets. Color 1: black, Color 2: red, Color 3: green, Color 4: blue. Contrast 1: low, Contrast 2: high. Interval represents 95% CI for the mean. The effect of target size is apparent, with increase in MT for each size. A size x contrast interaction is also apparent, with faster movement times for high contrast targets at the smaller sizes.

The second hypothesis proposed that MT will be slower for low contrast targets than for high contrast targets. The main effect of contrast was analyzed and was statistically significant $F(3, 6144) = 12.31$, $p = .001$. Movements towards high contrast targets were faster; with a mean difference 14.92 ms or 1.6%.

The third hypothesis proposed a size x contrast interaction which was statistically significant $F(3, 6144) = 4.53$, $p = .005$. The difference in MT increased from 8.9 ms to17.7 ms to 36.8 ms for the three smaller sized targets (see Figure 3). Simple main effects show contrast only had a significant effect on MT at the smallest size target: size 1, $F(1, 2046) = .33$, $p = .566$, size 2, $F(1, 2046) = 1.43$, $p = .232$, size 3, $F(1, 2046) = 3.76$, $p = .053$, and size 4, $F(1, 2046) = 9.01$, $p = .003$.

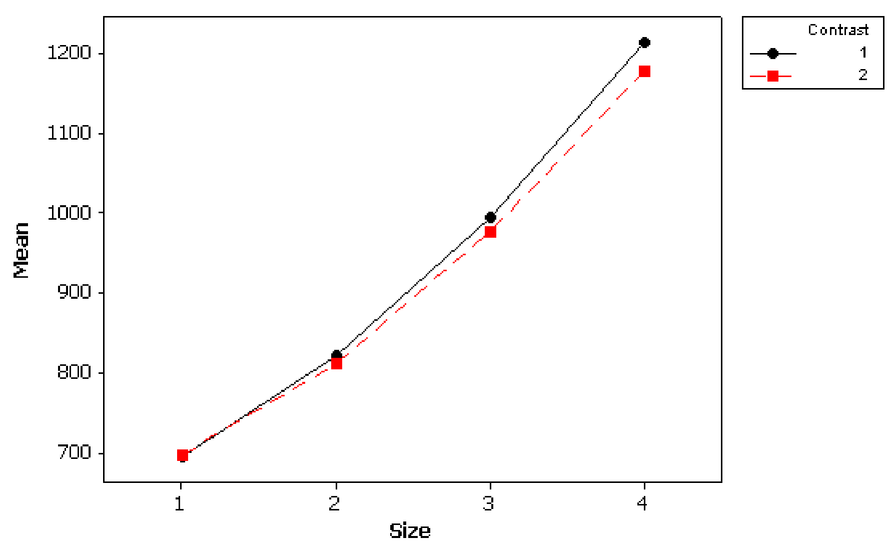


Figure 3. Interaction plot of mean movement time versus target size and target contrast. Sizes 1-4: large to small targets. Movement times towards high contrast targets (Contrast 2) become faster than movement times towards low contrast targets (Contrast 1) as size decreases. Difference in MT at Size 2: 8.9 ms or 0.1%, Size 3: 17.7 ms or 1.8%, Size 4: 36.8 ms or 3.1%.

The main effect of direction was also found to be significant, $F(1, 6144) = 11.10$, $p = .002$. The effect of direction on MT is displayed in Figure 4.

Movements to the left (direction 1) are consistently faster than movements to the right (direction 2) across all sizes. Mean MT to the left was 911.0 ms, and mean MT to the right was 936.7 ms, resulting in a difference of 25.7 ms, or 2.7%.

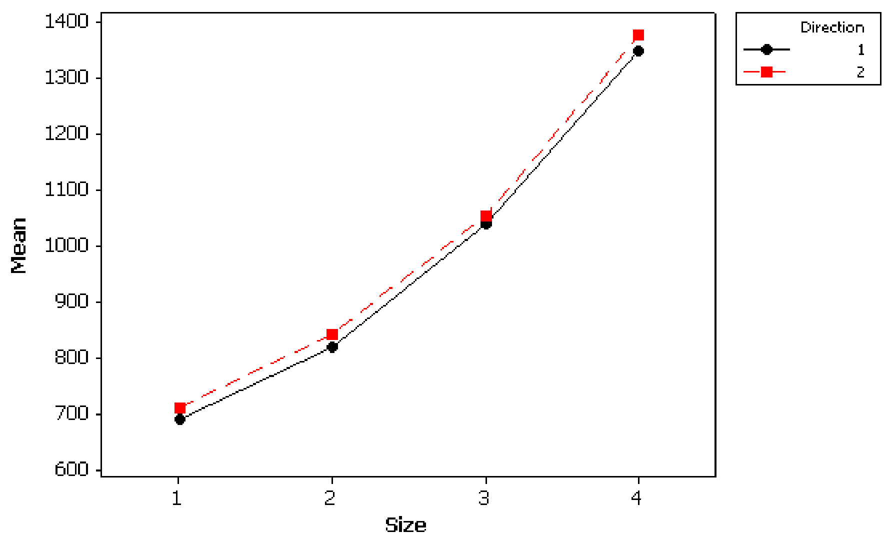


Figure 4. Interaction plot of mean movement time versus target size and direction of movement. Sizes 1-4: large to small targets. Movement times for directions to the left (Direction 1) are consistently faster than movements to the right (Direction 2). Difference in MT at Size 1: 22.5 ms or 3.2%, Size 2: 26.9 ms or 3.3%, Size 3: 23.3 ms or 2.4%, Size 4: 30.1 ms or 2.5%.

This effect of direction on MT was analyzed further using Fitts' law. An index of performance (IP) value is used for task analysis and comparison, which represents the rate of information processing (bits/sec) for a task (see Formula 4). IP values were calculated for the overall task and for each level of the factor of direction. The mean IP value for the overall task was 5.04 bits/sec; the mean IP value for trials to the left was 5.12 bits/sec; the mean IP value for trials to the right was 4.97 bits/sec (see Table 2).

Table 2

Index of performance values calculated from four different ID values, for overall task, and two different directions of movement.

	Overall Task		Direction: Left		Direction: Right	
ID	MT	IP	MT	IP	MT	IP
3.27	696.1	4.70	684.8	4.77	707.3	4.62
4.19	816.4	5.13	802.9	5.22	829.8	5.05
5.15	986.4	5.22	974.7	5.28	998.1	5.16
6.13	1196.5	5.12	1181.4	5.20	1211.5	5.06
Mean IP		5.04		5.12		4.97

Note. ID = index of difficulty; MT = movement time (ms); IP = index of performance (bits/sec) = ID/MT.

Errors

Errors are defined as misses when attempting to hit the target. If multiple misses occurred during a trial, error rates (ER) increased for that trial. 892 errors were recorded, occurring in 758 or 9.26% of the trials.

Error rates are presented with their corresponding mean MT in Appendix I. These values show that as MT increased, ER increased also, indicating the absence of a speed-accuracy tradeoff. Errors were analyzed using the same ANOVA model as movement time.

The two way interaction of size x contrast was significant, $F(3, 6144) = 5.45$, $p = .002$, with more errors occurring in the high contrast targets (see Figure 5). Simple main effects show contrast has an effect on errors at all but the largest size targets: size 2, $F(1, 2046) = 7.51$, $p = .006$, size 3, $F(1, 2046) = 4.34$, $p = .037$, and size 4, $F(1, 2046) = 10.01$, $p = .002$.

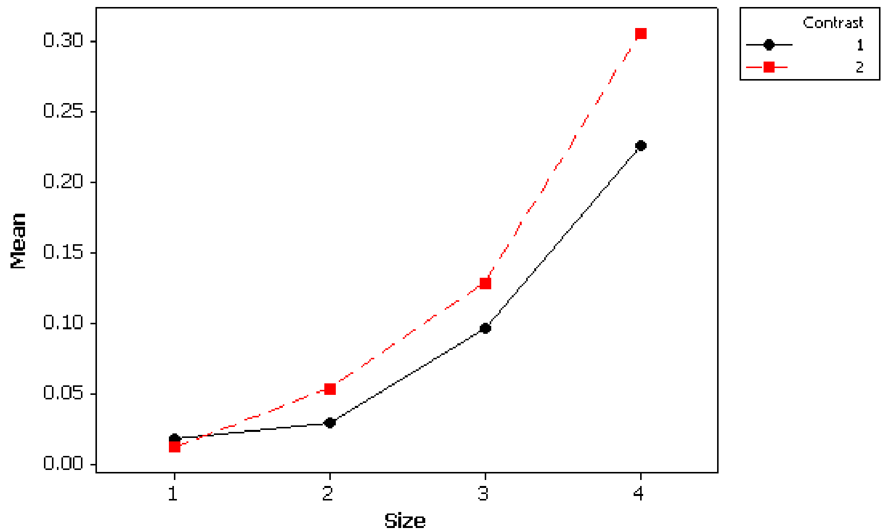


Figure 5. Interval plot of mean count of errors versus target size and contrast. Size 1-4: large to small targets. Contrast 1: low, Contrast 2: high. Percentage decrease in errors at Size 1, 33%, Size 2, 45%, Size 3, 25%, Size 4, 26%.

The omnibus ANOVA also reported a statistically significant three-way interaction of color x contrast x direction, $F(3, 6144) = 7.51$, $p = .015$. This three-way interaction is displayed in Figure 6. This interaction was investigated by analyzing simple main effects of color at each level of contrast and direction, and contrast at each direction and on color at each direction.

There was no statistically significant effect of color at either level of contrast, in either direction. The effect of contrast was statistically significant at each direction, left, $F(1, 4094) = 4.02$, $p = .045$, right, $F(1, 4094) = 13.33$, $p < .000$, and is visually more apparent in movements to the right. Contrast also had a statistically significant effect on colors 2 and 3 (red and green) in movements to the left, $F(1, 2046) = 5.83$, $p = .016$ and on colors 1, 3 and 4 (black, green and blue) in movements to the right $F(1, 3070) = 17.09$, $p < .000$.

A.

B.

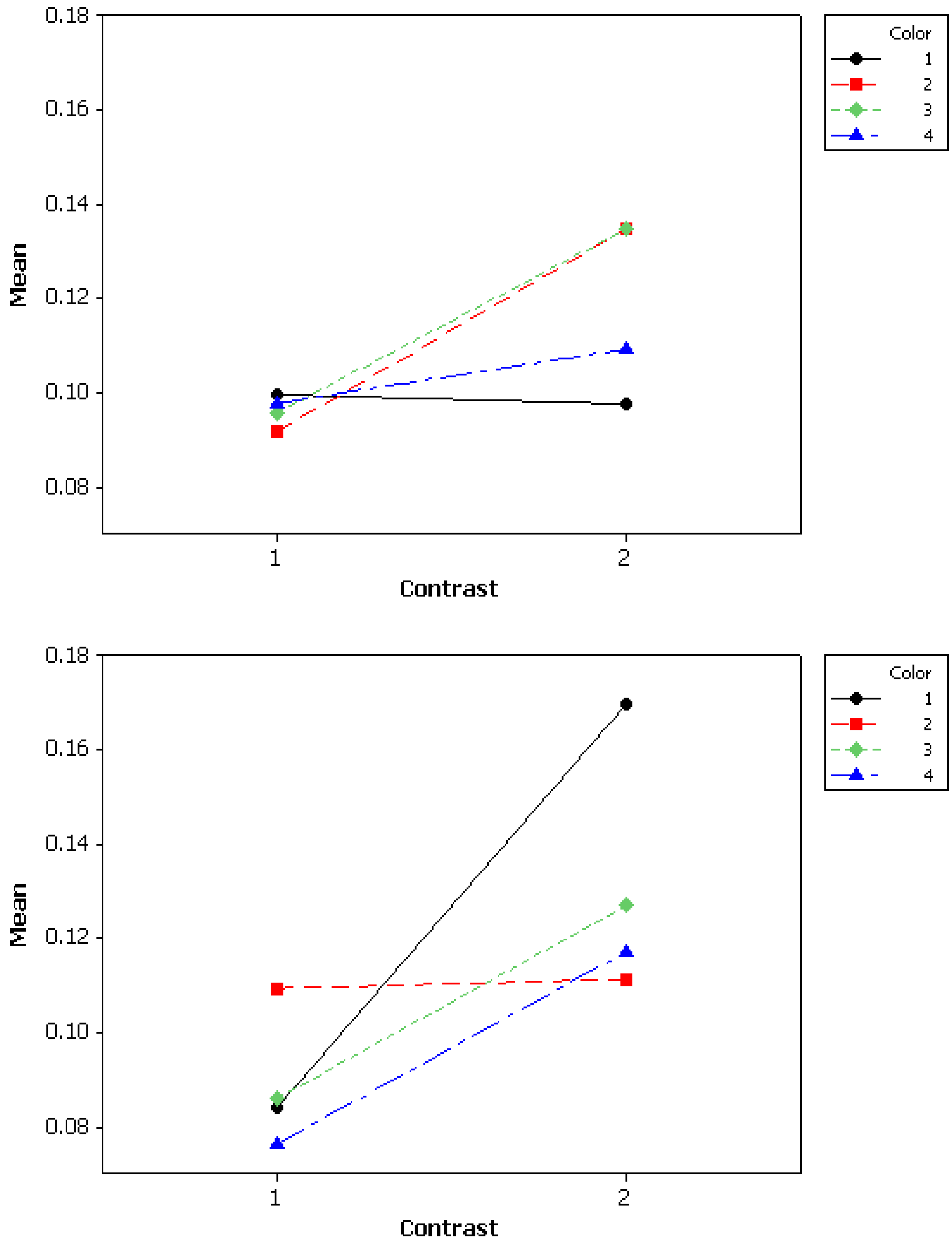


Figure 6. Interval plots of mean count of errors versus color and contrast at direction 1, left (A) and direction 2, right (B). The effect of contrast on errors is apparent here, with an increase of errors between low contrast (1) and high contrast (2). Also visible is the effect of color at high and low contrasts, at two different directions, with the color black having the most dramatic effect in direction 2. (Color 1, black, Color 2, red, Color 3, green, Color 4, blue.)

Discussion

Aimed movement tasks are executed throughout the day using a number of devices including machinery, handheld devices, and computers. Along with the variety of devices, comes a variety of interfaces one must interact with. Using a computer alone, the variety of graphic user interfaces encountered requires one to point and click on elements or targets of many different shapes, sizes, and colors.

The purpose of this study was to determine if some of these varieties of interactive elements encountered have any effect on performance within a graphic user interface. More precisely, how do the color and contrast of targets affect movement times in aimed movement tasks?

Modeling Fitts' Law

One goal of this experiment was to utilize Fitts' information processing model for task evaluation and to compare performance across experimental factors. Fitts' law states that within aimed movement tasks, the distance to the target directly affects movement times, and the size of the target inversely affects movement times, i.e. the closer or larger a target, the faster one can hit the target. The distance to and size of target values are used to calculate an ID value, which Fitts' law predicts to have a linear relationship to MT.

One distance and four sizes of targets were used to calculate three different sets ID values, based on three different proposed formulas (see Table 1). As predicted by Fitts' law, regression analysis of the overall task showed a high correlation between MT and ID (see Figure 1), with a linear R^2 value of 98.3%. ID values calculated using Welford's and Fitts' formulas, were very similar, with R^2 = 98% and 97.8%, respectively.

No significant difference in using these formulas was expected in this experiment. Variations in these formulas were proposed to better fit more extreme ID values, which where were not present in this experiment.

The close matching of these results to Fitts' law indicates the reliability of this experiment as an accurate representation and predictor of performance in aimed movement tasks.

Fitts' law utilizes an IP value for task comparison. Overall mean task IP was 5.04 bits/sec, which is very similar to that reported by MacKenzie (1991), whose IP value for pointing tasks using the mouse was 5.6 (MacKenzie's IP values for other tasks and devices ranged from 5.7 to 2.1).

IP values were also calculated for the factor of distance, resulting in 5.12 bits/sec processing for movements to the left, and 4.97 bits/sec processing for movements to the right, reflecting the faster movement times to the left (see Table 2).

Movement Time

It was hypothesized that using a computer mouse to click on targets of different colors would result in different movement times, and that clicking on targets with a lower level of contrast would result in slower movement times. In addition, an increased effect of contrast was expected as target size was reduced.

The expected effect of target color did not occur. There was no significant difference in movement times while aiming towards targets of different colors.

Despite the low level of S (blue sensitive) cones in the retina and the lack of S cones in the fovea, blue targets did not take any longer to hit, nor did they result in more errors, than the other colored targets.

According to these results, the convention of using blue to identify hypertext links on web pages is acceptable, as all of the colors tested provided equivalent performance; however, these results could possibly change if applied to different age groups.

The absence of an effect of color on movement times is consistent with the results of Pearson and van Schaik (2003), who found blue hypertext links out performed red hypertext links in pointing and searching tasks, but movement times specifically were not affected by the color of the link.

As predicted, contrast between the target and background did have an effect on movement time, with slower times for low contrast targets. This effect interacted with size and is visually apparent at all but the largest size targets (see Figure 2), but is only statistically significant at the smallest size with a difference in mean movement time of 36.8 ms.

Further analysis found the effect of color on contrast greatest at the smallest size for the color blue with a difference in mean movement time of 84.5 ms ($F(1,510) = 10.82$, $p = .001$). Although not statistically significant, results found low contrast blue targets and high contrast blue targets were the slowest and fastest respectively, within the smallest size targets.

This unique finding within the color blue may be attributed to the low level and poor distribution of S cones in the retina, which may only affect the perception of small low contrast blue objects. This effect is not apparent within analysis of errors. Error analysis of the color blue, did not stand out as any different than the other colors at that size, indicating if the distribution of S cones is responsible for this phenomenon, it only affects movement time, not accuracy.

Two directions of movement were used for this experiment, diagonally to the upper left and diagonally to the upper right. Analysis of direction on MT was found to be significant, with movement times to the upper left consistently faster than movement times to the upper right, across all sizes and colors.

This particular movement (right handed participants moving the mouse to the left) may be comparable to adductive limb movements, where a limb begins in its own (ipsilateral) space and moves contralaterally. Most research reviewed on limb movement reported better performance in the opposing abductive movements (limbs moving ipsilaterally), with the exception of experiments involving shorter traverse distances (Morgan et al., 1994; Jeannerod, 1990). These shorter distance experiments involved both full limb movements, and movements utilizing a writing instrument.

Physical hand movement in this experiment was approximately 4.5 cm. The biomechanics of maneuvering a computer mouse this distance may be similar to short limb movements or using a writing instrument, lending support to these results.

In addition, these results are consistent with Phillips, Triggs, and Meehan (2001), who studied the effect of cursor orientation on performance within a graphic user interface. Their results showed faster movement times to the left (right handed participants) for all cursor types tested (crosshair, leftward and rightward arrow).

Errors

Error analysis found 9.25% of trials contained errors. By size, beginning with the largest size (1), this broke down to, 1.42%, 4.10%, 10.35% and 21.19%. Over 10% of attempts to hit the third smallest target (16x16 pixels), and over 20% of attempts to hit the smallest target (8x8 pixels), resulted in errors.

Error analysis also revealed an interaction between contrast and target size. In all but the largest size, high contrast targets resulted in more errors than low contrast targets.

This observation was contrary to the hypothesized effect of contrast on MT, expecting performance to decrease with lower contrast targets. A possible explanation for these results is that focusing on the more difficult to see lower contrast targets, may result in longer eye fixation periods, allowing increased precision in hitting.

Research on eye tracking and fixation may lend some support to this theory. Immediately following the onset of stimuli, eye fixation locations, thus attention, have been shown to be correlated to areas of high contrast within a scene (Parkhurst, Law, & Niebur, 2002; Richardson & Spivey, 2004). However, when interpreting or extracting information from scenes, fixation duration tends to increase within areas of low contrast or areas with increased difficulty of perception (Loftus, 1985; Fukuda & Bubb, 2003).

With only one target displayed, and a cue to indicate position of that target, there should only be one focus of attention on the display. If that target is difficult to perceive, fixation periods may increase as more concentration is needed to see it. Increased fixation may result in increased closed-loop feedback, increasing accuracy in motor control. This theory is partially supported by the slower movement time reported for lower contrast targets. Results from an eye tracking experiment could also lend support this theory.

Significant to note is that a speed-accuracy tradeoff appears to occur within the context of contrast. High contrast targets produced both faster movement times and more errors, predominantly in the smaller size targets (see Figure 2 and Figure 5). The more visible high contrast targets may have affected participant's confidence in their ability to hit the target, increasing their movement times and decreasing their accuracy. This could be supported by surveying participants and documenting their perceived effort in aiming for the various styles of targets.

Also observed within the error analysis was an unusual three way interaction among color, contrast, and direction (see Figure 5). With no plausible explanation for these results, additional analysis was conducted. It was found that after removing the color black from the analysis, the interaction was no longer statistically significant, $F(3, 4608) = 1.70$, $p = .191$. It was further found that the high number of errors for the black high contrast movements to the right could be attributed to two participants' results. Again, after removing those two participants' data, the three-way interaction was no longer statistically significant, $F(3, 5760) = 2.83$, $p = .075$, while the size x contrast interaction remained statistically significant $F(3, 5760) = 4.06$, $p = .009$.

Further analysis of this interaction was abandoned, but this does indicate that a possible direction for additional research is to take into consideration individual sensitivities to contrast and color. More accurate contrast levels for individual participants could be obtained through heterochromatic flicker photometry (Legge, Parish, Luebker & Wurm, 1990), which would give more support to within subject effects of contrast on performance.

Individual color sensitivities may affect performance in this type of a task, but identifying them would require a between subject type of analysis. If significant variations were found across participants, generalization of results would be difficult, but they may lead to recommending individual testing for specialized tasks.

Conclusion

The main goal of this experiment was to determine the effect of both color and contrast of targets on performance in aimed movement tasks, using a pointing and clicking task on the computer.

No significant effect of color on movement time or errors was found. From this finding, there is no specific color of target recommended to optimize performance in pointing and clicking tasks on the computer.

Contrast however, did have an effect on movement time, with faster movements towards high contrast targets. This finding was only statistically significant at the smallest size target, with a difference of 36.8 ms or 3.1%. This finding probably has little practical significance in normal computer tasks, but within these results was an interesting finding with the color blue. The difference in mean movement time between high and low contrast small blue targets was 84.5 ms or 6.8%, which was greater than for any other color. These findings suggest that when speed is a concern and targets are small (below 16 x 16 pixels), higher contrast targets are recommended, particularly when the color blue is involved.

Direction of movement also had a statistically significant effect on movement time. Mean time for diagonal movements to the upper left was 25.7 ms faster than mean time for diagonal movements to the upper right, for right handed participants. Again, this 2.7% reduction in movement time probably has little practical significance in normal computer tasks, but what is interesting is the fact that this occurred across all sizes and colors of targets, and is supported by findings in similar research.

There may be a biomechanical explanation for this phenomenon, and this could play an important role in tasks where time is critical and traverse distances are short. These results suggest that within an interface, common or critical controls should be positioned to the left of the display for most efficient access. This also gives support to the left side positioning of navigational links, as are commonly found in web pages.

Additional research is recommended to determine whether these findings hold for additional angles of attack, and how results of left-handed participants relate.

Overall, errors occurred in 9.25% of the trials. Even within the smaller of the two recommended icon sizes, 16 x 16 pixels (Galits, 2002), over 10% of trials resulted in errors. From this finding, it is recommended that in tasks where speed and accuracy are important, target sizes should be 32 x 32 pixels or larger, which should result in accuracy rates greater than 95%.

Analysis of errors also resulted in some unexpected findings. On all but the largest sized target, more accurate performance occurred when aiming for the lower contrast targets. As unusual as it sounds, these results suggest that in cases where accuracy is important and targets are 32 x 32 pixels or smaller, lower contrast targets are recommended.

Additional research is recommended to confirm both theses results and the proposed theory to account for theses findings. Does the intrinsic target property of contrast affect fixation periods, and do those fixation periods allow for more accurate movements?

In summary, the intrinsic target property of color does not appear to have any effect on the speed or accuracy in hitting a target, but the target property of contrast does appear to have an effect on both speed and accuracy in hitting a target. Movement direction does appear to have an effect on movement time, as supported by other research with similar tasks and short traverse distances. Though some levels of effects may not be practically significant, concurrent findings can support further research and supplied recommendations could be applied to specific tasks.

References

Accot, J. & Zhai, S. (2002). More than dotting the i's – foundations for crossing-based interfaces. *Proceedings of the Conference on Human Factors in Computing Systems 2002, USA,* 73-80.

Albinsson, P. A, & Zhai, S. (2003). High precision touch screen interaction. *Proceedings of the Conference on Human Factors in Computing Systems 2003, USA,* 105-112.

Bauer, B., Jolicoeur, P., & Cowan W. B. (1996). Visual search for colour targets that are or are not linearly separable from distractors. *Vision Research 36*, (10), 1439-1465.

Brown, T. J. (1991). Visual display highlighting and information extraction. *Proceedings of the Human Factors Society 35th Annual Meeting 1991, USA*, 1427-1431.

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

Chapanis A. & Lindenbaum L.E. (1959) A reaction time study of four control-display linkages. *Human Factors 1.* 1-7.

Christ, R. E. (1975). Review and analysis of color coding research for visual displays. *Human Factors 17*, (6), 542-570.

Douglas, S. A., Kirkpatrick, A. E., & MacKenzie, I. S. (1999). Testing pointing device performance and user assessment with the ISO9241, Part 9 standard. *Proceedings of the Conference on Human Factors in Computing Systems 1999, USA,* 215-222.

Drury, C. G. (1995). Designing ergonomics studies and experiments. In J. R. Wilson and E. N. Corlett (Eds.) *Evaluation of Human Work: A Practical Ergonomics Methodology.* (2nd ed.). Bristol, PA: Taylor and Francis.

Farris, J. S., Jones, K. S., & Anders, B. E. (2002). Factors affecting the usefulness of impenetrable interface element borders. *Human Factors, 44 (4),* 578-591.

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

Fitts, P. M., & Peterson J. R. (1964). Information capacity of discrete motor responses. *Journal of Experimental Psychology, 67,* 195-204.

Fukuda, H., Bubb, H (2003). Eye tracking study on web-use: comparison between younger and elderly users in case of search task with electronic timetable service. *PsychNology Journal, 1*, 202-228.

Galitz, W. O. (2002). *Essential guide to user interface design.* New York, USA: John Wiley & Sons, Inc.

Gentilucci, M., Benuzzi, F., Bertolani, L., & Gangitano, M. (2001). Influence of stimulus color on the control of reaching-grasping movements. *Experimental Brain Research 137*, 36–44.

Goldstein, E. B. (2002). *Sensation and Perception.* Pacific Grove, USA: Wadsworth Group.

Gundlach C. & Macoubrey, C. (1931). The effect of color on apparent size. *American Journal of Psychology 43.* 109-111.

Gunther, K. L. & Dobkins, K. R. (2002). Individual differences in chromatic (red/green) contrast sensitivity are constrained by the relative number of L- verses M-cones in the eye. *Vision Research 42,*1367-1378.

Helsen, W. F., Elliott, D., Starkes, J. L. & Ricker, K. L. (1998). Temporal and spatial coupling of point of gaze and hand movements in aiming. *Journal of Motor Behavior 30,*249-260.

Hoffman, E. R. (1991). A comparison of hand and foot movement times. *Ergonomics, 34,* 397-406.

Jeannerod, M. (1990). *The Neural and Behavioural Organization of Goal-Directed Movements.* New York, USA: Oxford University Press.

Kerr, R. (1973). Movement time in an underwater environment. *Journal of Motor Behavior, 5,* 175-178.

Langolf, G. D. & Hancock, W. M. (1974). Human performance times in microscope work. *AIIE Transactions, 7,* 110-117.

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

Legge, G. E., Rubin, G. S., & Luebker, A. (1987). Psychophysics of reading: V. The role of contrast in normal vision. *Vision Research, 27 (7)*, 1165-1177.

Legge, G. E., Parish, D. H., Luebker A. & Wurm L.H. (1990). Psychophysics of reading: XI. Comparing color contrast and luminance contrast. *Journal of Optical Society of America A, 7*, 2002-2010.

Loftus, G. R. (1985). Picture perception: effects of luminance on available information and information-extraction rate. *Journal of Experimental Psychology: General, 114*, 342-356.

MacKenzie, I. S. (1991). *Fitts' law as a performance model in human-computer interaction*. Doctoral dissertation. University of Toronto: Toronto, Ontario, Canada.

MacKenzie, I. S. (1995). Movement time prediction in human-computer interfaces. In R. M. Baecker, W. A. S. Buxton, J. Grudin, & S. Greenberg (Eds.), *Readings in Human-Computer Interaction* (2^{nd} ed.) (pp. 483-493). Los Altos, CA: Kaufmann.

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

Morgan, M., Bradshaw, J. L., Phillips, J. G., Mattingley, J. B., Iansek, R., Bradshaw J. A., (1994). Effects of hand and age upon abductive and adductive movements: a kinematic analysis. *Brain and Cognition, 25*, 194-206.

Mottet, D., Guiard, Y., Ferrand, T., & Bootsma, R. J. (2001). Two-handed performance of a rhythmical Fitts task by individuals and dyads. *Journal of Experimental Psychology: Human Perception and Performance, 27,* 1275-1286.

Murch, G. M. (1984). Physiological principles for the effective use of color. *IEEE Computer Graphics and Applications 4*, (11), 49–54.

Parkhurst, D., Law, K., & Niebur, E. (2002). Modeling the role of salience in the allocation of overt visual attention. *Vision Research, 42*, 107-123.

Pearson, R., & van Schaik, P. (2003). The effect of spatial layout of and link colour in web pages on performance in a visual search task and in an interactive search task. *International Journal of Human-Computer Studies 59*, 327-353.

Phillips J. G., Triggs T. J. & Meehan J. W. (2001). Cursor orientation and computer screen positioning movements. *Human Factors, 43*, 435-442.

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

Richardson, D. & Spivey, M. (2004). Eye tracking: Characteristics and methods. In G. Wnek & G. Bowlin (Eds.) Encyclopedia of Biomaterials and Biomedical Engineering. Marcel Dekker, Inc.

Shannon, C. E. (1948). A mathematical theory of communication. *The Bell System Technical Journal, 27,* 372-423.

Shevel, S. K. (2003). *The Science of Color.* Oxford, UK: Elsevier.

Tedford, W. H., Bergquist, S. L., & Flynn, W. E. (1977). The size-color illusion. *The Journal of General Psychology 97,* 145-149.

Van Orden, K. F., Divita, J. & Shim M. J. (1993). Redundant use of luminance and flashing with shape and color as highlighting codes in symbolic displays. *Human Factors 35*, (2), 195-204.

Walker, N., Smelcer, J. B., & Nilsen, E. (1991). Optimizing speed and accuracy of menu selections: A comparison of walking and pull-down menus. *International Journal of Man-Machine Studies, 35,* 871-890.

Wallace, A. S., Newell, K. M., & Wade, M. G. (1978). Decision and response times as a function of movement difficulty in preschool children. *Child Development, 49,* 509-512.

Wallis, W. A. (1935). The influence of color on apparent size. *Journal of General Psychology 13.* 193-199.

Welford, A. T. (1968). *Fundamentals of skill.* London, Great Britain: Methuen & Co. Ltd.

Whisenand, T. G., & Emurian, H. H. (1995). Some effects of angle of approach on icon selection. *Proceedings of CHI 1995, USA*, 298–299.

Wolfe, J. M., (1996). Visual search. In H. Pashler (Ed.) *Attention.* London, UK: University College London.

Woodworth, R. S. (1899). The accuracy of voluntary movement. *Psychological Review Monographs 3,* 1-114.

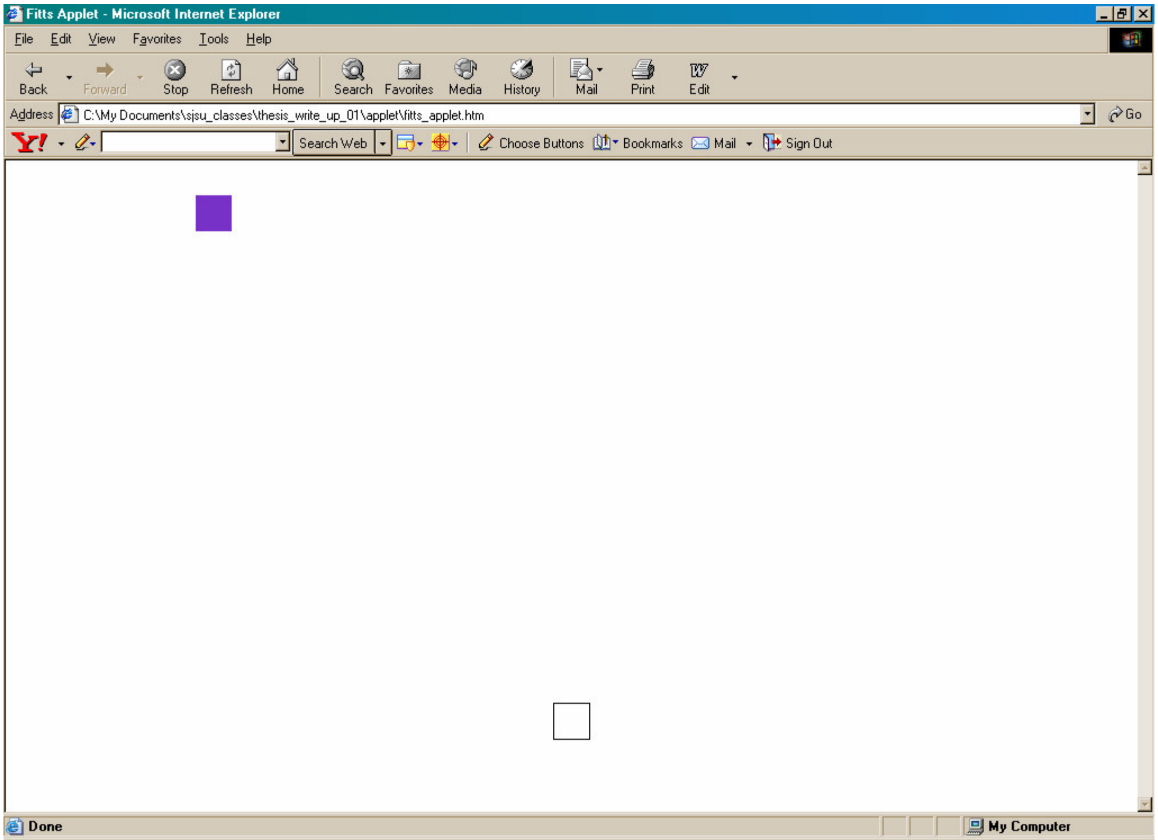
Appendix A

RGB Values for Target Colors

		Contrast	
	Color	Low (1)	High (2)
(1)	Black	230, 230, 230	65, 65, 65
(2)	Red	255, 220, 220	115, 0, 0
(3)	Green	200, 255, 200	0, 85, 0
(4)	Blue	230, 230, 255	0, 0, 170

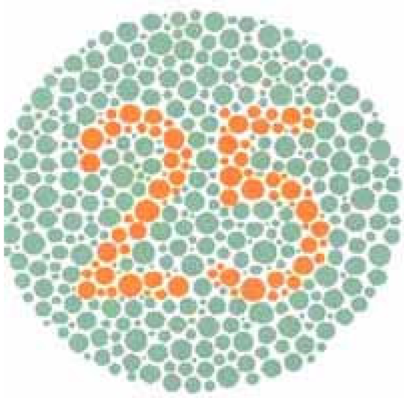
Appendix B

Screen Shot of Software

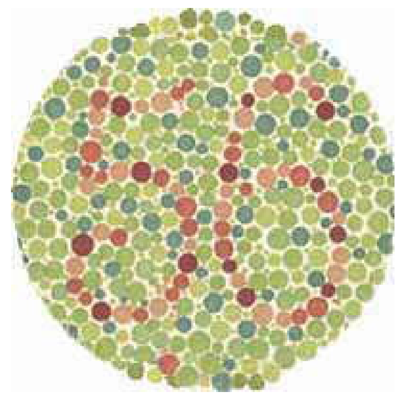


Appendix C

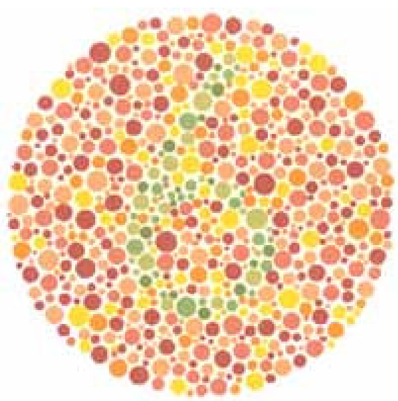
Ishihara Plates



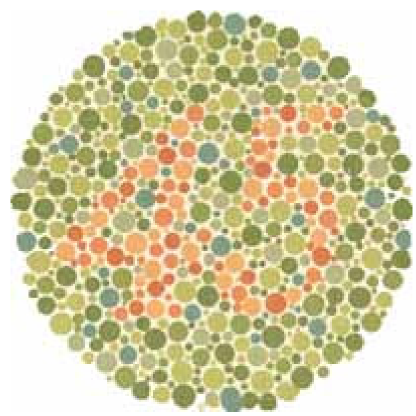
1



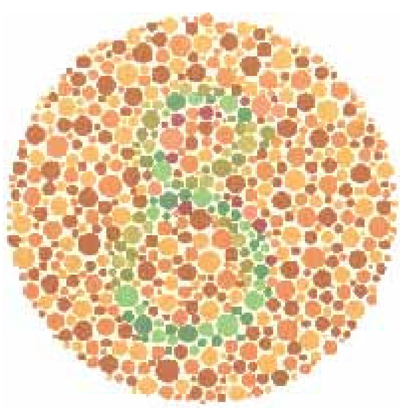
2



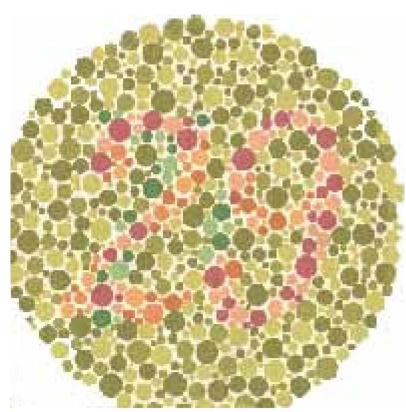
3



4



5



6

Appendix D

Color and Contrast in Aimed Movement Tasks

Instructions

For this experiment, you will be using software within a web browser, loaded on a desktop computer.

The display will consist of three elements. The first element, the *starting box,* is an outline of a square, consistently located at the lower center of the display. The second element, the *target*, is a solid square, varying in color, contrast, size and position. At the beginning of the session and between each trial, a *cue* will momentarily appear, as an outline of a square, indicating the position of the target for that trial.

The task for each trial in this experiment will be to first click within the starting box, then move the cursor and click the target as fast as possible, while maintaining accuracy.

A trial will be completed after the target is clicked on. At that time, the target will disappear and the cue will re-appear, indicated the beginning of the next trial and the position of the next target.

There will be 74 trials per experimental session. You will be requested to complete 5 experimental sessions. A break will be provided between each session. Before beginning the first session, you will be allowed a warm-up session.

Appendix E

Descriptive Statistics - Raw Data

	Color								Direction		
	Black		Red		Green		Blue		Direction		
Size	Low	High	Low	High	Low	High	Low	High	Left	Right	ALL
1	725	746	739	718	730	766	723	713	722	743	732
	190.1	235.3	259.5	170.5	224.5	332.9	176.6	176.3	228.8	225.0	227.1
2	849	878	883	844	861	869	854	842	851	869	860
	191.9	276.0	270.5	202.4	236.6	267.7	244.6	199.0	235.4	241.2	238.4
3	1077	1093	1069	1107	1069	1110	1105	1094	1078	1103	1091
	314.6	383.6	317.9	442.4	339.9	408.7	437.8	409.5	379.4	389.7	384.7
4	1383	1471	1382	1436	1389	1432	1423	1449	1423	1418	1421
	562.3	646.8	453.0	582.4	445.2	540.8	488.5	592.9	569.8	515.7	543.3
All	1009	1047	1018	1026	1012	1044	1026	1024	1019	1033	1026
	429.6	499.1	411.5	476.0	408.4	475.4	448.8	475.5	463.4	444.7	454.2

Note. Cell contents: movement times, mean and standard deviation

Appendix F

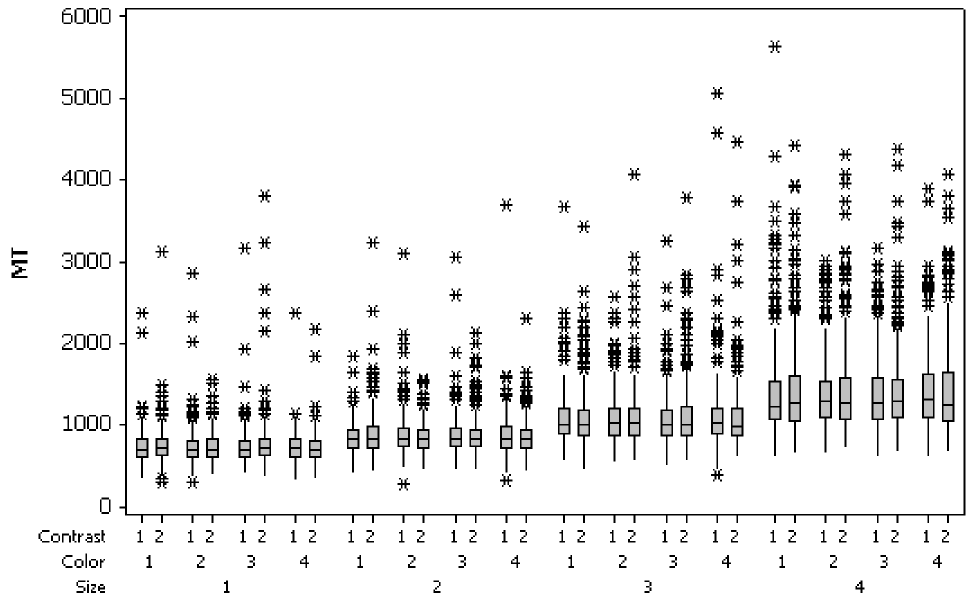
Descriptive Statistics - Adjusted Data

	Color								Direction		
	Black		Red		Green		Blue				
Size	Low	High	Low	High	Low	High	Low	High	Left	Right	ALL
1	695.6	711.0	692.7	694.8	687.9	700.2	700.5	685.7	684.8	707.3	696.1
	142.3	159.2	147.1	149.3	138.2	140.8	153.1	146.4	146.0	147.4	147.1
2	815.2	818.7	831.4	814.0	822.5	809.7	814.1	805.4	802.9	829.8	816.4
	169.7	168.8	177.1	162.3	166.2	172.0	170.4	157.8	165.5	169.5	168.0
3	1008.6	975.6	992.0	972.5	984.4	972.1	996.0	214.4	974.7	998.1	986.4
	214.5	202.1	200.6	190.4	213.7	205.4	211.4	989.8	202.5	210.3	206.7
4	1186.8	1175.8	1209.8	1186.8	1220.4	1191.7	1242.4	1157.9	1181.4	1211.5	1196.5
	251.2	307.5	266.9	238.2	299.0	268.7	317.6	260.5	277.7	277.9	278.1
All	926.6	920.2	931.5	917.0	928.8	918.4	938.3	909.7	911.0	936.7	923.8
	273.0	279.0	279.4	263.3	291.1	274.1	302.2	268.8	277.0	280.7	279.1

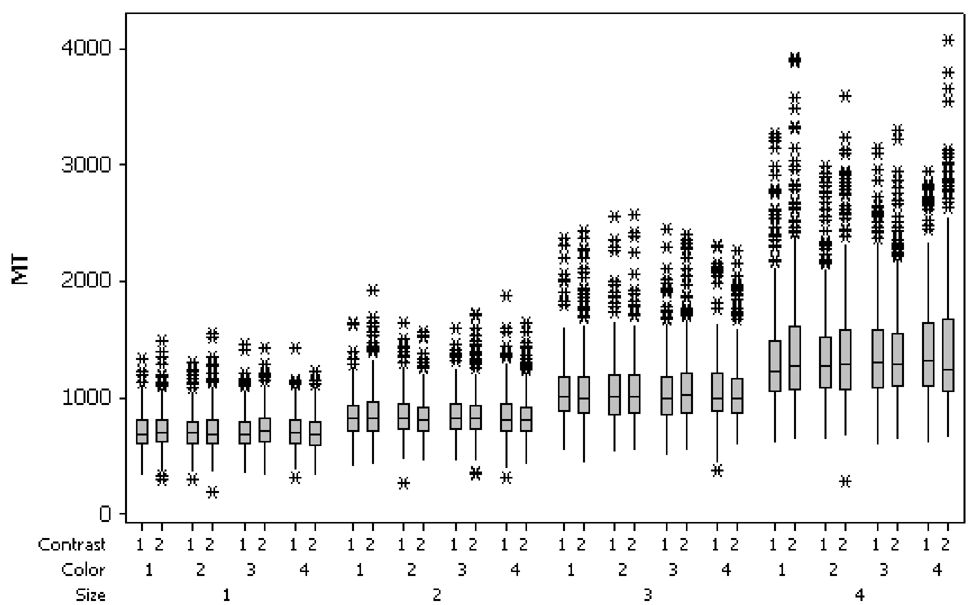
Note. Cell contents: movement times, mean and standard deviation

Appendix G
Boxplots of Movement Time

A.



B.

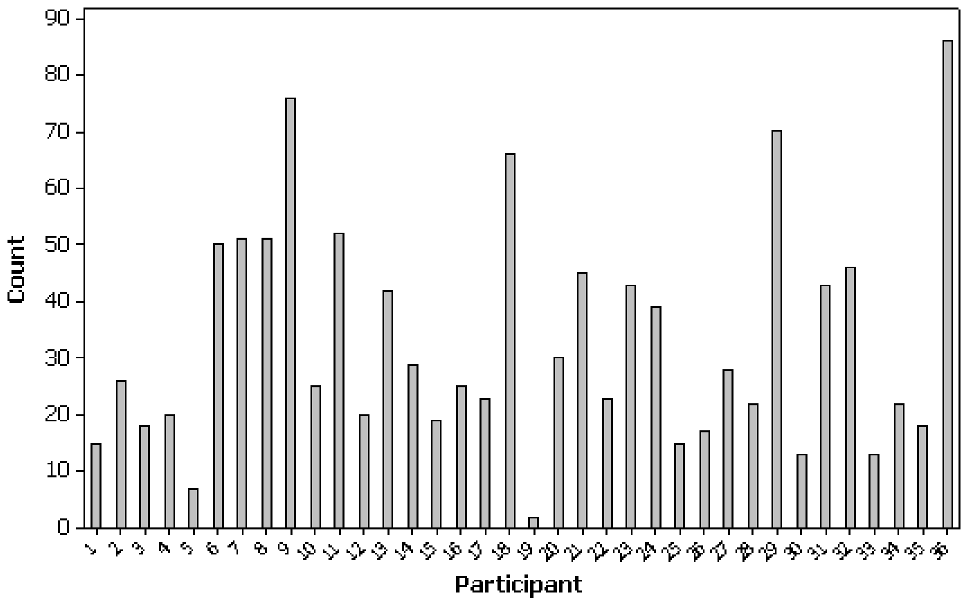


Boxplots of movement time versus size, color and contrast. Instead of the default 3x the interquartile range to identify outliers, a 4x multiplier was used to identify outliers in the raw data (A), resulting in the adjusted data (B).

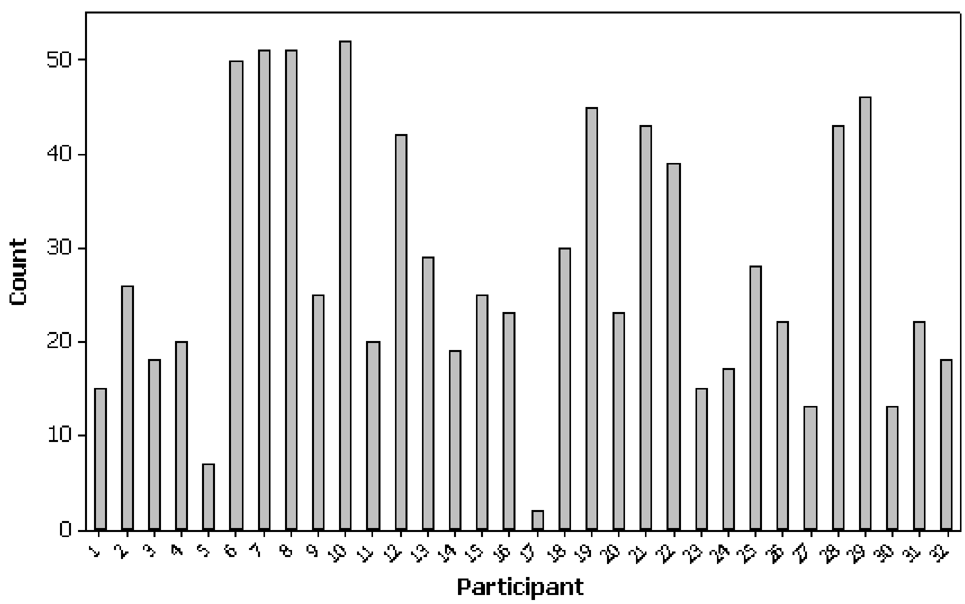
Appendix H

Barcharts of Errors

A.



B.



Barcharts of error counts versus participants. Unadjusted error data (A) identifies four participants (9, 18, 29, and 36) with a high number of errors. Those four participants' data was removed, resulting in the adjusted data (B).

Appendix I

Movement Time and Error Rates: Size x Color x Contrast on adjusted data

Size		Black Low	Black High	Red Low	Red High	Green Low	Green High	Blue Low	Blue High	ALL
1	MT (mean)	696	711	693	695	688	700	701	686	696
	ER (count)	4	3	5	4	6	4	3	1	30
	ER (mean)	0.0156	0.0117	0.0195	0.0156	0.0243	0.0156	0.0117	0.0039	0.0147
2	MT (mean)	815	819	831	814	823	810	814	805	816
	ER (count)	10	16	7	7	5	17	8	15	85
	ER (mean)	0.0391	0.0625	0.0273	0.0273	0.0195	0.0664	0.0313	0.0586	0.0415
3	MT (mean)	1009	976	992	973	984	972	996	214	986
	ER (count)	20	31	31	36	20	38	28	27	231
	ER (mean)	0.0781	0.1211	0.1211	0.1406	0.0781	0.1484	0.1094	0.1055	0.1128
4	MT (mean)	1187	1176	1210	1187	1220	1192	1242	1158	1197
	ER (count)	60	87	60	79	62	75	50	73	546
	ER (mean)	0.2344	0.3398	0.2344	0.3086	0.2422	0.2930	0.1953	0.2852	0.2666
All	MT (mean)	927	920	932	917	929	918	938	910	924
	ER (count)	94	137	103	126	93	134	89	116	892
	ER (mean)	0.0918	0.1338	0.1006	0.1230	0.0910	0.1309	0.0869	0.1133	0.1089