2004

The Effects of Object Weight and Three-Dimensional Movement on Human Movement Time and Fitts' Law

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The Effects of Object Weight and Three-Dimensional Movement on Human Movement Time and Fitts' Law

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A thesis submitted in partial fulfillment
of the requirement of the degree of
Masters of Science
(Industrial and Systems Engineering)
Rochester Institute of Technology
2004

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CERTIFICATE OF APPROVAL

MASTER OF SCIENCE DEGREE THESIS

The M.S. Degree Thesis of Kyle Hagadorn
has been examined and approved by the thesis committee
as satisfactory for the thesis requirement of the
Master of Science degree.

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1. Abstract

The speed and accuracy of movement depend on several factors that have been previously identified including target size and movement amplitude. According to Fitts' Law these variables comprise an Index of Difficulty that is directly related to the movement time. This principle of human performance has been studied extensively over a wide array of settings and contexts. The objective of this thesis was to investigate human movement time for tasks requiring precision placement of weighted objects, a task frequently encountered in industrial and occupational settings. Specifically, this thesis evaluated the effects of object weight, complexity of movement, and handedness on movement time. Complex movement in three dimensions and use of the dominant hand was found to significantly decrease movement time. It was also found that as probe weight increased, movement time increased in a logarithmic pattern. Fitts' Law in its original form was found to be an accurate predictor of overall movement time for the data obtained in this study. However, Fitts' original equations were improved by incorporating a term that accounted for the weight of the probe. The theoretical and practical implications of these results are discussed.

2. Introduction

Beginning with the work of W. L. Bryan in 1892, a large body of research has emerged that has investigated human movement. Many of these researchers have attempted to model the factors that affect human movement time in an attempt to better understand human motor control and to be able to predict movement times under various conditions. The experiment that has achieved the most notoriety and that has served as a common base in many subsequent experiments was performed in 1954 by Paul M. Fitts, who hypothesized that the human motor system has a fixed information transmission capacity. This experiment led to the movement time predictor known as "Fitts' Law."

Since the development of Fitts' Law, many researchers have successfully applied it in a wide variety of settings using a number of variations of the original model. This research investigates movement time within the context of industrial tasks that require precision placement. Specifically, these types of tasks involve human movement in three-dimensional space and require the human operator to move and place objects that may vary in weight. The effects of these variables on movement time and their relationship to Fitts' Law have not been studied. The main questions that this study will investigate are as follows:

1. How does three-dimensional movement of an object affect movement time in comparison to simple one-dimensional movements?

2. How does the weight of the object moved affect movement time?

3. Does Fitts' Law model predict movement time in the context of these task variables?

The results of this study could be applied to a large number of industrial, construction, manual material handling, and assembly tasks in which a human operator must move and precisely place some object.

3. Background

3.1 Fitts' Law

In his original study, Fitts (1954) hypothesized that the human motor system has a fixed information transmission capacity, and he performed one of the most well known studies in this area of research to test this hypothesis. Three experiments were performed: a reciprocal tapping task, a pin transfer task (pin from hole to hole), and a disc transfer task (washer from pin to pin).

Through these experiments, Fitts was able to prove the concept of a fixed information transmission capacity of the human motor system. It was shown that as tolerances were made tighter and amplitudes of movement were increased, movement times also increased. The opposite was also true. As tolerances were loosened and amplitudes decreased, movement times decreased. It was found that the movement time could be accurately predicted by the equation: Movement Time = $a + b \log_2 (2A / W)$, where a and b are regression coefficients, A is the amplitude of movement (the distance from the center of one target to the center of the other), and W is the width of the target, which in the pin transfer task, was the difference between the diameter of the pins and the holes.

The tasks performed all have an associated "Index of Difficulty"(ID) which is defined as $\log_2(2A / W)$ bits/second. The Index of Difficulty was developed to show the minimum amount of information required for each movement. Along with the Index of Difficulty, an Index of Performance was also proposed. The Index of Performance is $t \log_2(2A / W)$ where t is the average time in seconds per

movement. Fitts was able to test his hypothesis of a fixed information transmission capacity by comparing the movement times of tasks with respect to their Index of Performance. It was found that Index of Performance remained relatively constant over the best trials of each task, and it was shown that the best performance fell between 10 and 12 bits/second. The degree of consistency that was found helps to support the hypothesis that motor system performance capacity is relatively constant over a large range of tasks.

Previous authors (Ellison, 1949) had proposed that movement duration would remain constant as the amplitude of movement increases. Fitts' data helps to disprove this, however at the same time this showed that movement of different amplitudes but with equal difficulty would have very close to equal movement times. However, Fitts also noted that the capacity of the motor system most likely varies a great deal for different movements, limbs, and muscle groups.

Welford (1968) took Fitts' movement time equation and by analyzing various aspects, was able to make it slightly more robust. In Fitts' equation, multiplying the movement amplitude by two is arbitrary, but it originally seemed necessary to ensure that the logarithm was always positive. Welford found that by modifying the movement equation, a slightly more accurate prediction could be made. Welford's modified movement time equation is: $MT = k * \log_2 ((A/W) + (1/2))$. This equation also allows for the same problem that Fitts' had accounted for by multiplying the amplitude by two, in that the logarithm cannot be negative.

3.2 *Extensions and Applications of Fitts' Law*

Since Fitts' work was published, an extensive body of work has emerged to explore how variations in the original "Fitts' task" affect movement time. In the original Fitts' task it was found that target width and movement amplitude, the parameters that comprise the Index of Difficulty, were significant factors affecting movement time. Since then, these parameters have been altered and adapted to a wide variety of applications, as described below.

One of the first topics that was analyzed by a number of experimenters was the relationship between the target depth (dimensions of the target in the y-axis) and target width (dimensions of the target in the x-axis) in an effort to discover its effect on movement time. Further definitions of the x- and y-axes can be seen in Figures 1a-c. Crossman (1956) found results that were consistent with the results found by Fitts (1954). With regard to target width, Fitts' study was only concerned with the horizontal width of the target used, however Crossman demonstrated that the vertical length of the target also affects movement time, albeit to a smaller degree. It was found that the contact points where the subject hit the target formed roughly an ellipse with the long axis along the axis of movement and the short axis perpendicular to the axis of movement. From this data, he suggested that a combined Index of Difficulty using both the width and depth dimensions of the target should be used. The data suggested that the difficulty of the whole task consisted not of just the width of the target, but the sum of the difficulties for each direction. Crossman presented a new movement time formula, which was $MT = a + b\,[\log_2 (A/W) +$

$\log_2$ (A/D)]. This experiment was limited, however, because only two subjects were used to collect the data.

Hoffmann and Sheikh (1994a) also analyzed the Crossman data and stated that it was likely that vertical length of the target would have no effect unless it was smaller than the natural scatter of hits on the target. To prove this theory, an experiment was conducted to determine the effects of target depth (length) on movement time. Their experiment consisted of subjects performing both discrete and reciprocal tapping tasks. A constant amplitude was used, and the conditions used included three target widths and seven target depths (lengths). It was found that there are three well-defined regions of control. These were when the Index of Difficulty using the width in the direction of motion is larger than the Index of Difficulty based on the depth (length) of the target, when both the width and depth (length) constraints create the same Index of Difficulty, and when the Index of Difficulty using the depth of the target is larger, and therefore dominates movement time. Fitts' Law was found to hold true for two out of the three conditions. It was determined that when the target depth was equal to target width, Fitts' Law was not validated for discrete tasks. It was also found that target depth (length) and target width, as well as the interaction between the two were all significant in a reciprocal tapping task.

When analyzing target length, Drury (1971) proposed an alternate movement time equation. By performing a new experiment, Drury proposed that when determining movement time, the Index of Difficulty should be the maximum ID of the lateral width and the depth of the target. The proposed equation is

MT = function [maximum (ID_H, ID_V)] where ID_H is the Index of Difficulty when using the lateral width of the target, and ID_V is the Index of Difficulty when using the depth of the target. This equation uses the Index of Difficulty created by the governing target dimension. This equation was applied to the data collected by Hoffmann et al. and was shown to fit the reciprocal task data with an R^2 value of .97. This model did not fit the discrete data as well however.

3.3 Variations in Task Variables

3.3.1 Discrete vs. Reciprocal

While Fitts' experiment analyzed reciprocal tasks, where a probe is moved back and forth between adjacent targets, other researchers have found that discrete movements, where the probe is moved one time per trial, have a different effect on movement time. It has been shown in various studies that reciprocal movements are slower than discrete movements (Fitts and Peterson 1964, Hoffmann and Sheikh 1994a). This difference is attributed to a number of factors, the first being the "time on target," which refers to the time in which the probe is in contact with the target surface before the reciprocal movement is performed. This inevitably leads to longer recorded times when the individual movement times are analyzed. Hoffman and Sheikh (1994a) also showed that as task difficulty increased, so did the time on target. This is due to the fact that subjects spend larger amounts of time on target acquisition and movement planning as the difficulty of the task increases. The second reason is the "turn around time." The turn around time is the time it takes for the human motor system to bring the probe to a stop on the target, acquire the new target for the

reciprocal movement, and begin accelerating towards this new target. This is a necessary activity associated with any reciprocal movement.

3.3.2 Foot Movement

Fitts' Law has also been applied to tasks using different muscle systems of the body to see whether or not it was consistent with human performance. For example, Drury (1975) conducted an experiment dealing with the movement time of feet. This research was motivated by the fact that operators use foot-operated controls on a daily basis, and an understanding of human performance may be used to design better systems that allow the operator to use the equipment more quickly and effectively. This also applies to drivers in general as these results can be used to design passenger vehicles more effectively. It was shown that Fitts' Index of Difficulty equation was an accurate predictor of movement time with R^2 values of.9700 and .9758 for the two experiments conducted.

3.3.3 Two-Handed Movement

Mottet, Guiard, Ferrand, and Bootsma (2001) performed an experiment to evaluate the movement time of two-handed, reciprocal Fitts' tasks. The tasks analyzed included moving a pointer to a stationary target, moving a target to a stationary pointer, and moving the target and pointer to each other bimanually. It was found that Fitts' Law held for all of the tested conditions, having an R^2 range of .959 to .974.

3.3.4 Target Shape

The shape of the target has also been shown to have an effect on movement time and Fitts' Law. Sheikh and Hoffmann (1994b) conducted an experiment in which four different target shapes, a square, a circle, a diamond, and a rectangle, were used to evaluate the effect of target shape on movement time. It was found that for all target shapes, the ratio of standard deviation of hits in both the horizontal and vertical directions were constant. This meant that the movement time "could be expressed in terms of the constraint in the direction of motion." Fitts' original Index of Difficulty equation of $ID = \log_2(2A/W)$ was analyzed for each target shape, and it was found that a "shape factor" made the movement time vs. Index of Difficulty relationship constant between all shapes by translating the target's width into an "effective width" with a consistent formulation for all shapes. The new equation was $ID = \log_2(2A/K_SW)$ where K_s is the shape factor. Using shape factors to establish the effective width of the targets (when they are not rectangular) correlates the target shapes and can help describe the relationship between target shape and movement time.

3.4 Human Movement Time in Multiple Dimensions

Fitts' study only dealt with movement in a single dimension in which the subject moves the pointer between adjusted targets as shown in Figure 1a. This protocol obviously is not very realistic or consistent with real world activities since few activities are purely one-dimensional. Because of this, many researchers have sought to expand Fitts' research by involving multiple dimensions into their

studies. Some researchers have performed two-dimensional studies, while others have included all three dimensions in their work.

Most two-dimensional studies take place along the lateral and depth axes, and have seldom involved a vertical height axis. To illustrate these axes, a schematic has been provided below in Figures 1a-c.

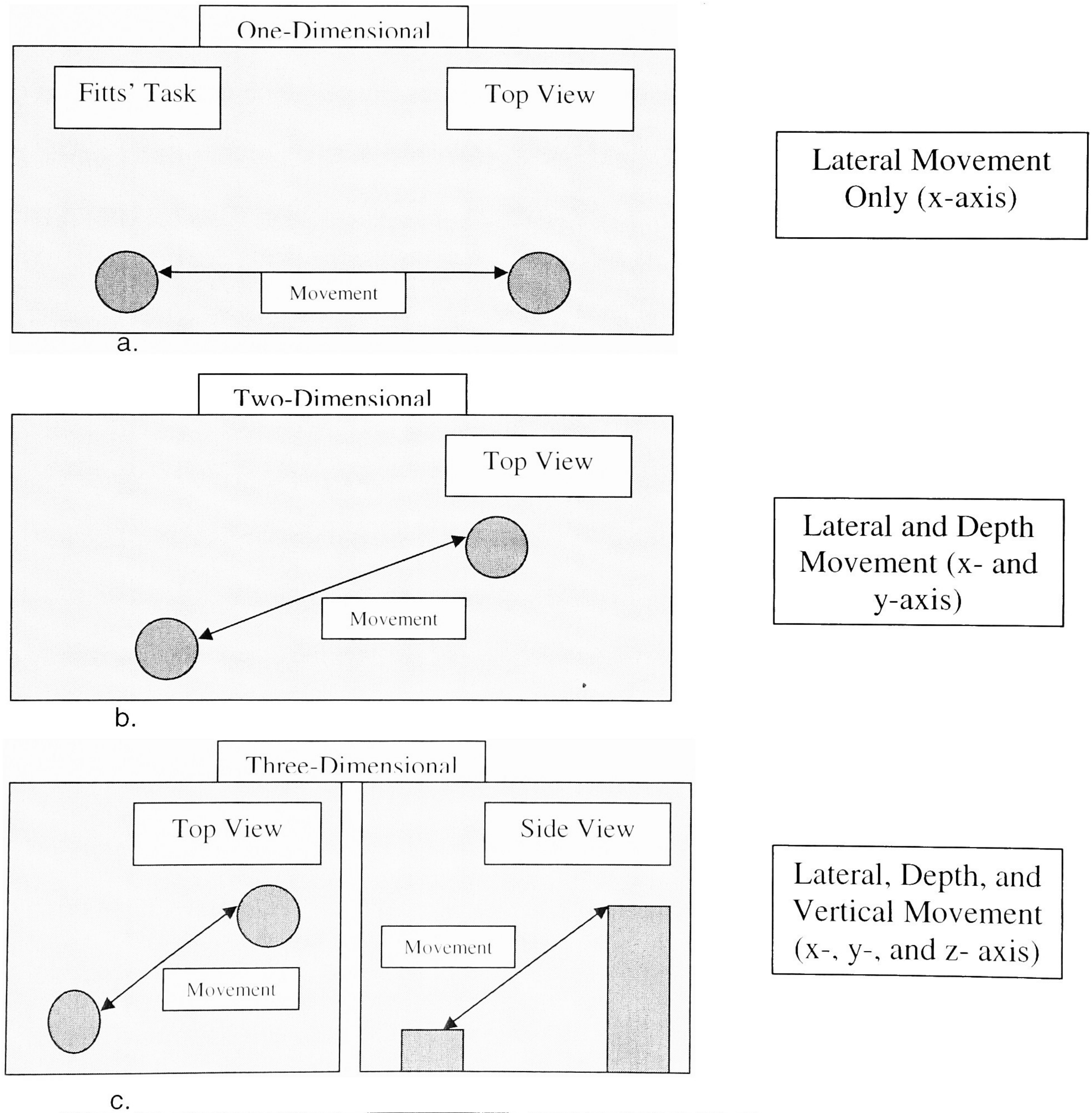


Figure 1a-c: ***One-, two-, and three-dimensional movement representations.***

Many researchers have sought to expand Fitts' research by adding a second dimension into their experiment in which the subjects move the pointer between targets that are offset in such a way that one target is farther away from the subject than the other. Mottet, Bootsma, Guiard, and Laurent (1994) conducted two experiments to see whether or not Fitts' Law was applicable to two-dimensional tasks. To do this, subjects were asked to draw a series of ellipses in which they had to pass through four targets, one at each apex of the ellipse. The size of these targets was varied to create different Indices of Difficulty for each axis, which varied between 3, 4 and 5 for each axis. For the first experiment, the lateral and depth axes had the same Indices of Difficulty, while in the second experiment the Index of Difficulty varied between the axes. Ellipse orientation was altered between having the long axis on the lateral and depth axis. For the first experiment, the only significant factor was found to be the Index of Difficulty ($p<.001$), and a significant linear fit between movement time and Index of Difficulty was found ($p<.001$). The second experiment found significance in Index of Difficulty for targets in the lateral axis ($p<.001$), Index of Difficulty for targets in the depth axis ($p<.001$), and in the interaction between the Index of Difficulties for the lateral and depth axes ($p<.001$). It was concluded that movement time in experiment two wasn't based on the highest Index of Difficulty between the lateral and depth axes as was hypothesized, but rather that interdependence exists between Indices of Difficulty of both the lateral and depth axes. To analyze this data with respect to Fitts' Law, the mean Index of Difficulty was used. It was found that Fitts' Law describes movement time for two-

dimensional tasks very accurately. Of the total variability, 94.9% was accounted for, thus giving Fitts' Law further validity for two-dimensional movement.

To further extend Fitts Law, some researchers have evaluated the Fitts' task for three-dimensional movement shown in Figure 1c, in which the subject must also move the pointer in a vertical direction. This scenario is typical of a wide variety of assembly and manual material handling operations common in industry. Murata and Iwase (2001) conducted an experiment to see how Fitts' Law related to a three-dimensional pointing task. The experiment involved subjects using their finger (with a position sensor attached) to touch various targets presented to them in three-dimensional space. It was found that there were large variations in movement time, which were dependent on movement direction. Because of this, Fitts' Law in its original form did not model the movement time satisfactorily. A new Index of Difficulty formula was developed and the formula was $ID = \log_2 (A/W + 1.0) + c \sin \theta$, where c is an arbitrary constant determined through linear regression. It was found that movement times to targets in the upper directions (moving the pointer upwards) were typically longer than those to targets in the lower directions (moving the pointer downwards). This effect may be partially because downward movements are able to use gravity to assist in the movement, while upward movements must work against gravity forces. Because movement time varies so much with the direction of movement, Fitts' Law couldn't adequately predict movement times for three-dimensional movement and needed to be modified.

3.5 Force and Psychomotor Responses

Another task variable that should affect the movement time for precision placement is the weight of the object moved. From the standpoint of motor control and biomechanics it is intuitive that heavier objects should take more time to move. Thus for applications such as assembly work, construction work, manual material handling and precision placement, it is unclear what effect object weight has on the information transmission capacity described by Fitts.

In his original study, Fitts (1954) analyzed stylus weight in the reciprocal probe-tapping task. For the reciprocal tapping task, two different styluses were used. One was of a very light weight that wasn't specified, and the second was ~1 pound. Fitts looked at the errors associated with each stylus weight, and found that there was a miss rate of 1.2% and 1.3% for the lighter and heavier styluses respectively. Such small error rates showed that the subjects were able to modify their performance to adjust to the change in stylus weight. It was also found that the largest proportion of errors was 3.6% for the lighter stylus and 4.1% for the heavier stylus. Fitts however, failed to analyze the movement time and information transmission rate with respect to stylus weight. It was simply noted that the performance rate with the heavier stylus was "relatively stable," the rate was slightly reduced, and that the region of optimum performance corresponded to the conditions with smaller amplitudes. Fitts failed to incorporate object weight into his equations for the Index of Difficulty, Index of Performance, and movement time. When analyzing Fitts' data, it can be demonstrated that weight has a significant effect on movement time. This

analysis is shown in the Appendix. This failure to include weight when calculating information transmission capacity and movement time needs to be addressed since it may be a significant factor.

Another experiment that investigated the effects of object weight on movement time was performed by Papzxanthis, Pozzo, and Stapley (1998). Their experiment consisted of vertical arm pointing movements in two directions, namely up and down, under loads of 0 and 0.5 kg. When analyzing the data, it was found that acceleration time (when computed relative to total movement time) was greater for downward movements than for upward movements. It was also shown that downward movements had smaller peak acceleration and higher peak deceleration in comparison to the upward movements. Interestingly enough, contrary to Fitts' data, no effects of load on movement time or relative acceleration were observed. This could have been because the weight used was almost negligible. The authors concluded that the results suggested a different planning process for movements with and against gravity. They also propose that gravitational force influences the processes controlling movement execution.

Jaric, Milanovic, Blesic, and Latsh (1999) performed another experiment that examined the effects of object weight on human movement. Their experiment analyzed the movement kinematics of single-joint movements while exposing subjects to expected and unexpected loads. A rigid "manipulandum" was used and this only allowed movement about the elbow in the horizontal plane. Different weights were attached to the manipulandum to change the moment of inertia. Subjects were instructed to move between a start and stop

point and the loads over the various trials were changed without the subject's knowledge (although the subjects did know that load changes could occur). The subjects were specifically told not to try and predict load changes and to assume that the load would be the same as the previous trial. It was found that when the load increased, there was also a significant increase in movement time. This was accompanied by a significant decease in peak velocity as well. It was also found that the expected load had no significant effect on either movement time or peak velocity. There were no significant changes in movement time and peak velocity between conditions of moving expected and moving unexpected loads.

An important limitation of this study as it relates to the proposed work is that the study did not simultaneously investigate how the weight of an object moved may have a combined effect with the variables that define a Fitts' task (e.g. amplitude and target width).

3.6 Fitts' Law and Precision Placement Tasks in Industry

The application of interest for this research is precision placement in manufacturing and industrial settings in which workers must align a "probe" object with some defined target. A simple example of this is using precision placement to place a part onto a tray or to align one component of an assembly with another. From an industrial engineering standpoint, there are many reasons why an understanding of movement time is important within this context. As was noted above, knowing the movement time of a task allows for a better prediction of the overall task time, which for traditional work movement methods allows for a more accurate workflow balance. Also, understanding the various effects that a

certain factor will have on movement time allows for tasks to be designed more effectively to take advantage of the conditions in which performance improves in order to achieve higher productivity from operators. Based on the research described above, there are clear gaps that this thesis intends to address. Specifically, very little research has been performed in the area of three-dimensional movement and it's relationship to movement time. In fact, the only study that was found involved a pointing task, and did not involve movement of objects in any way. In industry, a majority of the tasks involving movement time occurs in three dimensions.

This thesis will also investigate the effects of object weight on movement time. Past experiments have focused on weight and its effect on movement time, but very few of these experiments have direct industrial applications. Specifically, this previous work did not incorporate variables such as target width and movement amplitude, which are central to Fitts' Law. Fitts' original study considered probe weight to some extent, but the maximum weight used was only one pound, which has limited use in industry.

Though Fitts' Law has been analyzed from many different perspectives, certain factors important in precision placement tasks have not been analyzed in a way that is applicable in the field. This thesis will analyze the effects of three-dimensional movement and object weight on the movement time for a Fitts' task. Along with the original Fitts' factors of movement amplitude and target width this research will investigate the effects of hand dominance on movement time. A

comparison to Fitts' Law will also be used to test the validity of the original study under the various conditions of the experiment.

4. Methods

4.1 Overview

The purpose of the experiment was to determine the effects of object mass and three-dimensional movement on human performance for a precision placement task, as measured by movement time. To meet these objectives, an experiment was conducted in which subjects moved probes of various weight between targets of one-dimensional and three-dimensional orientation with their right hand, left hand, and both hands. To apply Fitts' Law to these results, target width and movement distance were varied systematically for all conditions.

4.2 Equipment

The "probe" used in this experiment consisted of a wooden handle to which weights could be added, and the "targets" consisted of two circular PVC pipe sections having effective diameters of 2.375 and 3.5 inches. These targets could be placed in a variety of orientations to achieve the necessary experimental conditions. Four 2.5 lbs circular weights were used to adjust the weight of the wooden probe. To obtain times, a stopwatch was used in conjunction with a video camera to verify the acquired times.

4.3 Subjects

The subjects for this experiment were male volunteers who were recruited from the student population at Rochester Institute of Technology and the surrounding Rochester, New York area. Subject age was between 20 and 23

years with a mean age of 21.3 years and a standard deviation of 1.1 years. Subjects were paid for their participation, and were required to sign an informed consent form prior to experimental testing. Subjects who had a history of musculoskeletal problems (joint, tendon, or muscle problems) were not allowed to participate in this study, as this experiment could have exacerbated those problems.

4.4 Procedure

The entire experiment was performed in the Human Performance Lab located in the Kate Gleason College of Engineering. To test the hypotheses of this experiment subjects performed a reciprocal placement task by moving a probe between the starting location (origin) and the chosen target for a variety of conditions. Subjects first performed a series of baseline trials in which the placement task was completed in one dimension as shown in Figure 1a (target origin on the same vertical level and at the same depth). The experiment was then replicated for three-dimensional movement in which the target was located at a different height and depth than the origin as can be seen in Figure 1c.

For both baseline and three-dimensional phases, a number of experimental conditions were varied to evaluate the proposed hypothesis. Consistent with the traditional Fitts' task, two different sized targets, 2.375 and 3.5 inches, were used. Also, two movement amplitudes, 10 and 20 inches, were used, allowing for four indices of difficulty. These movement amplitudes are vector distances since the three dimensional conditions require subjects to move simultaneously in x, y, and z directions. A drawing of the layout is shown in

Figures 2a and 2b. To evaluate the effects of object mass, the probe was also loaded with three different weights, ~1, 5, and 10 pounds. The subjects used both their right and left hands for each condition. Subjects also used both hands for the 10 pound probe weight for each condition.

Prior to performing the experiment, subjects stood in front of the table with their arm holding the probe that was resting in the origin. The table height was adjusted so that the subject's elbow was at 90°. Probe length was carefully maintained to remove whatever effect varied probe length might have. To do this, there was a specified area on the probe that the subjects were required to hold, regardless of the weight being used. This was controlled to prevent subjects from grasping the probe at a lower point when less weight was in place. Subjects were given approximately ten minutes to practice using the probes and targets prior to beginning the experiment. Both the one-dimensional and three-dimensional experiments were randomized for each subject, but all one-dimensional tasks were performed before three-dimensional tasks began. A rest period of one minute was provided between each experimental condition to allow the subjects to rest their muscles. A total of 56 trials were performed by each subject (28 three-dimensional and 28 baseline), and testing lasted approximately two hours per subject. These tasks were randomized for each dimension, with all of the baseline trials being conducted before any of the three-dimensional trails. Photographs of some of the various experiments performed can also be seen below in Figures 3a-f.

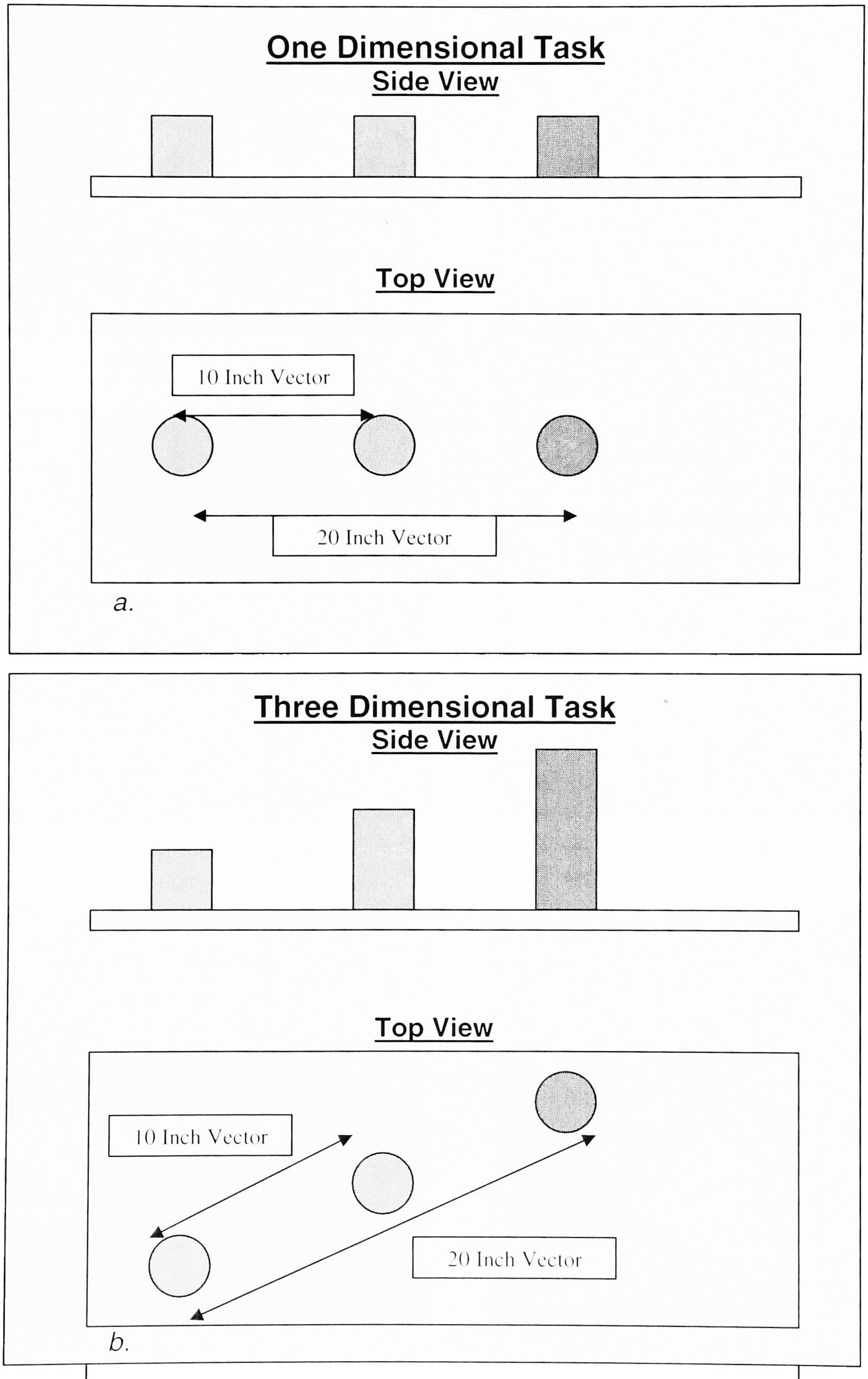
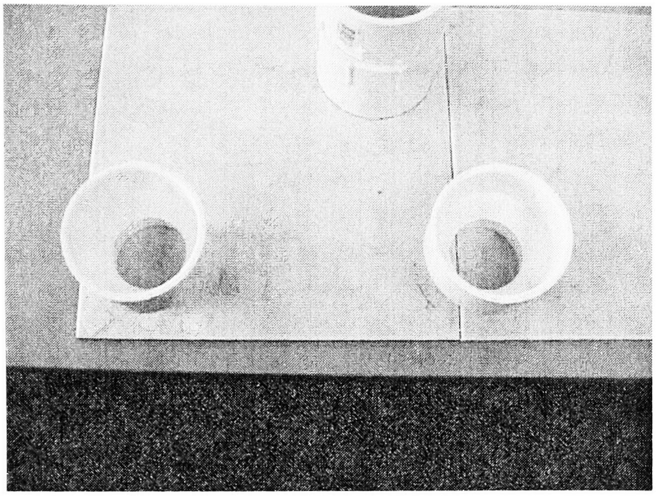
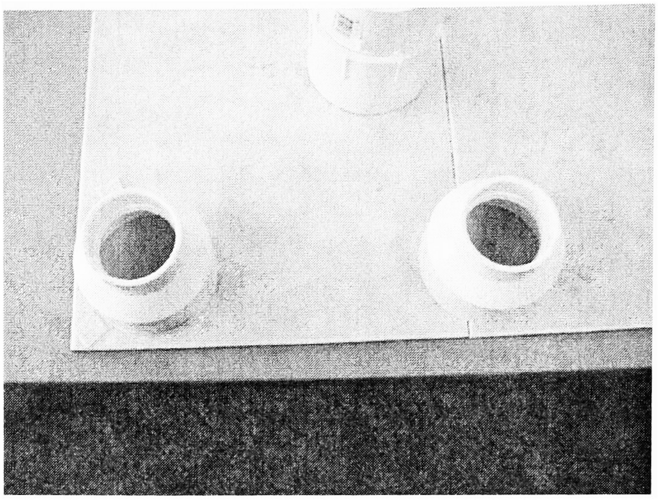
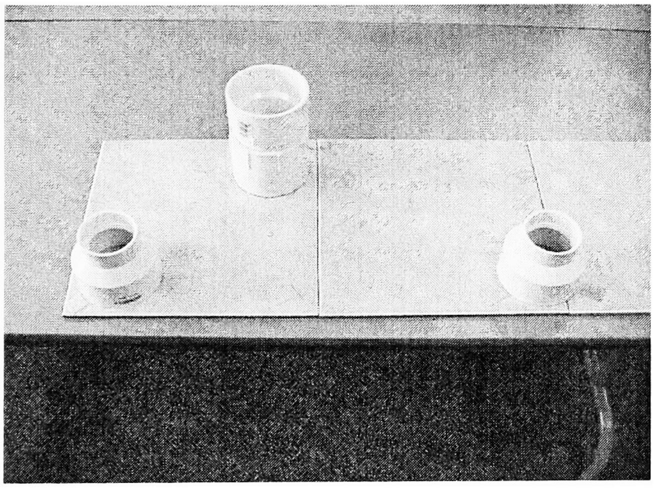
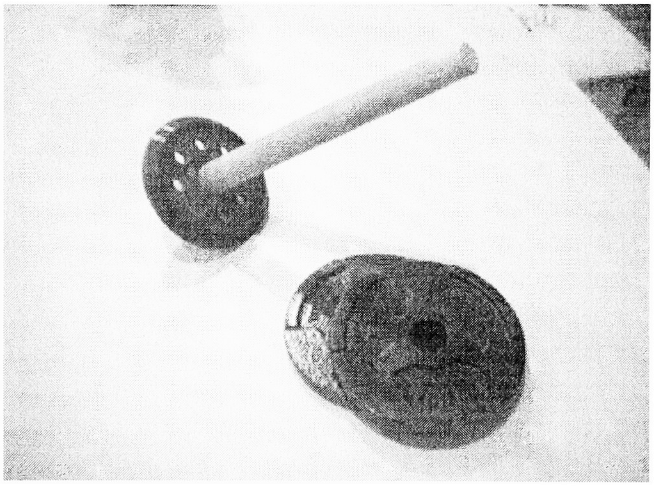


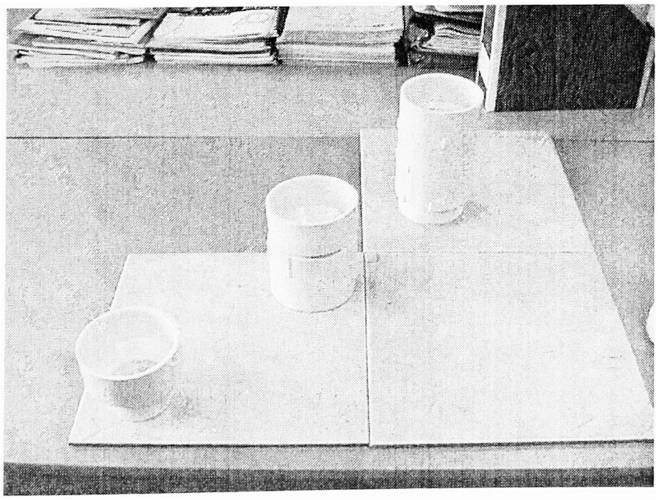
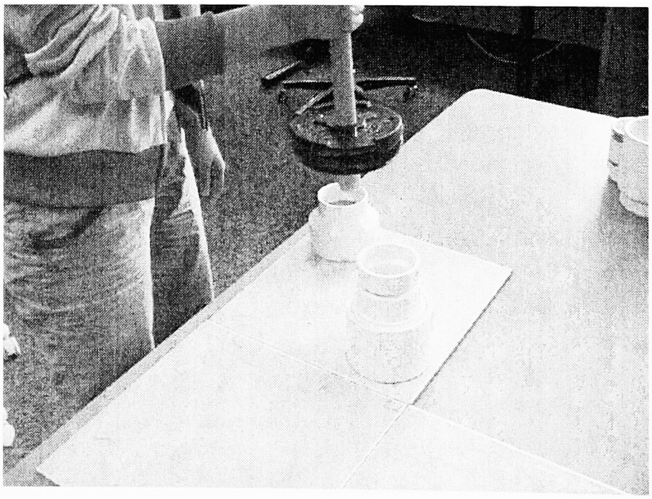
Figure 2a-b: One- and three-dimensional tasks performed in this experiment.

a. b.

c. d.

e. f.

<u>Figure 3a-f:</u> Various experimental conditions.

4.5 Analysis

Once the data had been collected, Analysis of Variances (ANOVA) were used to test for significant main and interaction effects. Tukey comparisons were used in conjunction with ANOVA in order to determine where significant differences existed between mean values. When an interaction was present, paired t-tests and one-way ANOVA were used to establish where the interaction occurred. Minitab statistical software was used for this analysis.

The dependent variable analyzed in this study was movement time in seconds. The following independent variables were analyzed:

- Movement Amplitude (10 and 20 inches)
- Target Width (1.25 and 2.375 inches)
- Hand Used (dominant, non-dominant, or both)
- Probe Weight (~1, 5, and 10 pounds)
- Dimensional Condition (one-dimensional and three-dimensional)

Once the main and interaction effects were analyzed, Fitts' Law was applied to the data to determine how the experimental factors may alter the relationship between movement time and Index of Difficulty.

5. Results

Table 1 lists all of the independent variables and interactions with their corresponding degrees of freedom, F- and p-values.

Independent Variable	Degrees Of Freedom	F-value	p-value
Movement Amplitude(Amp)	1	186.95	0.000
Weight(Wt)	2	225.09	0.000
Width(Wdt)	1	76.34	0.000
Hand	1	33.26	0.000
Condition(Con)	1	16.96	0.003
Interactions	**Degrees Of Freedom**	**F-Value**	**p-value**
Amp*Wt	2	9.84	0.001
Amp*Wdt	1	1.15	0.311
Amp*Hand	1	0.03	0.863
Amp*Con	1	3.35	0.100
Wt*Wdt	2	0.63	0.543
Wt*Hand	2	0.42	0.664
Wt*Con	2	1.04	0.373
Wdt*Hand	1	0.31	0.592
Wdt*Con	1	0.12	0.739
Hand*Con	1	0.48	0.507
Amp*Wt*Wdt	2	0.13	0.883
Amp*Wt*Hand	2	2.78	0.089
Amp*Wt*Con	2	0.11	0.893
Wt*Wdt*Hand	2	5.61	0.013
Wt*Wdt*Con	2	2.40	0.120
Wdt*Hand*Con	1	0.32	0.585

Table 1: Summary of all independent variables and interaction effects.

5.1 Movement Amplitude

5.1.1 Interactions

A significant, two-way interaction effect was observed between movement amplitude and probe weight ($F(2,18) = 9.84$, $p = .001$) as can been in Table 1 and is thus described first. Along with the Minitab analysis, two paired t-tests were conducted and an interaction plot was constructed to better understand the interaction. To perform this paired t-test, the data were first broken up in two different ways. For the first test, the data were broken up by amplitude and probe weight was analyzed. For the second test, the data was broken up by probe weight and movement amplitude was analyzed.

Figure 4 illustrates the interaction effect. The interaction occurs in that for the 20-inch amplitude a highly significant difference occurs between the five-pound and ten-pound weights (p=.00055) for the 10-inch amplitude, pairwise t-tests still reveals a statistically significant difference ($p=6.4 \times 10^{-14}$), but the significance level is much greater, which results in the interaction. This can be seen qualitatively in Figure 4 between five and ten pounds for the 10-inch amplitude compared to the 20-inch. While the interaction effect was statistically significant, its practical difference is negligible as it primarily represents subtle differences in the main effect. The t-tests for this analysis are shown in the Appendix.

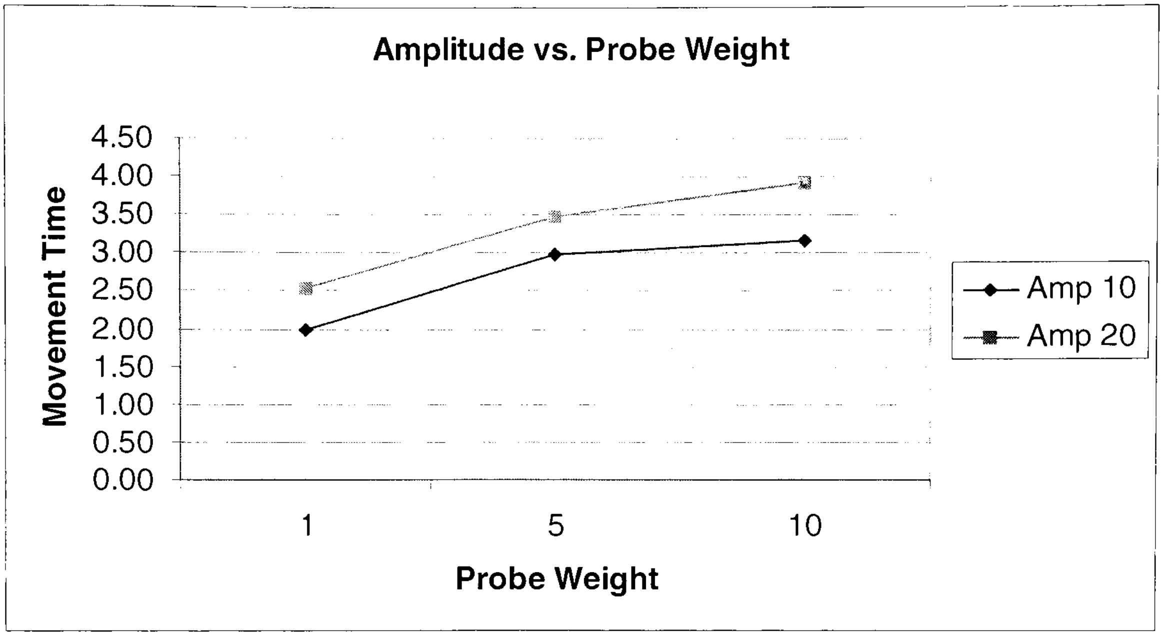


***Figure 4:* Movement time with respect to probe weight separated by movement amplitude.**

5.1.2 Main Effect

Although movement amplitude was involved in a two-way interaction as noted above, the single factor main effect was still analyzed because the interaction effect was so subtle. The main effect of movement amplitude was highly significant ($F(1, 9) = 186.95$, $p = .000$) and is illustrated below in Figure 5. The Minitab results are shown in the Table 1. The average movement time for the 10-inch movement was 2.71 seconds and the standard deviation was .77. The average movement time for the 20-inch movement was 3.31 seconds with a standard deviation of .85. Tukey comparison also showed that these mean values were significantly different from each other. Not surprisingly and consistent with Fitts' Law, more time is required to move the probe a longer distance.

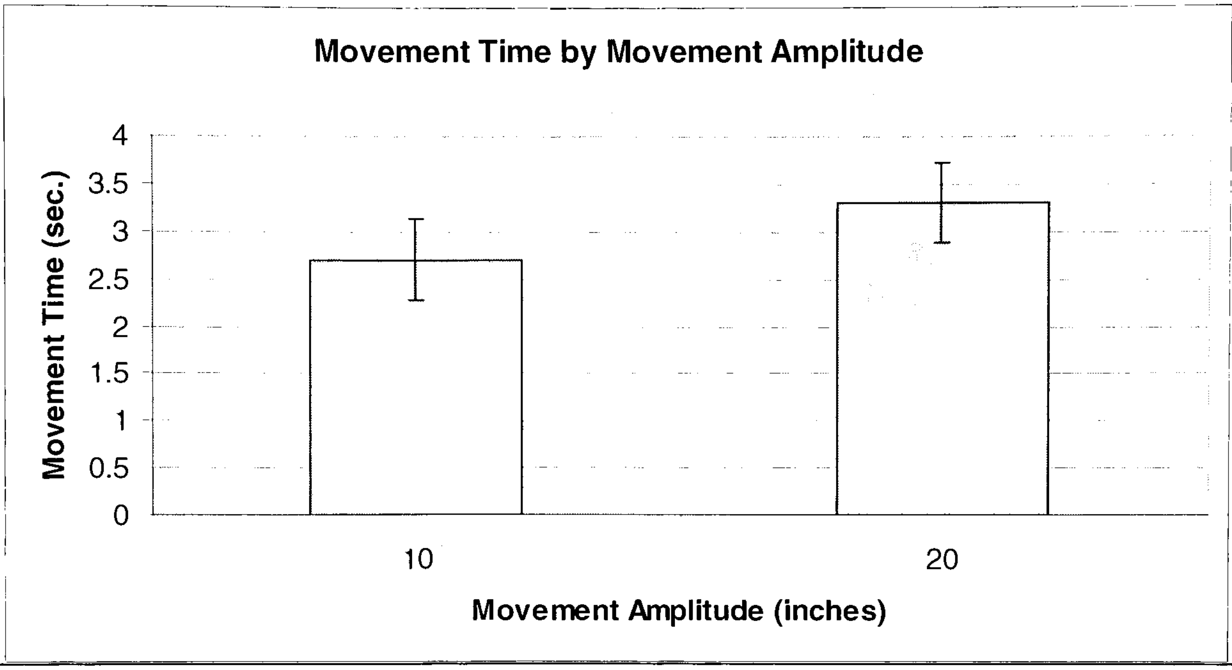


Figure 5: ***Average movement time for each level of movement amplitude.***

5.2 Probe Weight

5.2.1 Interactions

There was a significant interaction with movement amplitude as was noted above. In addition, probe weight was involved a significant three-way interaction ($F(2,18) = 5.61$, $p = .013$) with target width and hand used. Because the practical significance of the interaction was minimal, it is described in a separate section.

5.2.2 Main Effects

Although weight was involved in both a two and three-way interaction, the main effect was also analyzed because both interactions had little practical significance. The main effect of probe weight was also highly significant ($F(2,18)$ $F= 225.09$, $p = .000$) and is illustrated in Figure 6. The Minitab output can be

seen in the Table 1. The average movement time for ~1 pound condition was 2.26 seconds with a standard deviation of .60. For the 5-pound condition, the average movement time was 3.22 seconds with a standard deviation of .66. The average movement time for the 10-pound condition was 3.55 seconds with a standard deviation of .74. As was hypothesized, weight did have a significant effect on movement time. Tukey comparison also showed that the three levels of probe weight (~1, 5, and 10 pounds) were significantly different from one another. As was expected, more time is required to move the probe with a heavier weight. However, as can be seen from the graphs below in Figure 6, the relationship was not linear. The increase in movement time between the 5 and 10 pound conditions was 0.33 seconds, while the increase from the ~1 to 5 pound conditions was much higher at 0.97 seconds. It should be noted however that because only three weights were used, the relationship between movement time and probe weight should not be assumed to apply to all weights.

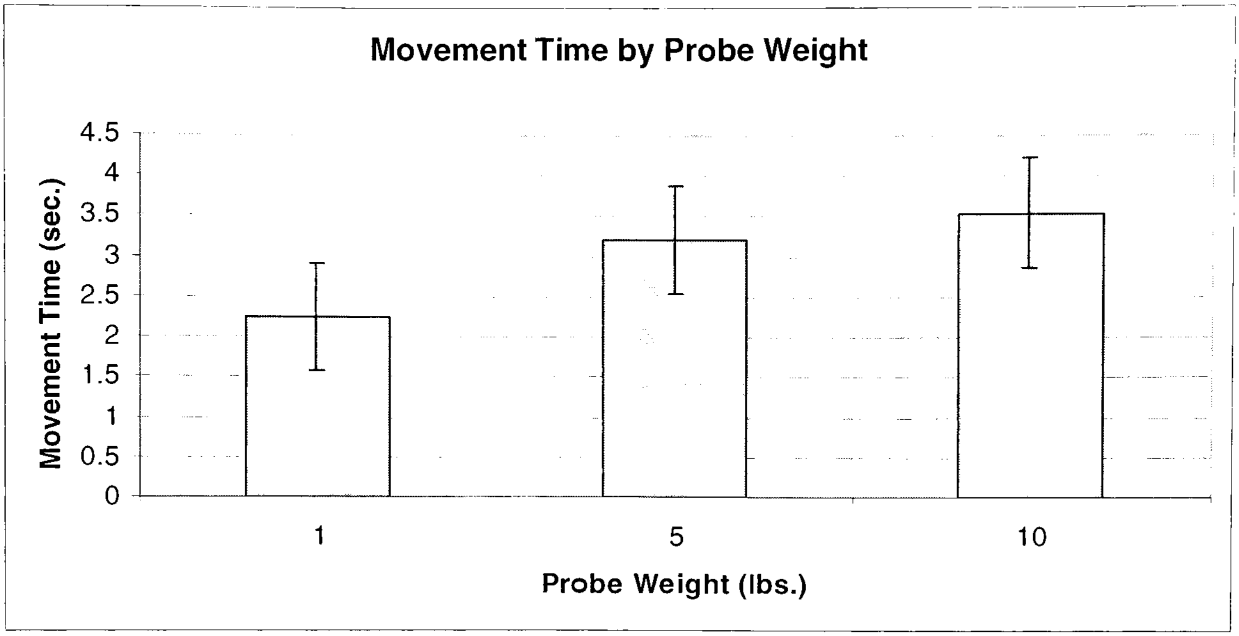


Figure 6: ***Average movement time for each level of probe weight.***

5.3 Target Width

5.3.1 Interaction Effects

There was a significant interaction between target width, hand, and probe weight as was noted above and described below. Once again, the effect had minimal practical significance.

5.3.2 Main Effects

The main effect of target width was also analyzed. This main effect was found to be highly significant ($F(1,9) = 76.34$, $p = .000$), and is illustrated in Figure 7. The average movement time for the target width of 1.125 inches was 3.21 seconds with a standard deviation of .88. The average movement time for the target width of 2.375 inches was 2.8091 seconds with a standard deviation of .81. As with the previous factors, an analysis of the Tukey comparison shows

that the target width conditions of 1.250 and 2.375 are significantly different from one another. Consistent with Fitts' Law, a smaller target width leads to a longer movement time.

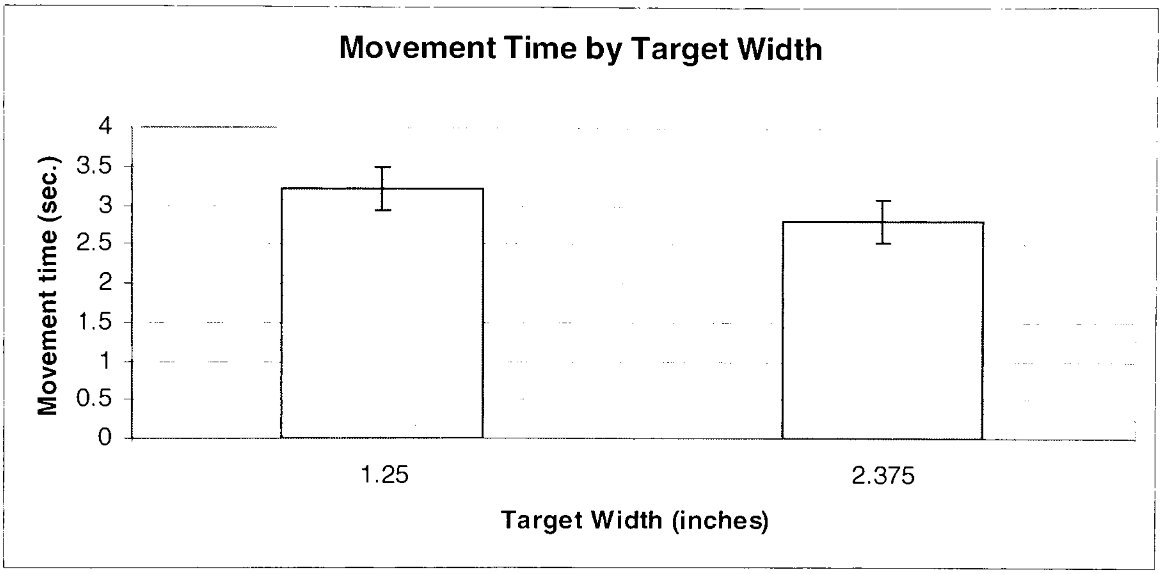


***Figure 7:* Average movement time for each level of target width.**

5.4 Hand

5.4.1 Interaction Effects

There was a significant interaction between hand, target width, and probe weight as was noted above and described below. Once again, the effect had minimal practical significance.

5.4.2 Main Effect

The main effect of hand condition was also evaluated. Since the two-hand condition was only evaluated for the ten-pound weight, analysis of hand effect

was separated into two components for evaluating the main effect. The first analysis considered the effect of dominant versus non-dominant hand, which was performed for all probe weights, and the second analysis incorporated the two-hand movement.

The main effect of hand (considering dominant and non-dominant conditions) was found to be significant ($F(1,9) = 33.26$, $p = .000$) and is illustrated in Figure 8. The average movement time for the dominant hand was 2.92 seconds with a standard deviation of 0.83, and the average movement time for the non-dominant hand was 3.10 with a standard deviation of 0.89. This factor had the largest p-value of all of the single factor analyses, which indicates that although it was significant, it was the least significant of all the single factors. Tukey comparison also showed that there was a significant difference between the dominant and non-dominant conditions. Looking at the data, it can be seen that on average, the dominant hand had faster movement times than the non-dominant hand.

The both-hand condition was then analyzed. Because the both-hand condition was only performed using the 10-pound probe weight, the analysis only used the data from the 10-pound condition. This analysis can be seen in the Appendix and below in Figure 9. All three hand conditions (dominant, non-dominant, and both) were analyzed and it was found that, for the 10-pound condition, hand was not a significant factor. Looking at the movement time averages, it is seen that the both-hand condition is the fastest, and the non-dominant hand is the slowest. A Tukey comparison was performed in order to

see whether there was a significant difference between the levels of the hand condition, and it was found that there were no significant differences between the three hand conditions. This was surprising in that the significant hand effect and significant Tukey comparison from the dominant and non-dominant hand that was obtained across all weights is no longer present when just looking at the 10-pound weight.

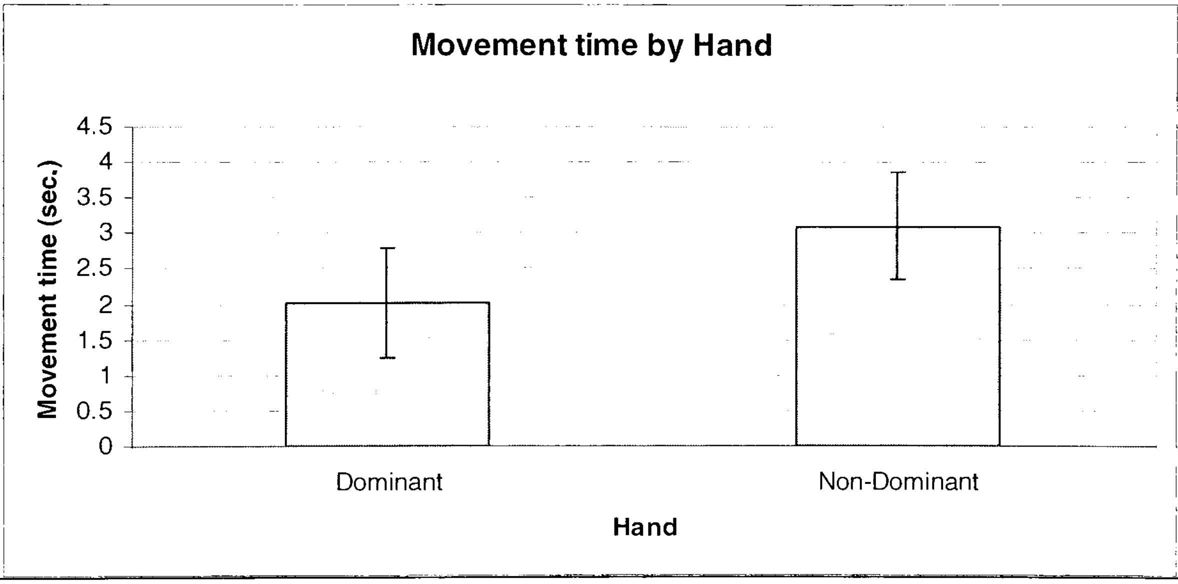


Figure 8: ***Average movement time for each level of hand.***

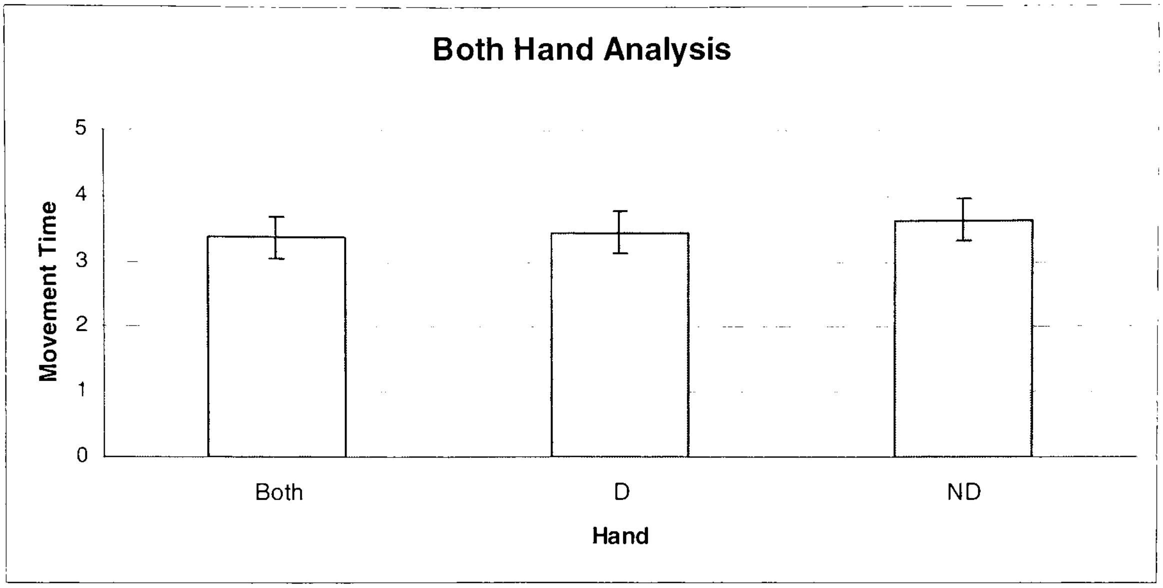


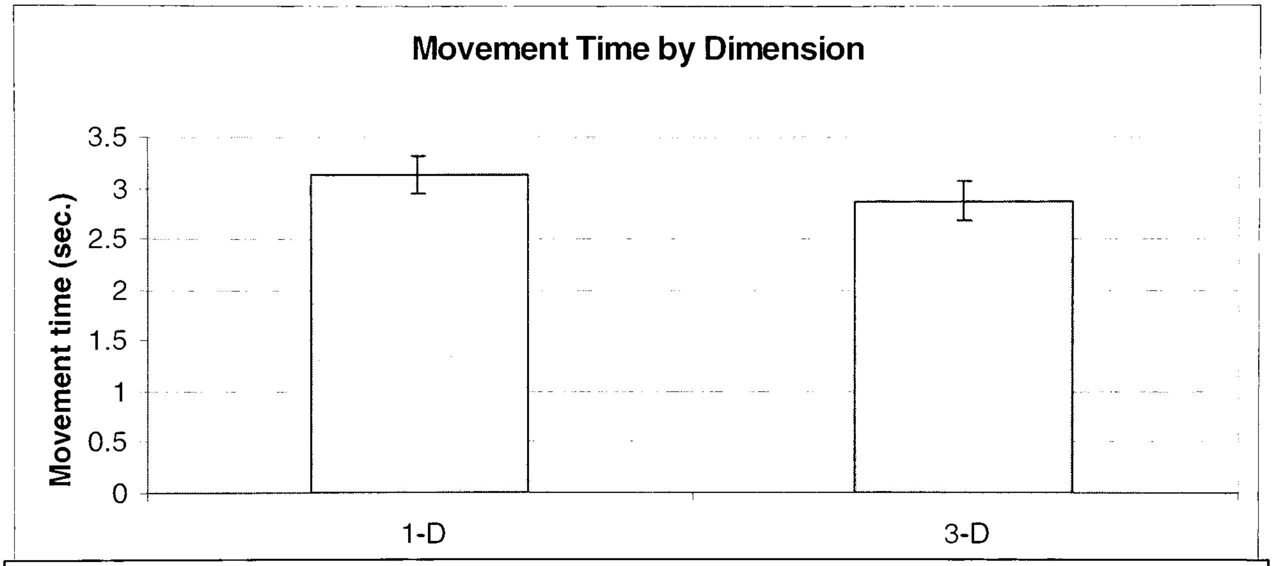
Figure 9: ***Average movement time for each level of hand (including the both-hand condition).***

5.5 Effect of Three-Dimensional Movement

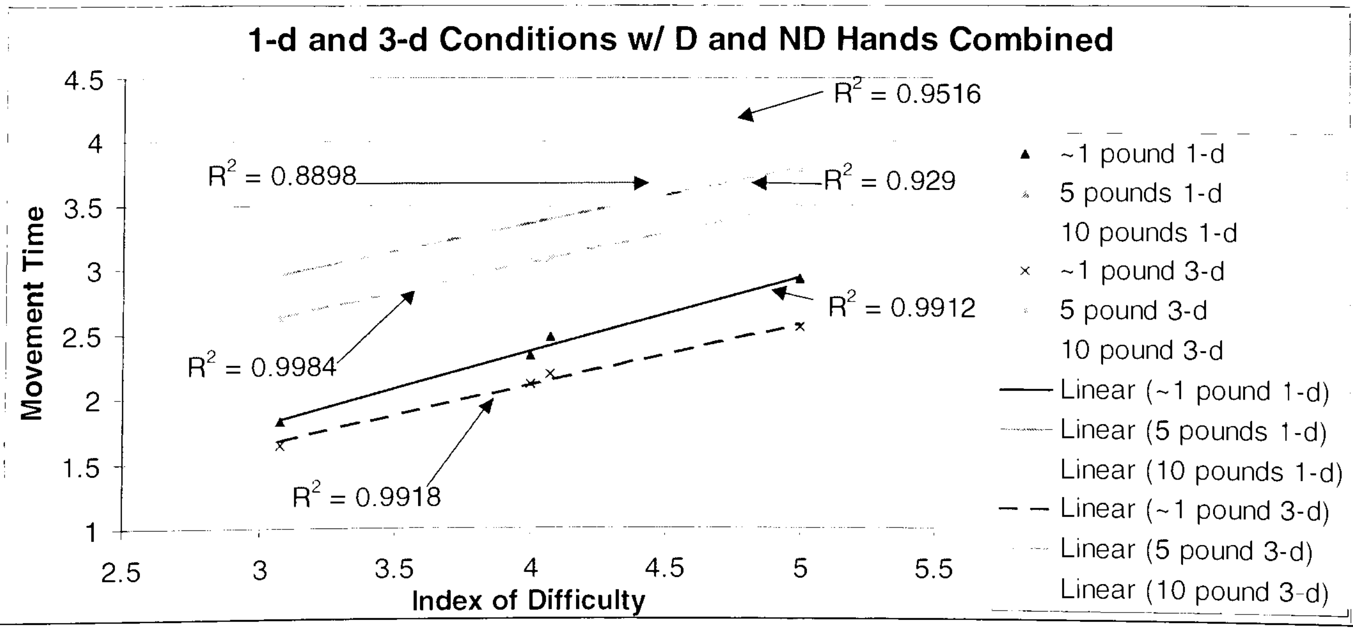
5.5.1 Main Effects

Dimensional condition (one-dimensional or three-dimensional) was not involved in any significant interactions. The main effect was analyzed and was found to be highly significant ($F(1,9) = 16.96$, $p = .003$). Figure 10 illustrates the main effect. The results of the analysis can be seen in Table 1. The average movement time for the one-dimensional condition was 3.14 seconds with a standard deviation of .91, and the average movement time for the three-dimensional condition was 2.88 seconds with a standard deviation of .80. Tukey comparison also showed that there was a significant difference between the two conditions. Surprisingly, movement time while performing the task in three dimensions was faster than the one-dimensional task by .26 seconds averaged across all conditions. An additional graph showing the decrease in movement

time between dimensions has been shown below in Figure 11, with the solid lines representing one-dimensional movement and the dashed lines representing three-dimensional movement.



<u>Figure 10:</u> Average movement time for each level of dimensional condition.

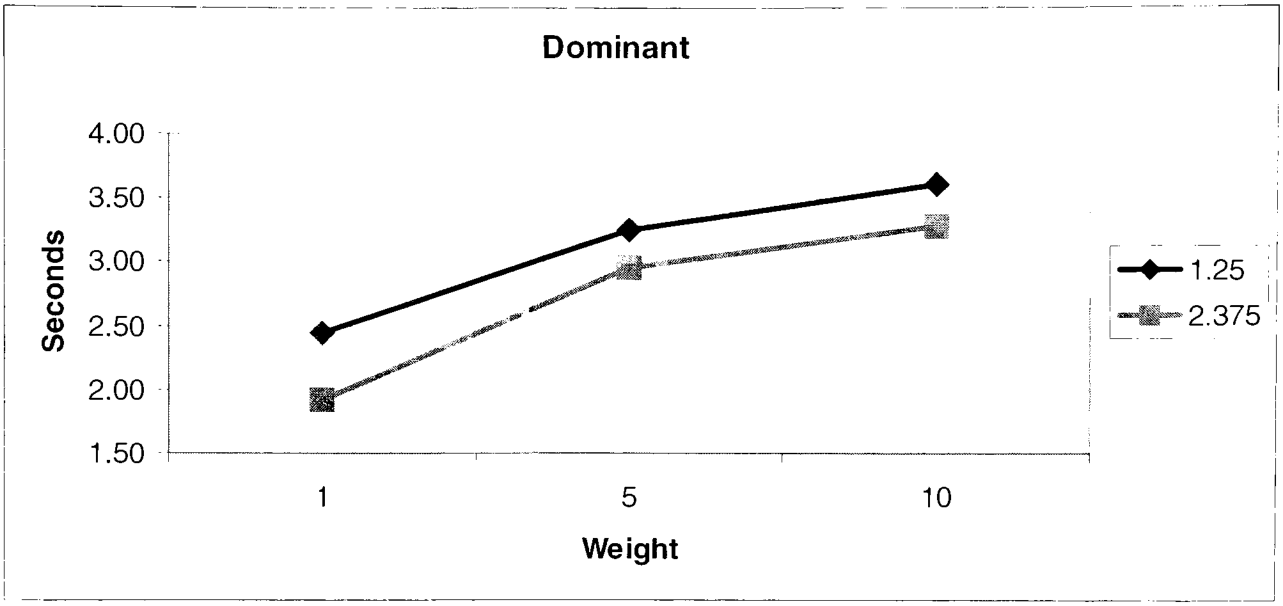


<u>Figure 11:</u> Fitts' Index of Difficulty plotted against movement times for each weight separated by dimensional condition.

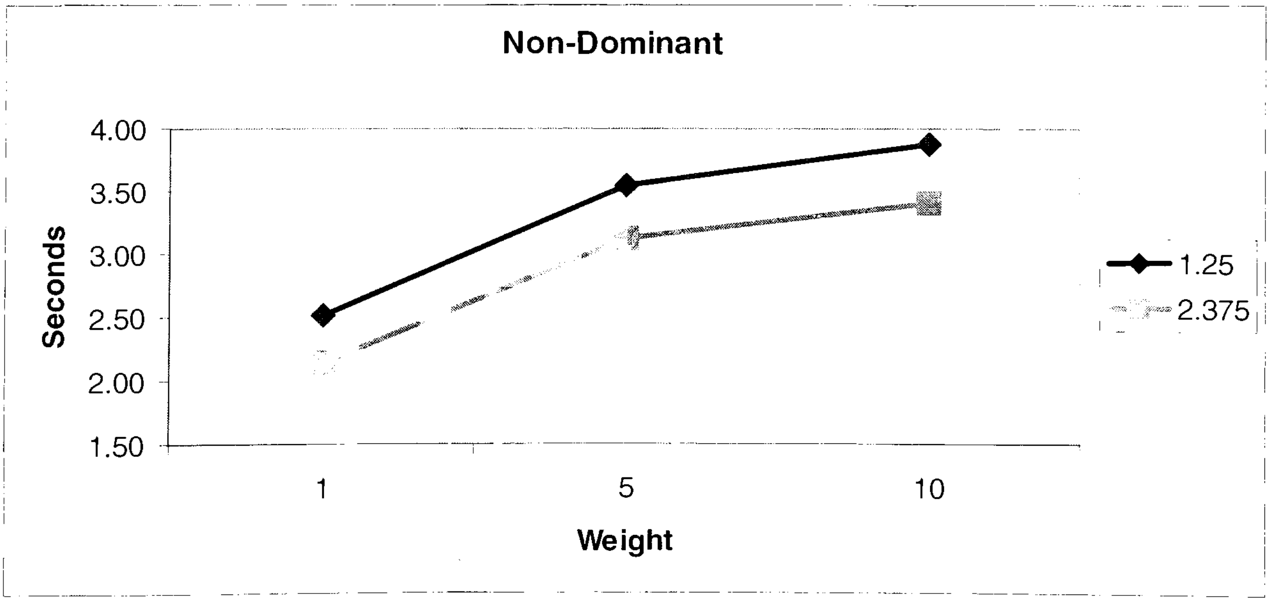
5.6 *Three-way Interaction*

A significant interaction was observed (F(2,18) = 5.16, p = .013) which involved target width, probe weight, and hand. The results of this analysis showing this interaction can be seen in Table 1, and the entire analysis can be seen in the Appendix. To help further understand this interaction, the factors were analyzed using paired t-tests in an attempt to isolate where the interaction was occurring. These t-tests can be seen in the Appendix. Since a three-way interaction implies that the behavior of a two-way interaction of two of the factors is different depending on the level of the third factor, Figures 12a and 12b represent the probe weight and target width interaction plot for both dominant and non-dominant levels of hand.

After performing a series of pairwise t-tests, it was found that the interaction was very subtle. For the dominant hand, the movement time increased significantly as probe weight increased from five to ten pounds for each of the two target widths. However, for the non-dominant hand, the movement time increase was still significant, but not as significant (p=.004 for 1.25 width, p=.0002 for 2.375 width). While the three-way interaction was statistically significant, it is of minimal practical significance.



a.



b.

Figure 12a-b: ***Movement time with respect to probe weight separated by target width and hand.***

5.7 *Application of Fitts' Law*

5.7.1 Low Weight Task

In order to compare this study with the original Fitts study, the movement time data from this experiment was plotted against Fitts' Index of Difficulty for both one- and three-dimensional data using a combination of dominant and non-dominant hand data (hereby referred to as the "combined" hand condition). All of the data in the graphs referenced below is from the ~1-pound condition, which occurred when the pointer was empty (i.e. no additional weights) and was the case for the original Fitts' Task. These graphs can be seen in Figures 13 and 14. It should be noted that Fitts' original task was only concerned with dominant hand movement.

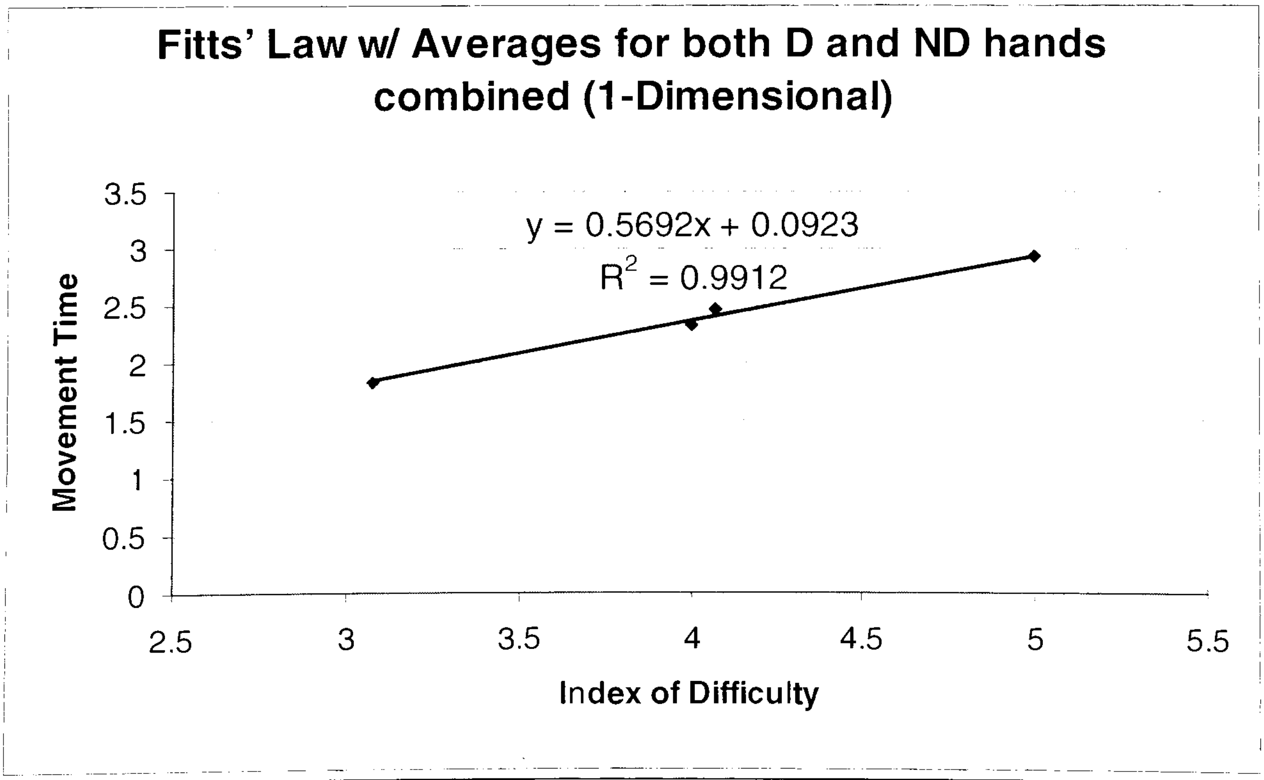


Figure 13: Movement time plotted against Fitts' Index of Difficulty for the baseline, one-dimensional task.

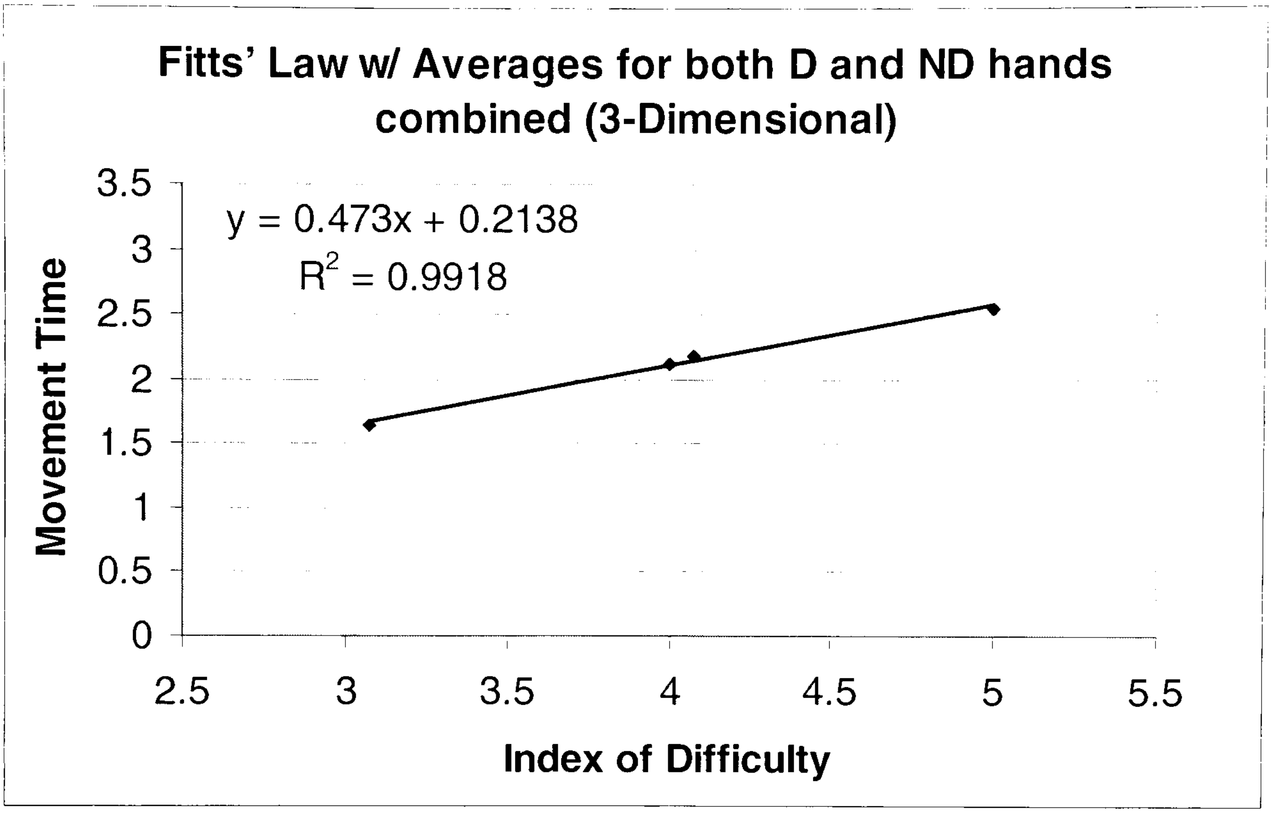


***Figure 14*: Movement time plotted against Fitts' Index of Difficulty for the baseline, three-dimensional task.**

As can be seen from the figures shown above, not surprisingly, Fitts' Law applies well to the low weight movement times. R^2 values were very high, ranging from .9912 to .9918.

5.7.2 Weighted Tasks

To evaluate the validity of Fitts Law for the movement of weighted objects, the average movement time was plotted against Index of Difficulty for each condition and a best-fit line was applied to the graph. These graphs were also separated by dimension. Essentially, the same conditions that were shown in the graphs referenced above for the ~1-pound condition were re-evaluated across all of the tested weights. An overall best-fit line was then applied to the graph in

order to see how well Fitts' Index of Difficulty fit the entire combined data set (all weights combined) for each graph. These graphs can be seen in Figures 15 and 16 below. The both-hand data was omitted from the majority of this Fitts' Law analysis because the both-hand condition was only used for the 10-pound probe weight.

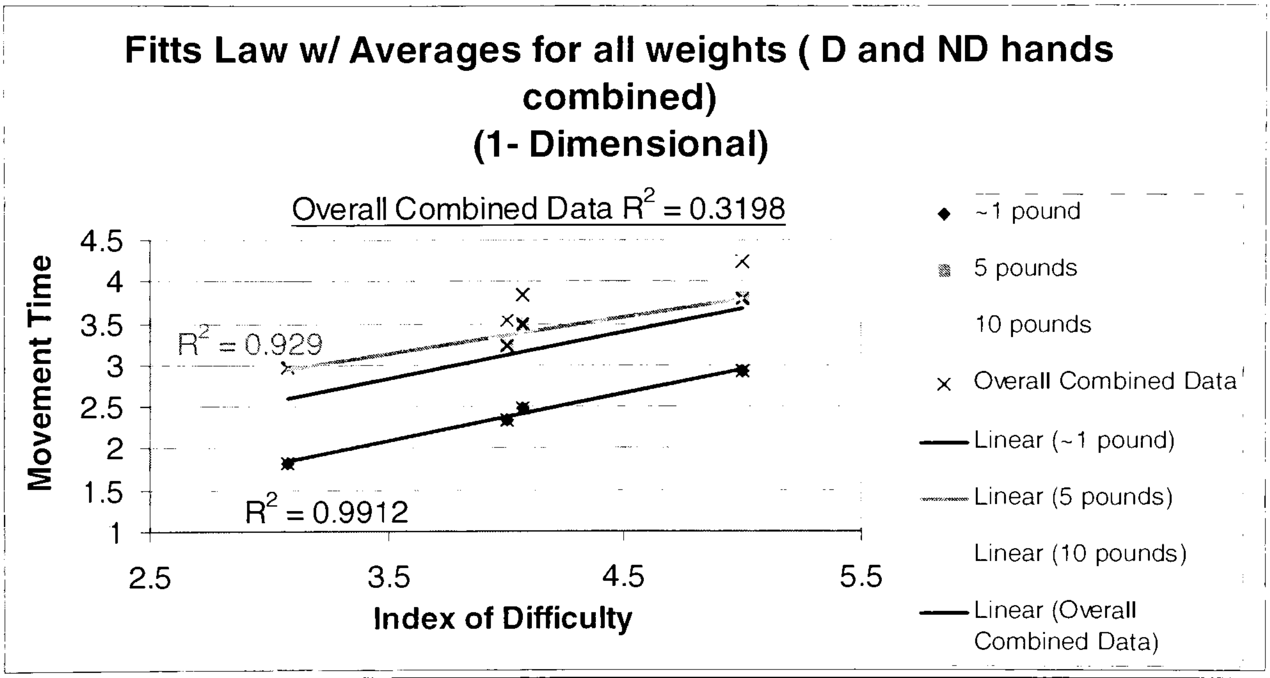


***Figure 15:* Movement time plotted against Fitts' Index of Difficulty for each weight condition for the one-dimensional, baseline task.**

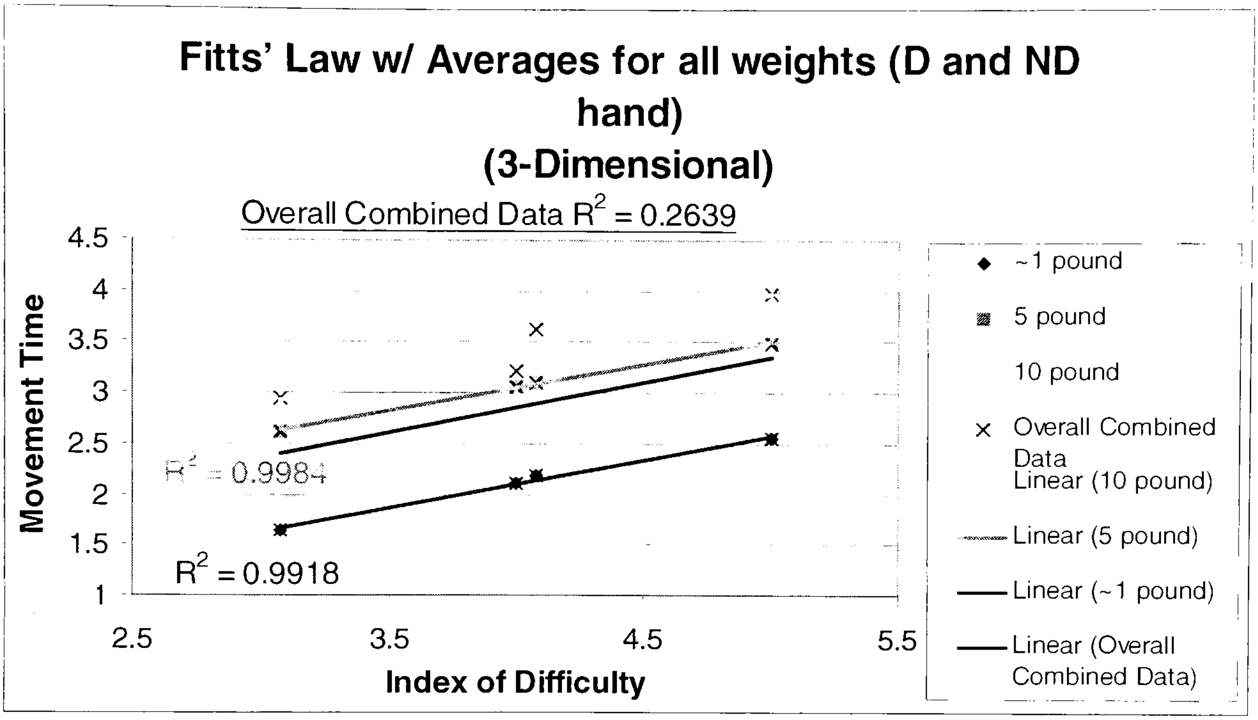


***Figure 16:* Movement time plotted against Fitts' Index of Difficulty for each weight condition for the three-dimensional task.**

As can be seen from the graphs shown above, in both the one- and three-dimensional conditions the R^2 values of the best-fit line for each individual weight condition provided very good fits to the data, with R^2 values ranging from .8898 to .9984. The overall combined data (all weights combined) R^2 values for both the one- and three-dimensional conditions did not provide as good a fit with R^2 values of .3198 and .2639 respectively.

As can be seen from the R^2 values listed above, Fitts' original Index of Difficulty did not provide a good fit to the data when looked at across weights. The differences in movement times between the three different weight conditions show that there is a highly significant effect of weight on movement time that is not accounted for in Fitts' original Index of Difficulty.

Index of Difficulty alone does not govern human movement time. Fitts' original Index of Difficulty was shown to lack the capability to accurately predict movement times in weighted tasks in one and three dimensions. It was determined that Fitts' original Index of Difficulty needed to be extended to include a term that incorporated weight and form a new equation for task difficulty. To do this, movement time was plotted with respect to the three weights used in this experiment and analyzed in order to see if the data followed any patterns or trends. When analyzing this data, it was seen that the movement time followed a logarithmic pattern as weight increased. Two best-fit lines were fitted to the graph, one being a standard straight line and the other being a logarithmic function. This graph can be seen below in Figure 17.

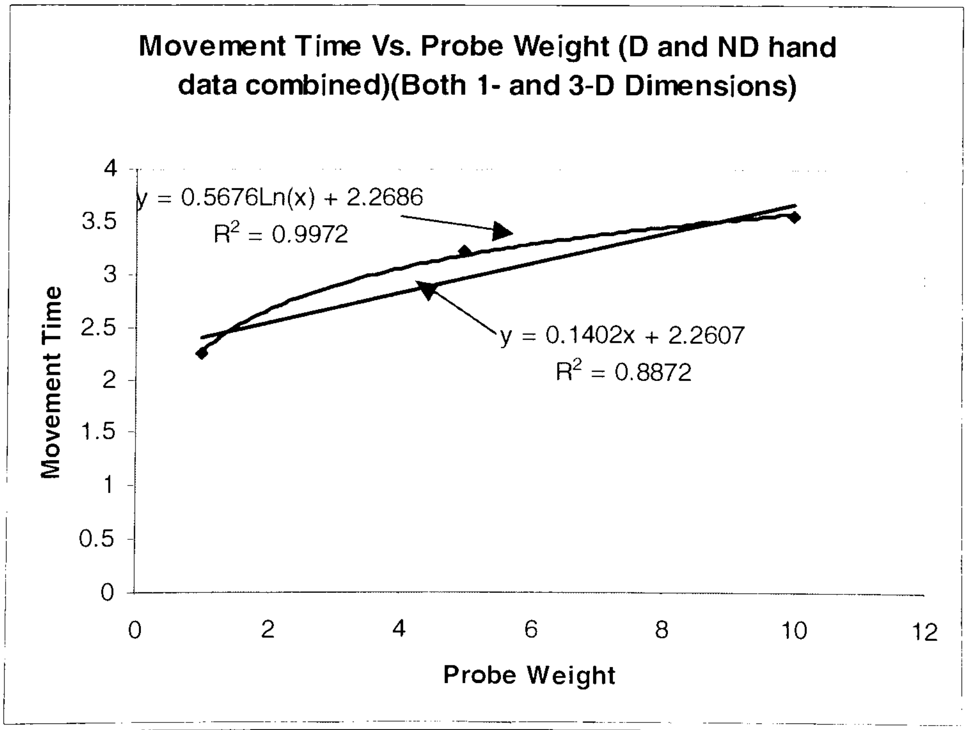


***Figure 17:* Average movement time by probe weight. Two best-fit lines are shown. The first is a linear best-fit line and the other is a logarithmic best-fit line.**

As can be seen from the graph above, the logarithmic best-fit line provided a much more accurate fit than the standard, straight-line function. The logarithmic function uses an equation based on the Natural Log (Ln) of the data series. This Natural Log function provided a very accurate fit to the movement time vs. weight data with an R^2 value of .9972. Therefore, it was determined that a factor Ln(Wt) should be added to Fitts' original Index of Difficulty equation forming a new, modified "Task Difficulty" equation of **Task Difficulty = $\mathbf{Log_2}$ (2A/W) + c Ln(Wt)** where *c* is an arbitrary constant chosen through regression, and *Wt* is the Object Weight. The units of this new equation are bits/response as in the original Index of Difficulty equation, plus a weight adjustment factor as to not redefine Fitts' original Index of Difficulty.

When looking at the potential values of *c*, the first value tested was a value of 1 to see how the standard Ln(Wt) extended term fit the data without an additional constant. The tests to determine R^2 values for each potential coefficient were performed on the entire data set (excluding both hand trials). An R^2 value of .9804 was found for the coefficient of 1, showing that a *c*-value of 1 produced a very good fit to the data, slightly improving on Fitts' original Index of Difficulty R^2 value of .9728, although for all practical purposes, the high R^2 values of each of these task difficulties fit the data equally well.

The next value of *c* that was tested was .5676 which was the constant listed before the Ln(Wt) term when performing a regression on MT vs. ID + (Ln(Wt)) as can be seen in Figure 17. The R^2 value produced by a *c* of .5676 was worse than previous values, with a value of .887.

Next, a value greater than 1 was tested to see if there was a trend with increasing R^2 values as the c was increased. To do this, an arbitrary value of 1.6 was chosen for *c*. The R^2 value produced by this coefficient was .956. As can be seen, this R^2 value was slightly worse than the $c = 1$ condition. It was therefore determined that the optimal value of *c* in this experiment fell between .5676 and 1.6.

In order to establish a more accurate relationship between *c* and it's effect on movement time, *c* values of 0, .1, .2, .3, ..., 2 and the R^2 values produced by each were plotted and can be seen in Figure 18. It was determined that the optimal *c* value was 1.1 as can be seen below.

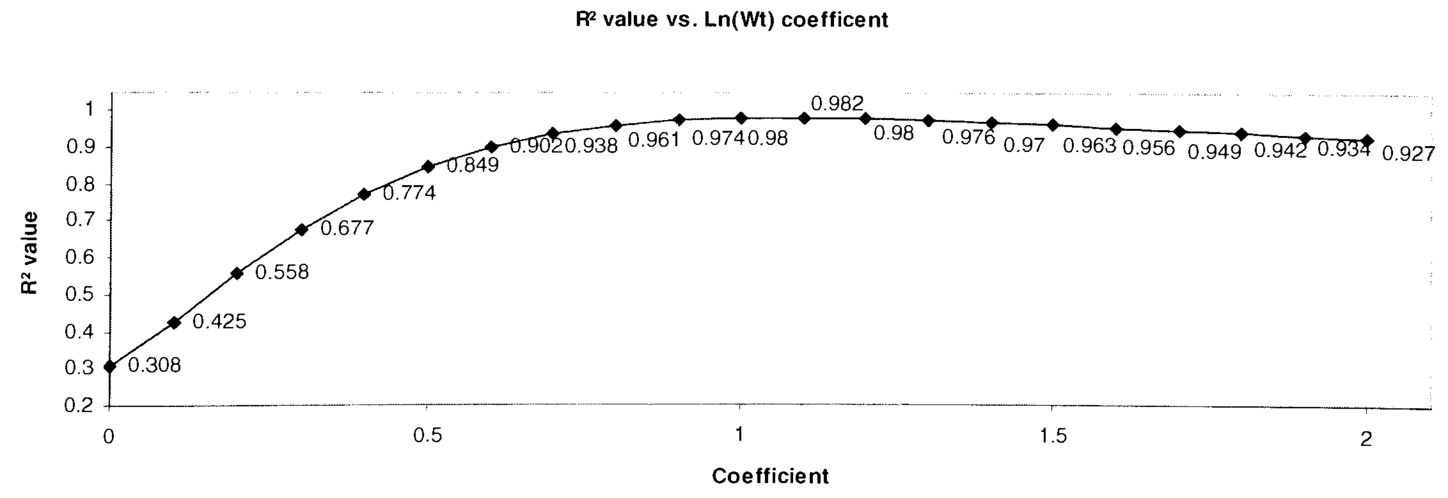
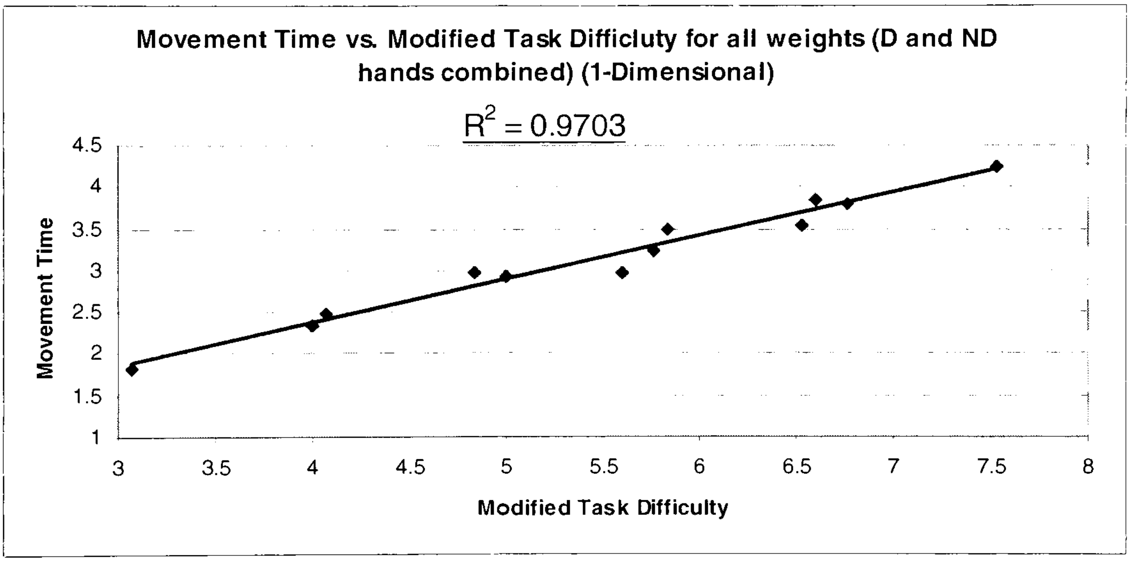


***Figure 18:* Values of c and their corresponding R^2 values when applied to the entire data set.**

5.7.3 Modified Task Difficulty

When applying this modified Task Difficulty with the *c*-value of 1.1 to the same overall combined data for the one- and three-dimensional conditions using the combined hand data analyzed above, R^2 values of .9703 and .9833 were found respectively. Figures illustrating the effect of the new Task Difficulty can be seen below in Figures 19 and 20.



<u>Figure 19:</u> Movement Time plotted against the Modified Task Difficulty equation for each weight across the one-dimensional condition.

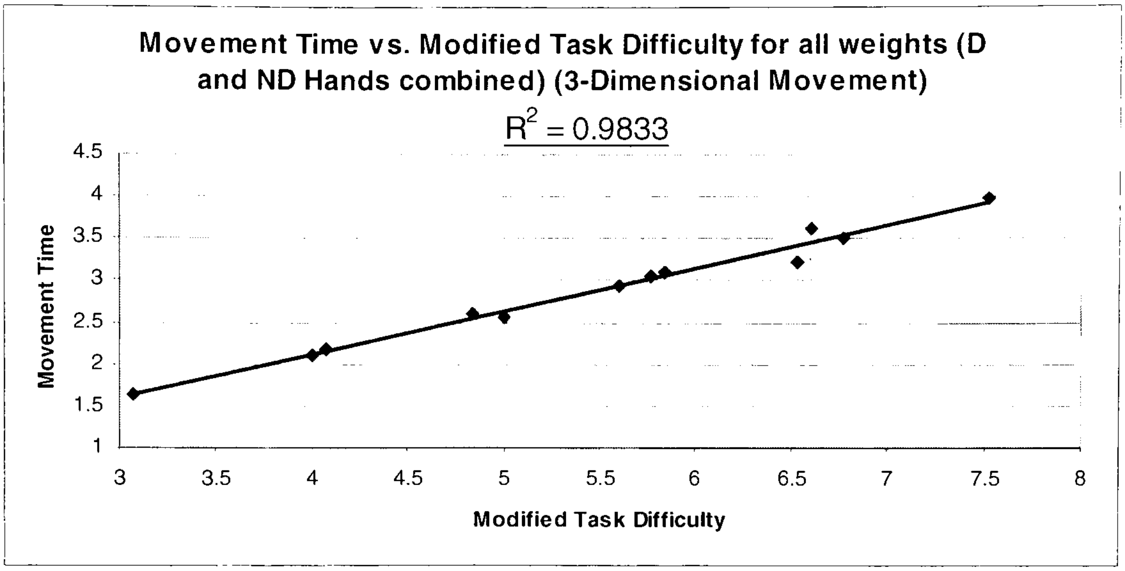


***Figure 20:* Movement Time plotted against the Modified Task Difficulty equation for each weight across the three-dimensional condition.**

The modified Task Difficulty equation was not applied to each individual weight set, because the added term of c Ln(Wt) would produce no change in the Task Difficulty of each of the average movement times across an individual weight data set because the weight must vary for the added term to have any effect on the Task Difficulty.

When applying this Modified Task Difficulty equation to the data, it is apparent that a much more accurate model for the movement time has been developed.

5.7.4 Fitts' Law and Pooled Data

Fitts' Law was also applied to the entire data set of all the conditions combined (excluding the both-hand data) to see how well the original Index of Difficulty equation fit the data. To do this, an average movement time was obtained for each level of the Index of Difficulty. These average movement time values were then plotted against Index of Difficulty and a best-fit line was applied to the graph. An R^2 value of .9728 was found for Fitts' original Index of Difficulty equation. This graph can be seen below in Figure 21.

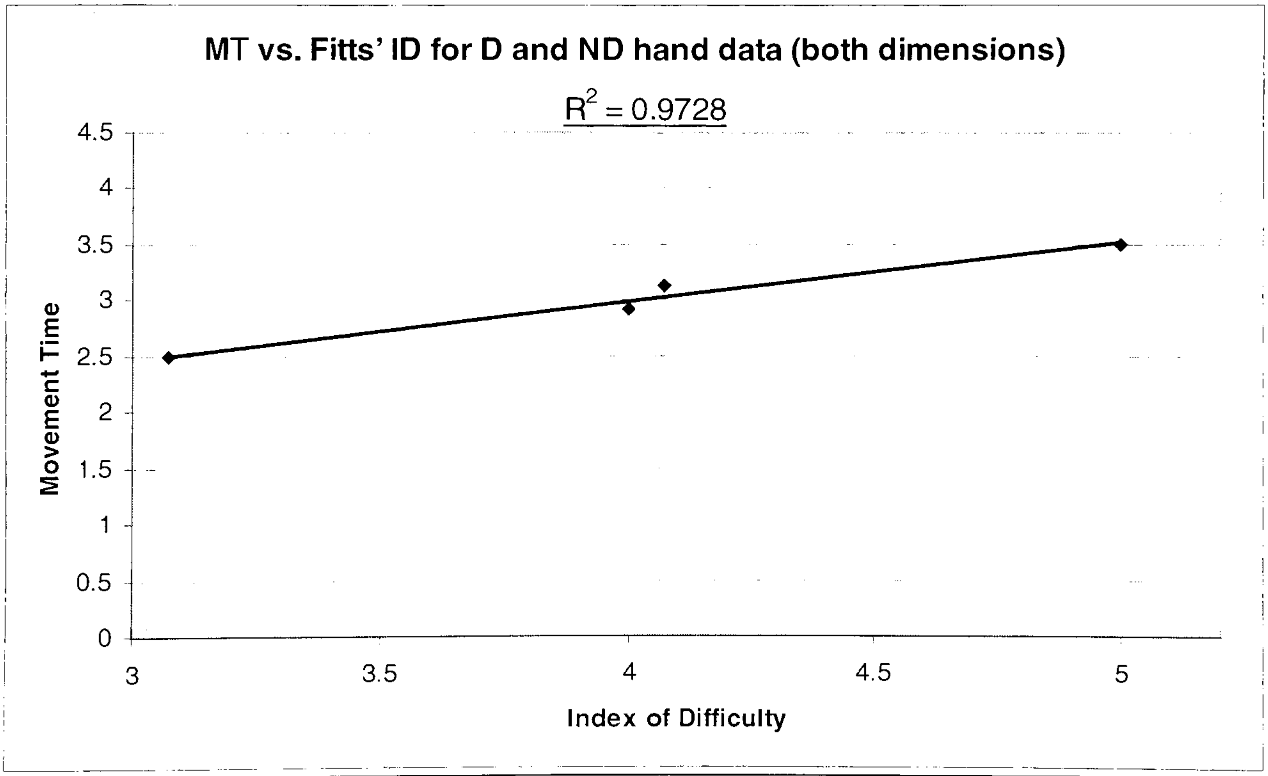


***Figure 21:* Movement Time plotted against Fitts' Index of Difficulty equation for the entire data set.**

Upon initial inspection of the graphs, it appears that Fitts' original Index of Difficulty equation provides a very good fit to the data; however, this is

misleading. When using the average movement times across each Index of Difficulty, the one-, five-, and ten-pound weights are lumped into a single point and effectively averaged. Therefore the weight factor is effectively removed from the analysis. When the data is broken down and separated by weight, it is apparent that Fitts' original Index of Difficulty formula is not an accurate predictor of movement time as was shown previously in Figures 15 and 16. Therefore it was necessary to perform the further analysis of probe weight and movement time in order to establish their relationship and develop a modified Task Difficulty equation.

The modified Task Difficulty that was described previously was also used to model the same data in order to form a comparison to Fitts' original Equation. Average movement times were once again calculated for each level of the Index of Difficulty, and then plotted with a best-fit line. The modified Task Difficulty yielded an R^2 value of .9817. These results lend support to the modified Task Difficulty equation. This graph can be seen below in Figure 22.

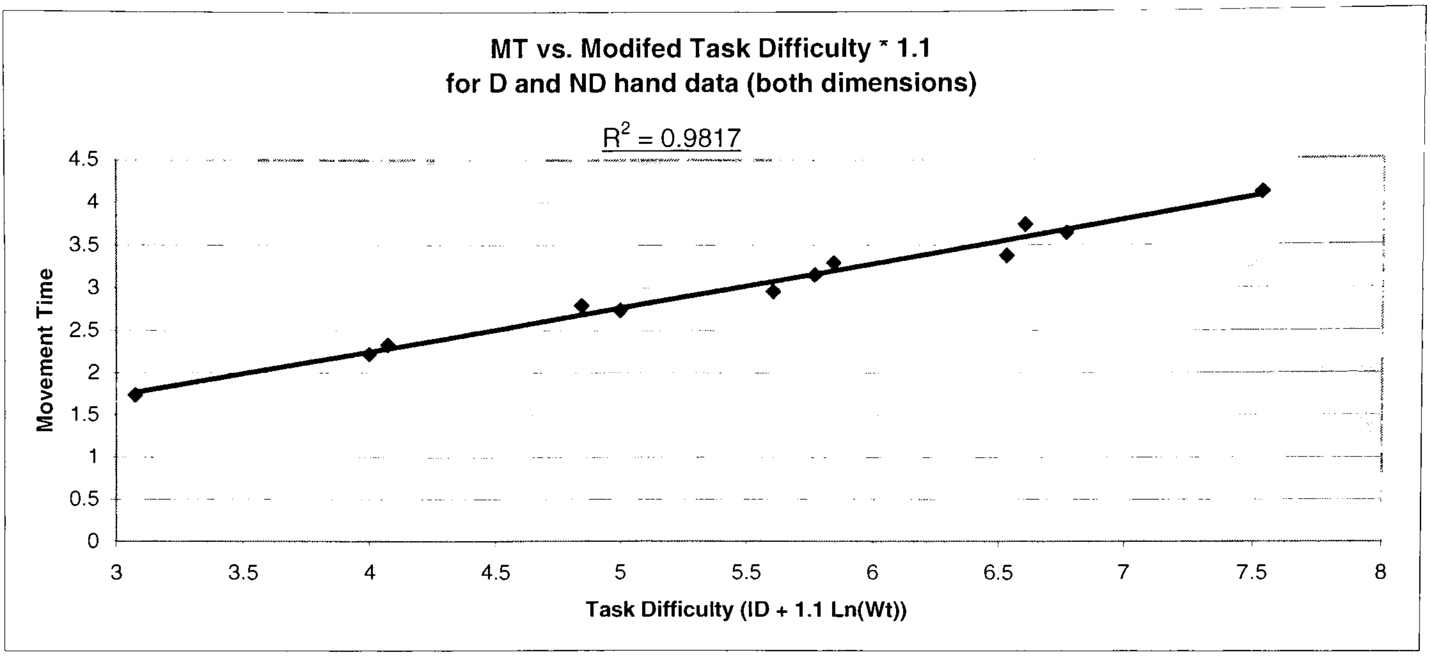


***Figure 22:* Movement Time plotted against the Modified Task Difficulty equation for the entire data set.**

6. Discussion

There were three objectives of this experiment. The first was to investigate how three-dimensional movement of an object affects movement time. The second objective was to analyze how the weight of the object being moved affects movement time. The final objective was to determine how well Fitts' Law models performance in the context of these two task variables. These objectives are discussed in separate sections below.

6.1 Three-Dimensional Movement

It was found that, contrary to the original hypothesis, movement time decreased with three-dimensional movement. It was originally hypothesized that movement time would increase due to the increased complexity of the task as the subject must account for three axes of movement as opposed to one.

One possible explanation is the three-dimensional movement is much more of a "natural" movement. Fitts' original one-dimensional task incorporates movements that are very seldom seen in everyday situations. The movement in one dimension is a somewhat awkward movement, and is not as commonly seen outside of an experimental setting. In everyday situations, the three-dimensional movement is much more prevalent than the side-to-side, one-dimensional movement. Three-dimensional movement is involved heavily in a person's everyday tasks including simple things such as putting away items in a cupboard, grabbing a can of soda, or pointing the remote at the TV for example. The

increased exposure to three-dimensional movement would make the subjects more adept due to practice, and therefore improve their performance.

Considering the three-dimensional orientation, it should also be noted that the subject's head and eyes have less distance to travel between the starting point and the ending target then when compared to the one-dimensional orientation. This may lead to quicker target acquisition when the targets are in the three-dimensional orientation, which could translate into a decreased movement time.

Another possible reason for the decreased movement time is that more muscle groups are involved in the movement. The weight of the probe can be distributed among multiple muscle groups instead of the entire load being carried by one isolated muscle group like may be the case in the one-dimensional condition. Using multiple muscle groups lightens the stress on each individual group, and these different muscle groups work together to perform the motion and to stabilize each other. This may lead to move accurate, faster movements.

Three-dimensional movement also relates to the topic of information transmission capacity set forth by Fitts (1954). Fitts' found that the human motor system has a fixed information transmission capacity for a given muscle group. However, Fitts also stated that the absolute level of information transmission capacity probably varies a great deal over different limbs, muscle groups, and different movements. Because different muscle groups are used in a three-dimensional movement, the information transmission capacity is likely different than that of a one-dimensional movement. Fitts' stated in his experiment that

more complex movements might have a higher information transmission capacity because information can be generated along several dimensions simultaneously, and the results of this experiment support this idea.

When comparing this data to the experiment conducted by Murata and Iwase (2001), there are limited conclusions that can be drawn. The study performed by Murata and Iwase dealt primarily with the validity of Fitts' Law for three-dimensional movements over various angles θ, and they did not describe how three-dimensional movements affected movement time when compared to one-dimensional movements. Because this study only dealt with one angle θ, it is simply noted that future research could be performed in the area of weight and its effect on movements of multiple levels of the angle θ.

The results found in this thesis support the idea that more natural, three-dimensional movements result in faster movement times than one-dimensional movements. These results reflect well on most industrial and occupational movements as they typically occur in three-dimensional space.

6.2 Object Weight

These results confirmed the initial hypothesis that increasing object weight slowed movement time. This is not surprising for a number of reasons. Newton's first law of motion states that force is equal to mass of an object times the acceleration of said object. Therefore as the weight of the probe increases, more force is needed to accelerate the object at the same pace. Therefore, as object load increases, the subject must use a greater percentage of his/her

Maximum Voluntary Contraction (%MVC) to move the object from one target to the other. Because the muscle groups involved in the movement are doing more work simply to support the weight, less of the muscle can be used for control and accuracy purposes and movement time is increased. A good example of this can be seen by watching weight lifters place weights back onto their holding racks. The heavier the weight, the move time and effort it takes to lift the weight and place it in its designated position.

Another finding which should be pointed out is that for the three conditions (~1, 5, and 10 pounds), the 5 and 10 pound conditions, where more muscle exertion is needed, show an average movement time difference that is notably smaller than between the ~1 pound and the 5 pound condition. The difference in movement time between the 5 and 10 pound conditions was 0.33 seconds, while the difference between the ~1 to 5 pound conditions was much higher at 0.97 seconds. These results suggest that the relationship between movement time and object weight is not linear, but one that tapers off in a logarithmic pattern with weight having less and less of an effect as more weight is added. Obviously, this would not be a continuous effect. The maximum movement time would occur when the subject is no longer able to lift the probe in the fashion outlined by the experiment. A hypothetical graph representing movement time verses probe weight is shown in Figure 23 with the projected weight effect based on the modified Task Difficulty function outlined in the results.

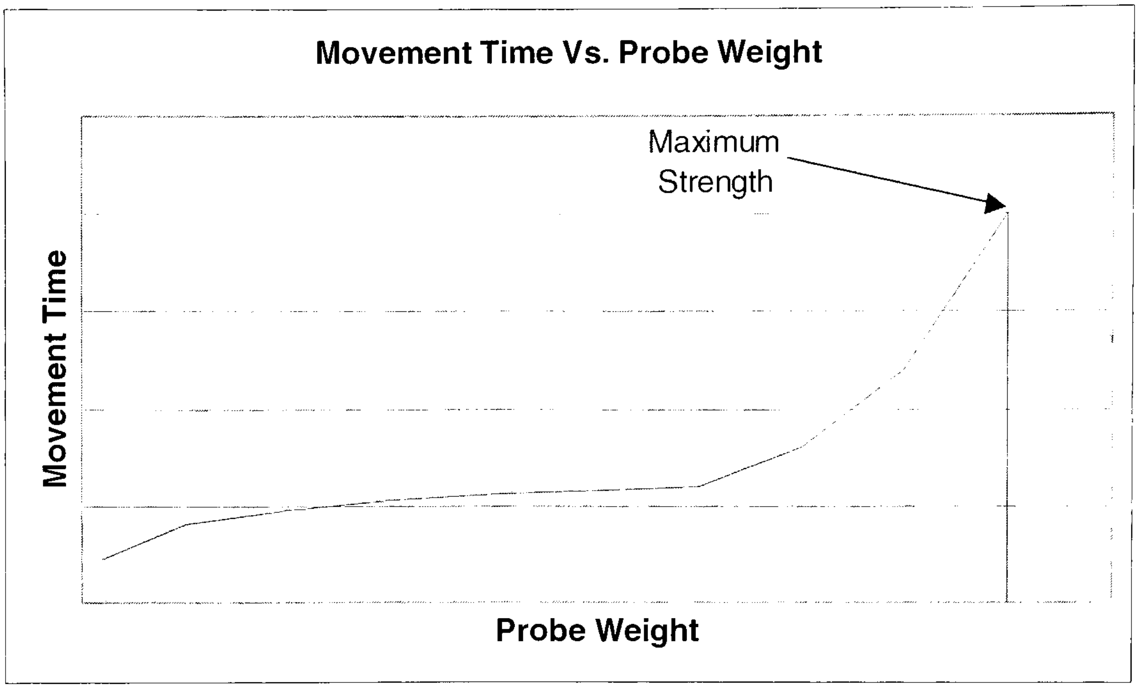


***Figure 23:** Hypothesized relationship between object weight and movement time.*

As shown in the graph, the projected movement time as weight increases tapers off as weight increases initially, but it is expected that the movement time would increase sharply as the weight of the probe approached the subjects' lifting capacity. Movement time would drop to zero and would no longer be applicable if subjects were unable to lift the object. This hypothetical relationship should be considered cautiously as only three weights were used in this experiment. Additional studies that use a larger number of weights would lead to a better understanding of this relationship.

It is also interesting to note that when incorporating the both-hand trials and analyzing just the 10-pound weight, the significant effect that was present between hand and movement time is no longer present. The significant

difference between dominant and non-dominant hand that was found in the Tukey comparison is also no longer present. This would suggest that as weight is increased, the effect of dominant verses non-dominant hand is reduced. One explanation of this would be that the performance of the dominant hand only significantly differs from the non-dominant hand in tasks involving fine motor control. When a sufficient amount of weight is added to a task, the fine motor control component of the task is lessened greatly as the hand supports the added weight, and hand no longer becomes a significant factor.

This data was compared to previous studies involving probe weight in order to see how well the results correlated with previous findings. Fitts (1954) original study used styluses of different weights, but little analysis was performed. It was simply noted that the rate of the weighted stylus was relatively stable but was slightly reduced. Fitts' failed to analyze whether stylus weight had a significant effect on movement time, but when his data was analyzed with respect to stylus weight, weight had a significant effect ($p < .000$) on movement time. The results from this thesis were consistent with Fitts' findings.

In contrast, the experiment performed by Papzxanthis, Posso, and Stapley (1998) consisted of vertical arm pointing in two directions with loads of 0 and 0.5 kg (1.1lbs). It was found that no effect on movement time occurred in the various tasks. This is contrary to the Fitts' study as well as the data in this thesis, which found a significant effect of object weight on movement time. One possible explanation for this discrepancy is that the weights used in the two studies varied greatly. Papzxanthis et al used weights of 0 and 1.1 pounds, while this study

used weights of ~1, 5 and 10 pounds. It is possible that the 1.1-pound maximum load used was not sufficiently heavy to produce a significant difference in movement time. This, however, does not explain the difference in results between the Papzxanthsis' et al and Fitts' studies. The weights used were very similar, as Fitts' weighted stylus was ~1 pound compared to the 1.1 pounds used by Papzxanthsis et al. However, Papzxanthsis et al performed an experiment that dealt with pointing to targets in a vertical direction (along the z-axis). While Fitts' studied movement of a probe in a horizontal direction (along the x-axis). The difference between these two experiments is that there is the added effect of gravity in the direction of movement of Papzxanthsis et al's experiment, which was not a factor in Fitts' study and could explain the differences in findings.

Also, even though both Fitts' and Papzxanthsis' studies involved movement to a designated target, one was a pointing task and one was a probe movement task. These two tasks cannot be assumed to follow the same exact rules for movement time because although similar in nature, the placement of an object is essentially different than pointing of a finger. Placing an object requires the object to be held and oriented in space when being moved and placed, while pointing a finger does not have these same requirements. This thesis most closely corresponds to the experiment performed by Fitts, so it stands to reason that the studies would have similar results.

The results from this experiment and from analyzing Fitts' data were also supported by an experiment conducted by Jaric, Milanovic, Blesic, and Latsh (1999). Their experiment analyzed the movement kinematics of single-

joint movements while subjects were exposed to expected and unexpected loads. Their results found that as load increased, there was also a significant increase in movement time, which is consistent with the results obtained here.

With regard to real world situations, the findings of this thesis suggest that additional time should be expected to complete precision placement tasks involving heavy weights. However, it would be dangerous to extrapolate the results beyond the levels of weight that were tested in this experiment since as weight increases, strength rapidly becomes an additional factor. Also, the biomechanical strains of weight from an ergonomic standpoint cannot be overlooked. Heavier weights will increase the strain on the body, which can have a number of effects such as increased discomfort and more rapid fatigue. Therefore, if the task being analyzed is of a significant weight, these factors must be taken into account for movements over an extended period of time.

6.3 Fitts' Law

The third objective of this study was to evaluate how well Fitts' model fit the performance recorded by this experiment. For the baseline, one-dimensional Fitts task using the combined hand data with the one-pound probe, the R^2 value was .9912. This shows a very good fit for Fitts' original Index of Difficulty and the results are not surprising. In fact, this R^2 is larger than the .97 value obtained in Fitts' original study. The baseline task was able to validate Fitts' Law and has once again proven that it is an accurate predictor of movement time for a one-dimensional task with negligible weight. This study also lends support to the

research performed by Mottet et al (2001) in which two-handed movement was analyzed relative to Fitts' Law. This experiment was in concurrence with Mottet et al's study, which found that Fitts' Law was an accurate predictor of two-handed movement time.

This study also validated Fitts' Law for a number of conditions not previously analyzed. When adding in probe weights of 5 and 10 pounds into the baseline one-dimensional condition using the combined hand data, it was found that Fitts' Index of Difficulty equation was still very accurate for each individual weight condition, with R^2 values ranging from .9290 to .9912. When applying Fitts' original Index of Difficulty to the overall combined weight data however, the R^2 values of .3198 and.2639 for the one- and three-dimensional conditions showed that Fitts' original Index of Difficulty was not an accurate predictor of movement time for weighted tasks in one- or three-dimensions.

When the modified Task Difficulty formula was applied to the entire data set (excluding both hand trials) from this experiment, it was found that the R^2 value remained very good with an R^2 value of .9817 for a *c* value of 1.1.

The modified Task Difficulty proposed in the analysis provided a better or equal fit to all of the analyses performed above. This modified Task Difficulty is a more accurate predictor of movement time under all conditions involving weight that were tested in this experiment. Fitts' Index of Difficulty in its original form was insufficient at modeling data of varying weights, and the new Task Difficulty equation provides a much better prediction of movement time. It should once again be noted however that only three weights were used in this experiment,

and applying these results to weights outside of the weights used in this thesis is not advisable.

The modified Task Difficulty equation can also be slightly modified by the work performed by Welford (1968). Welford modified Fitts' original Index of Difficulty in order to ensure that the logarithm was always positive. Because only the Index of Difficulty changed, the modified Task Difficulty equation can still be used for Welford's Index of Difficulty. Using his modified Index of Difficulty formula would give a modified Task Difficulty of Task Difficulty = $Log_2((A/W)+(1/2)) + c\ Ln(Wt)$.

Three-dimensional movement was also a variable that was analyzed with respect to Fitts' Law. When looking at the three-dimensional task plotted against Index of Difficulty, it can be seen that Fitts' Law once again provides an accurate fit to the data. In the baseline three-dimensional task using combined hand data, the R^2 value was found to be .9918. This is very close to the R^2 value of .9912 obtained in the one-dimensional task.

These results are inconsistent with the study performed by Murata and Iwase (2001). Murata and Iwase found that unlike movements in one-dimensional space, Fitts' Law in its original form did not accurately model movement time. However, this study found that Fitts' Law was a very accurate predictor of movement time in three-dimensional movement.

This difference between the results from Murata et al and the results obtained by this thesis may be explained by differences between the methods and procedures of the experiments. Murata et al used various levels of a

variable angle θ to compare movement times of different three-dimensional movements. The three-dimensional movements that were conducted in this experiment were all along the same angle θ but were performed at different amplitudes. The new Index of Difficulty formula that was developed by Murata ($ID=\log_2 (A/W+1.0) + c \sin \theta$) would not be applicable to the data obtained in this thesis because θ would remain the same and the expression $c \sin \theta$ would be constant.

This also explains why Fitts' Law was found to be applicable using data from this thesis but not using the data obtained by Murata and Iwase. Because $c \sin \theta$ is effectively a constant, this term would remain the same for all of the conditions in this thesis, and thus would have the same effect on the Indices of Difficulty. Because of this, any effect that the "$c \sin \theta$" term wouldn't be noticed in this thesis's analysis.

6.4 Hand

Hand was also analyzed and as was hypothesized, dominant hand was significantly faster than non-dominant hand. Although this factor had the highest p-value of .020, it was still found to be significant. When looking at the both hand analysis, it was found that for the 10-pound conditions across dominant, non-dominant, and both hand conditions, that hand was not a significant factor. Since the both hand condition was not analyzed for any other weights, additional analysis for other weights was unable to be performed.

Applying these results to real world applications shows that, if only one hand is to be used, the person performing the task should use their dominant

hand. This will allow for faster movement times, and will therefore increase productivity.

7. Limitations

There were a number of limitations associated with this study. Firstly, only males between the ages of 20 and 23 years old were used as subjects, which limits the applicability of the results. In future studies, women should be included along with a wider age group to expand the population to which the results could be applied. The results of this thesis would possibly differ if women and people of varying ages were used, as strength would likely vary significantly between different demographics.

Another area of potential improvement would be to incorporate additional three-dimensional movement angles into this experiment. Only having one angle of movement in three-dimensions limited the findings of this experiment, as additional analysis wasn't able to be performed to help further establish the relationship between movement time and various three-dimensional movements. It was also assumed in this experiment that movement time in the ascending and descending directions was the same. Previous studies have shown this not to be the case, and a more detailed analysis could be performed to better understand three-dimensional movement.

The experimental procedure had other areas of potential improvement as well. A more precise recording mechanism could potentially improve the accuracy of the results. The manual recording method used in this experiment was subject to the reaction time of the movement time recorder, which could produce errors. In addition the movement times recorded did not take into effect "time on target" and "turn around time" that were described in the research

performed by Fitts et al (1964) and Hoffmann et al (1994a). More accurate movement times could be obtained by incorporating these factors. However, because the recording convention was kept consistent throughout this experiment, these two factors would have no practical effect on the results. Also, the error rate of each condition could have been obtained in order to compare weight and three-dimensional movement's effect on the error rates found in previous studies such as were discussed in Fitts' (1954) original study. It should be noted however that across all 10 subjects, the error rate was small.

The other area of potential improvement in the experimental procedure would have been to randomize the one- and three-dimensional trials. In this experiment, the one- and three-dimensional trails were randomized individually, however the entire one-dimensional task was always performed first. This may have had an effect on the results, as it was shown that three-dimensional movement, which was conducted after the one-dimensional task, had a decreased movement time. This may indicate a learning effect, however, because the subjects were given sufficient time to practice the various tasks, there is much less of a possibility that a learning effect was present.

Target shape was also not taken into account in this experiment. Much of the research described in the Background section of this thesis examined the effects of target shape and the Index of Difficulty in both the lateral width and depth dimensions. Because a circle was used in this experiment, the results obtained by Hoffmann et al (1994a), Crossman (1956), and Drury (1971) could neither be confirmed nor denied, as the vertical and horizontal constraints of the

circle target are equal in the reciprocal tapping task performed in this experiment. The experiment performed by Hoffmann et al (1994b) in which target shape was considered could be analyzed in a future study to see if target shape effects three-dimensional and weighted movements in the same way as was previously discovered.

The final limitation noted in this study deals with the modified Task Difficulty. It was found that for weights less than one pound, the extended term of $c\,\mathrm{Ln}(Wt)$ becomes a negative number and the new formula no longer applies. Therefore it was determined that a minimum weight value of one should be used. When using weights less than one, the additional term of $c\,\mathrm{Ln}(Wt)$ should be omitted. More weights should also be tested in order to help support this new Task Difficulty equation, as it has only been proven to be an effective predictor of movement time for the three weights tested in this thesis.

8. Conclusions

This thesis attempted to determine the effects of three-dimensional movement and probe weight on movement time. It also sought to determine the accuracy of Fitts' original model to the extended conditions of this research.

The three-dimensional movement condition in this experiment had a significant effect on movement time. It was shown that, contrary to the original hypothesis, three-dimensional movement decreased the movement time required to perform the task. It was suggested that the movement in three-dimensions is a much more common and natural movement than the original one-dimensional Fitts' Task. Subjects are exposed to three-dimensional movement in a large variety of everyday events, and have much more practice at this type of condition than with one-dimensional movements.

Probe weight was found to have a significant effect on movement time. As was originally hypothesized, increased probe weight resulted in increased movement times. This was to be expected, as it is a physical Law that as mass of an object increases, the force needed to accelerate it at the same speed is increased. However, the relationship between probe weight and movement time was not linear, but rather one that followed a logarithmic pattern. This increase in force required to move the object requires more of the muscle to be used in moving the object, which allows less of the muscle to be used for precision placement. It was also proposed that movement time would climb sharply as a subject neared their lifting capacity, but this would vary across different subjects because of different levels of strength.

Regarding Fitts' Law, It was found that for the one angle of three-dimensional movement used in this experiment, Fitts' Law was an accurate predictor of movement time and was on par with the baseline one-dimensional movement conditions. In a future study however, more three-dimensional movements should be incorporated in order to further deduce the effects of three-dimensional movement on movement time, which may provide a more accurate understanding of the relationship between Fitts' Law and three-dimensional movement.

While Fitts' Law was found to provide a good fit to each of the individual weights, it was not sufficient in modeling movement time when different weight conditions were involved. Fitts' original movement Index of Difficulty was modified to create a new Task Difficulty equation that included a weight adjustment factor of c Ln(Wt) in order to account for the effects of weight on movement time. It was found that this modified Task Difficulty equation provided a more accurate fit to the data than Fitts' original equation. For ~one-, five, and ten-pound conditions, this modified Task Difficulty equation was shown to be a very accurate predictor of movement time. More weights should be included in a future study in order to test the validity of this equation across weights not yet tested.

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The Effects of Object Weight and Three-Dimensional Movement on Human Movement Time and Fitts' Law

Appendix

Kyle T. Hagadorn
2004

Table of Contents

1. Minitab Analysis

1.1 General Linear Model – All Factors

General Linear Model: Movement Time (sec.) versus Independent Variables

Factor	Type	Levels	Values
Subject	random	10	1 2 3 4 5 6 7 8 9 10
Amp	fixed	2	10 20
Wt	fixed	3	1 5 10
Wdt	fixed	2	1.250 2.375
Hand	fixed	2	D ND
Con	fixed	2	1 2

Analysis of Variance for Movement, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	9	79.0072	79.0072	8.7786	9.65	0.000 x
Amp	1	43.7236	43.7236	43.7236	186.95	0.000
Subject*Amp	9	2.1049	2.1049	0.2339	9.29	0.675 x
Wt	2	144.2423	144.2423	72.1212	225.09	0.000
Subject*Wt	18	5.7674	5.7674	0.3204	1.34	0.317 x
Wdt	1	19.1161	19.1161	19.1161	76.34	0.000
Subject*Wdt	9	2.2538	2.2538	0.2504	1.45	0.440 x
Hand	1	4.0095	4.0095	4.0095	33.26	0.000
Subject*Hand	9	1.0851	1.0851	0.1206	0.68	0.716 x
Con	1	8.2609	8.2609	8.2609	16.96	0.003
Subject*Con	9	4.3847	4.3847	0.4872	5.03	0.357 x
Amp*Wt	2	1.4963	1.4963	0.7481	9.84	0.001
Subject*Amp*Wt	18	1.3684	1.3684	0.0760	1.27	0.518 x
Amp*Wdt	1	0.0633	0.0633	0.0633	1.15	0.311
Subject*Amp*Wdt	9	0.4939	0.4939	0.0549	0.62	0.763
Amp*Hand	1	0.0025	0.0025	0.0025	0.03	0.863
Subject*Amp*Hand	9	0.7087	0.7087	0.0787	0.70	0.702
Amp*Con	1	0.2646	0.2646	0.2646	3.35	0.100
Subject*Amp*Con	9	0.7099	0.7099	0.0789	1.26	0.322
Wt*Wdt	2	0.1722	0.1722	0.0861	0.63	0.543
Subject*Wt*Wdt	18	2.4516	2.4516	0.1362	3.98	0.422 x
Wt*Hand	2	0.1236	0.1236	0.0618	0.42	0.664
Subject*Wt*Hand	18	2.6531	2.6531	0.1474	2.64	0.201 x
Wt*Con	2	0.1840	0.1840	0.0920	1.04	0.373
Subject*Wt*Con	18	1.5894	1.5894	0.0883	1.35	0.402 x
Wdt*Hand	1	0.0490	0.0490	0.0490	0.31	0.592
Subject*Wdt*Hand	9	1.4271	1.4271	0.1586	1.22	0.452 x
Wdt*Con	1	0.0172	0.0172	0.0172	0.12	0.739
Subject*Wdt*Con	9	1.3114	1.3114	0.1457	0.77	0.651 x
Hand*Con	1	0.0660	0.0660	0.0660	0.48	0.507
Subject*Hand*Con	9	1.2440	1.2440	0.1382	0.74	0.670
Amp*Wt*Wdt	2	0.0221	0.0221	0.0111	0.13	0.883
Subject*Amp*Wt*Wdt	18	1.5859	1.5859	0.0881	0.87	0.620
Amp*Wt*Hand	2	0.6265	0.6265	0.3133	2.78	0.089
Subject*Amp*Wt*Hand	18	2.0274	2.0274	0.1126	1.11	0.350
Amp*Wt*Con	2	0.0143	0.0143	0.0072	0.11	0.893
Subject*Amp*Wt*Con	18	1.1270	1.1270	0.0626	0.62	0.884
Wt*Wdt*Hand	2	0.5045	0.5045	0.2522	5.61	0.013
Subject*Wt*Wdt*Hand	18	0.8090	0.8090	0.0449	0.44	0.976
Wt*Wdt*Con	2	0.5013	0.5013	0.2506	2.40	0.120
Subject*Wt*Wdt*Con	18	1.8835	1.8835	0.1046	1.03	0.431
Wdt*Hand*Con	1	0.0601	0.0601	0.0601	0.32	0.585
Subject*Wdt*Hand*Con	9	1.6823	1.6823	0.1869	1.84	0.065
Error	160	16.2791	16.2791	0.1017		
Total	479	357 4745				

x Not an exact F-test.

Unusual Observations for Movement

Obs	Movement	Fit	SE Fit	Residual	St Resid
2	2.37000	1.99000	0.26044	0.38000	2.06R
42	2.19000	2.65250	0.26044	-0.46250	-2.51R
62	3.94000	3.45042	0.26044	0.48958	2.66R
63	4.31000	3.90958	0.26044	0.40042	2.17R
105	6.12000	5.17708	0.26044	0.94292	5.12R
115	2.75000	3.52542	0.26044	-0.77542	-4.21R
125	3.60000	3.20417	0.26044	0.39583	2.15R
126	3.69000	4.09375	0.26044	-0.40375	-2.19R
136	4.37000	3.98250	0.26044	0.38750	2.10R
183	5.06000	4.41083	0.26044	0.64917	3.53R
193	3.25000	3.87417	0.26044	-0.62417	-3.39R
203	3.94000	3.49792	0.26044	0.44208	2.40R
213	3.97000	4.38708	0.26044	-0.41708	-2.26R
223	3.94000	4.69583	0.26044	-0.75583	-4.10R
233	5.75000	5.01917	0.26044	0.73083	3.97R
333	2.81000	3.23417	0.26044	-0.42417	-2.30R
345	3.21000	3.79042	0.26044	-0.58042	-3.15R
355	3.28000	2.86708	0.26044	0.41292	2.24R
428	3.28000	3.70875	0.26044	-0.42875	-2.33R
438	3.85000	3.44250	0.26044	0.40750	2.21R
442	3.41000	3.81125	0.26044	-0.40125	-2.18R

R denotes an observation with a large standardized residual.

1.2 Balanced Anova – All Factors

ANOVA: Movement Time (sec.) versus Independent Variables

Factor	Type	Levels	Values						
Subject	random	10	1	2	3	4	5	6	7
			8	9	10				
Amp	fixed	2	10	20					
Wt	fixed	3	1	5	10				
Wdt	fixed	2	1.250	2.375					
Hand	fixed	2	D	ND					
Con	fixed	2	1	2					

Analysis of Variance for Movement

Source	DF	SS	MS	F	P
Subject	9	79.0072	8.7786	86.28	0.000
Amp	1	43.7236	43.7236	186.95	0.000
Subject*Amp	9	2.1049	0.2339	2.30	0.019
Wt	2	144.2423	72.1212	225.09	0.000
Subject*Wt	18	5.7674	0.3204	3.15	0.000
Wdt	1	19.1161	19.1161	76.34	0.000
Subject*Wdt	9	2.2538	0.2504	2.46	0.012
Hand	1	4.0095	4.0095	33.26	0.000
Subject*Hand	9	1.0851	0.1206	1.18	0.308
Con	1	8.2609	8.2609	16.96	0.003
Subject*Con	9	4.3847	0.4872	4.79	0.000
Amp*Wt	2	1.4963	0.7481	9.84	0.001
Subject*Amp*Wt	18	1.3684	0.0760	0.75	0.758
Amp*Wdt	1	0.0633	0.0633	1.15	0.311
Subject*Amp*Wdt	9	0.4939	0.0549	0.54	0.844
Amp*Hand	1	0.0025	0.0025	0.03	0.863
Subject*Amp*Hand	9	0.7087	0.0787	0.77	0.641
Amp*Con	1	0.2646	0.2646	3.35	0.100
Subject*Amp*Con	9	0.7099	0.0789	0.78	0.639
Wt*Wdt	2	0.1722	0.0861	0.63	0.543
Subject*Wt*Wdt	18	2.4516	0.1362	1.34	0.171
Wt*Hand	2	0.1236	0.0618	0.42	0.664
Subject*Wt*Hand	18	2.6531	0.1474	1.45	0.116
Wt*Con	2	0.1840	0.0920	1.04	0.373
Subject*Wt*Con	18	1.5894	0.0883	0.87	0.618
Wdt*Hand	1	0.0490	0.0490	0.31	0.592
Subject*Wdt*Hand	9	1.4271	0.1586	1.56	0.132
Wdt*Con	1	0.0172	0.0172	0.12	0.739
Subject*Wdt*Con	9	1.3114	0.1457	1.43	0.178
Hand*Con	1	0.0660	0.0660	0.48	0.507
Subject*Hand*Con	9	1.2440	0.1382	1.36	0.211
Amp*Wt*Wdt	2	0.0221	0.0111	0.13	0.883
Subject*Amp*Wt*Wdt	18	1.5859	0.0881	0.87	0.620
Amp*Wt*Hand	2	0.6265	0.3133	2.78	0.089
Subject*Amp*Wt*Hand	18	2.0274	0.1126	1.11	0.350
Amp*Wt*Con	2	0.0143	0.0072	0.11	0.893
Subject*Amp*Wt*Con	18	1.1270	0.0626	0.62	0.884
Wt*Wdt*Hand	2	0.5045	0.2522	5.61	0.013
Subject*Wt*Wdt*Hand	18	0.8090	0.0449	0.44	0.976
Wt*Wdt*Con	2	0.5013	0.2506	2.40	0.120
Subject*Wt*Wdt*Con	18	1.8835	0.1046	1.03	0.431
Wdt*Hand*Con	1	0.0601	0.0601	0.32	0.585
Subject*Wdt*Hand*Con	9	1.6823	0.1869	1.84	0.065
Error	160	16.2791	0.1017		
Total	479	357 4745			

1.3 Single Factor Analysis

1.3.1 One-way ANOVA: Movement Time (sec.) versus Amp

```
Analysis of Variance for Movement
Source     DF        SS        MS        F        P
Amp         1    43.724    43.724    66.61    0.000
Error     478   313.751     0.656
Total     479   357.474
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ------+---------+---------+---------+
10        240    2.7069    0.7656  (---*---)
20        240    3.3105    0.8524                       (---*----)
                                   ------+---------+---------+---------+
Pooled StDev =   0.8102                2.75      3.00      3.25      3.50
```

1.3.2 One-way ANOVA: Movement Time (sec.) versus Wt

```
Analysis of Variance for Movement
Source     DF        SS        MS        F        P
Wt          2   144.242    72.121   161.33    0.000
Error     477   213.232     0.447
Total     479   357 474
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -------+---------+---------+---------
 1        160    2.2566    0.6029  (-*-)
 5        160    3.2218    0.6597                   (-*--)
10        160    3.5477    0.7364                          (-*-)
                                   -------+---------+---------+---------
Pooled StDev -   0.6686                 2.50      3.00      3.50
```

1.3.3 One-way ANOVA: Movement Time (sec.) versus Wdt

```
Analysis of Variance for Movement
Source     DF        SS        MS        F        P
Wdt         1    19.116    19.116    27.01    0.000
Error     478   338.358     0.708
Total     479   357 474
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  -----+---------+---------+---------+-
1.250     240    3.2083    0.8761                    (----*-----)
2.375     240    2.8091    0.8051  (----*-----)
                                   -----+---------+---------+---------+-
Pooled StDev =   0.8413               2.80      3.00      3.20      3.40
```

1.3.4 One-way ANOVA: Movement Time (sec.) versus Hand

```
Analysis of Variance for Movement
Source     DF        SS        MS        F        P
Hand        1     4.010     4.010     5.42    0.020
Error     478   353.465     0.739
Total     479   357 474
                                   Individual 95% CIs For Mean
                                   Based on Pooled StDev
Level       N      Mean     StDev  ------+---------+---------+---------+
D         240    2.9173    0.8331  (--------*--------)
ND        240    3.1001    0.8860                (--------*--------)
                                   ------+---------+---------+---------+
Pooled StDev     0.8599                2.88      3.00      3.12      3.24
```

1.3.4.1 One-way ANOVA: Movement Time (sec.) versus Hand (both hand data included)

```
Source   DF       SS     MS     F      P
Hand      2    3.010  1.505  2.78  0.064
Error   237  128.473  0.542
Total   239  131.482

S = 0.7363   R-Sq = 2.29%   R-Sq(adj)   1.46%

                               Individual 95% CIs For Mean Based on
                               Pooled StDev
Level   N    Mean   StDev   ------+---------+---------+---------+---
Both   80  3.3740  0.7433   (----------*----------)
D      80  3.4541  0.6596       (----------*----------)
ND     80  3.6413  0.7992                 (----------*----------)
                            ------+---------+---------+---------+---
                                3.30      3.45      3.60      3.75

Pooled StDev   0.7363
```

1.3.5 One-way ANOVA: Movement Time (sec.) versus Con

```
Analysis of Variance for Movement
Source     DF        SS        MS       F        P
Con         1     8.261     8.261   11.31    0.001
Error     478   349.214     0.731
Total     479   357 474
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  ------+---------+---------+---------+
1         240    3.1399    0.9106                   (------*-------)
2         240    2.8775    0.7950   (------*------)
                                   ------+---------+---------+---------+
Pooled StDev =    0.8547                 2.85      3.00      3.15      3.30
```

1.3.6 One-way ANOVA: Movement Time (sec.) versus Subject

```
Analysis of Variance for Movement
Source     DF        SS        MS       F        P
Subject     9    79.007     8.779   14.82    0.000
Error     470   278.467     0.592
Total     479   357.474
                                  Individual 95% CIs For Mean
                                  Based on Pooled StDev
Level       N      Mean     StDev  -----+---------+---------+---------+-
 1         48    2.4781    0.5726  (----*---)
 2         48    3.0502    0.7365             (---*---)
 3         48    3.2740    0.8842                 (---*----)
 4         48    3.5183    0.9213                      (---*----)
 5         48    3.0685    0.9199             (---*----)
 6         48    3.3206    0.8116                  (---*----)
 7         48    2.5921    0.7265    (----*---)
 8         48    3.6300    0.8311                        (----*---)
 9         48    2.5646    0.5907    (---*----)
10         48    2.5904    0.5932    (----*---)
                                   -----+---------+---------+---------+-
Pooled StDev       0.7697               2.50      3.00      3.50      4.00
```

1.4 General Linear Model for significant factors (w/ Tukey)

General Linear Model: Movement Time (sec.) versus significant factors

Factor	Type	Levels	Values
Subject	random	10	1 2 3 4 5 6 7 8 9 10
Amp	fixed	2	10 20
Wt	fixed	3	1 5 10
Wdt	fixed	2	1.250 2.375
Con	fixed	2	1 2
Hand	fixed	2	D ND

Analysis of Variance for Movement, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	F	P
Subject	9	79.007	79.007	8.779	70.36	0.000
Amp	1	43.724	43.724	43.724	350.44	0.000
Wt	2	144.242	144.242	72.121	578.04	0.000
Wdt	1	19.116	19.116	19.116	153.21	0.000
Con	1	8.261	8.261	8.261	66.21	0.000
Hand	1	4.010	4.010	4.010	32.14	0.000
Amp*Wt	2	1.496	1.496	0.748	6.00	0.003
Wt*Wdt	2	0.172	0.172	0.086	0.69	0.502
Wt*Hand	2	0.124	0.124	0.062	0.50	0.610
Wdt*Hand	1	0.049	0.049	0.049	0.39	0.531
Wt*Wdt*Hand	2	0.504	0.504	0.252	2.02	0.134
Error	455	56.769	56.769	0.125		
Total	479	357.474				

Unusual Observations for Movement

Obs	Movement	Fit	SE Fit	Residual	St Resid
28	3.81000	2.99125	0.08061	0.81875	2.38R
38	3.81000	2.92100	0.08061	0.88900	2.59R
47	2.87000	2.13058	0.08061	0.73942	2.15R
62	3.94000	2.96496	0.08061	0.97504	2.84R
63	4.31000	3.11846	0.08061	1.19154	3.46R
71	1.63000	2.32263	0.08061	-0.69263	-2.01R
105	6.12000	3.48079	0.08061	2.63921	7.67R
128	4.82000	4.12600	0.08061	0.69400	2.02R
136	4.37000	3.65713	0.08061	0.71287	2.07R
139	3.94000	2.90108	0.08061	1.03892	3.02R
174	2.61000	3.55415	0.08061	-0.94415	-2.75R
183	5.06000	3.63302	0.08061	1.42698	4.15R
233	5.75000	4.65015	0.08061	1.09985	3.20R
236	5.15000	4.43806	0.08061	0.71194	2.07R
428	3.28000	3.98544	0.08061	-0.70544	-2.05R
444	5.03000	4.16565	0.08061	0.86435	2.51R

R denotes an observation with a large standardized residual.

* NOTE * No multiple comparisons were calculated for the following terms which contain or interact with random factors.

Subject

1.4.1 Tukey – Movement Amplitude

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Movement
All Pairwise Comparisons among Levels of Amp

Amp = 10 subtracted from:

Amp     Lower    Center     Upper  ------+---------+---------+---------+
20     0.5403    0.6036    0.6670  (-----------------*-----------------)
                                   ------+---------+---------+---------+
                                       0.560     0.595     0.630     0.665
Tukey Simultaneous Tests
Response Variable Movement
All Pairwise Comparisons among Levels of Amp

Amp = 10 subtracted from:

Level   Difference       SE of            Adjusted
Amp       of Means  Difference  T-Value    P-Value
20          0.6036     0.03224    18.72    -0.0000
```

1.4.2 Tukey – Probe Weight

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Movement
All Pairwise Comparisons among Levels of Wt

Wt = 1 subtracted from:

Wt     Lower    Center     Upper  ----+---------+---------+---------+--
 5    0.8727    0.9651     1.058                     (--*-)
10    1.1986    1.2911     1.383                              (--*--)
                                  ----+---------+---------+---------+--
                                    0.35      0.70      1.05      1.40
Wt = 5 subtracted from:

Wt     Lower    Center     Upper  ----+---------+---------+---------+--
10    0.2335    0.3259    0.4184   (-*--)
                                  ----+---------+---------+---------+--
                                    0.35      0.70      1.05      1.40
Tukey Simultaneous Tests
Response Variable Movement
All Pairwise Comparisons among Levels of Wt

Wt   1 subtracted from:

Level  Difference       SE of            Adjusted
Wt       of Means  Difference  T-Value    P-Value
 5         0.9651     0.03949    24.44    -0.0000
10         1.2911     0.03949    32.69    -0.0000

Wt = 5 subtracted from:

Level  Difference       SE of            Adjusted
Wt       of Means  Difference  T-Value    P-Value
10         0.3259     0.03949    8.253    -0.0000
```

1.4.3 Tukey – Target Width

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Movement
All Pairwise Comparisons among Levels of Wdt

Wdt = 1.250 subtracted from:

Wdt       Lower    Center     Upper  -+---------+---------+---------+-----
2.375   -0.4625   -0.3991   -0.3358  (---*----)
                                     -+---------+---------+---------+-----
                                   -0.45     -0.30     -0.15      0.00
Tukey Simultaneous Tests
Response Variable Movement
All Pairwise Comparisons among Levels of Wdt

Wdt = 1.250 subtracted from:

Level     Difference       SE of             Adjusted
Wdt         of Means  Difference   T-Value    P-Value
2.375        -0.3991     0.03224    -12.38    -0.0000

Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Movement
All Pairwise Comparisons among Levels of Hand

Hand = D subtracted from:

Hand      Lower    Center     Upper  ------+---------+---------+---------+
ND       0.1194    0.1828    0.2462  (-----------------*-----------------)
                                     ------+---------+---------+---------+
                                         0.140     0.175     0.210     0.245
```

1.4.4 Tukey - Hand

```
Tukey Simultaneous Tests
Response Variable Movement
All Pairwise Comparisons among Levels of Hand

Hand = D subtracted from:

Level     Difference       SE of             Adjusted
Hand        of Means  Difference   T-Value    P-Value
ND            0.1828     0.03224     5.669     0.0000
```

1.4.4.1 Tukey – Hand (both hand data included)

```
Tukey 95% Simultaneous Confidence Intervals
All Pairwise Comparisons among Levels of Hand

Individual confidence level = 98.10%


Hand - Both subtracted from:

Hand     Lower  Center   Upper  -----+---------+---------+---------+----
D      -0.1948  0.0801  0.3551           (--------*--------)
ND     -0.0077  0.2672  0.5422                 (--------*--------)
                                -----+---------+---------+---------+----
                                   -0.30      0.00      0.30      0.60


Hand = D subtracted from:

Hand     Lower  Center   Upper  -----+---------+---------+---------+----
ND     -0.0878  0.1871  0.4621              (--------*--------)
                                -----+---------+---------+---------+----
                                   -0.30      0.00      0.30      0.60
```

1.4.5 Tukey – Dimensional Condition

```
Tukey 95.0% Simultaneous Confidence Intervals
Response Variable Movement
All Pairwise Comparisons among Levels of Con

Con - 1 subtracted from:

Con     Lower    Center     Upper  ---+---------+---------+---------+---
2     -0.3257   -0.2624   -0.1990  (------*-----)
                                   ---+---------+---------+---------+---
                                    -0.30     -0.20     -0.10     -0.00

Tukey Simultaneous Tests
Response Variable Movement
All Pairwise Comparisons among Levels of Con

Con = 1 subtracted from:

Level   Difference       SE of              Adjusted
Con       of Means  Difference  T-Value      P-Value
2          -0.2624     0.03224   -8.137      -0.0000
```

1.5 Task Difficulty Coefficient Testing

Regression Analysis: MT avg versus ID

The regression equation is
MT avg = 0.894 + 0.524 ID

Predictor	Coef	SE Coef	T	P
Constant	0.8935	0.2538	3.52	0.072
ID	0.52394	0.06200	8.45	0.014

S = 0.0844991   R-Sq = 97.3%   R-Sq(adj) = 95.9%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	0.50991	0.50991	71.42	0.014
Residual Error	2	0.01428	0.00714		
Total	3	0.52419			

Regression Analysis: MT versus ID2 (modified task difficulty)

The regression equation is
MT   0.055 + 0.553 ID2

Predictor	Coef	SE Coef	T	P
Constant	0.0549	0.1351	0.41	0.693
ID2	0.55304	0.02470	22.39	0.000

S = 0.101064   R-Sq = 98.0%   R-Sq(adj) = 97.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	5.1188	5.1188	501.15	0.000
Residual Error	10	0.1021	0.0102		
Total	11	5.2209			

Regression Analysis: MT versus coeff 0

```
The regression equation is
MT = 0.57 + 0.593 coeff 0


Predictor     Coef  SE Coef     T      P
Constant     0.565    1.171  0.48  0.640
coeff 0     0.5934   0.2812  2.11  0.061


S = 0.601062   R-Sq = 30.8%   R-Sq(adj) = 23.9%


Analysis of Variance

Source          DF      SS      MS     F      P
Regression       1  1.6081  1.6081  4.45  0.061
Residual Error  10  3.6128  0.3613
Total           11  5.2209
```

Regression Analysis: MT versus coeff .1

```
The regression equation is
MT = 0.404 + 0.625 coeff .1


Predictor     Coef  SE Coef     T      P
Constant    0.4035   0.9703  0.42  0.686
coeff .1    0.6251   0.2297  2.72  0.022


S = 0.547693   R-Sq = 42.5%   R-Sq(adj) = 36.8%


Analysis of Variance

Source          DF      SS      MS     F      P
Regression       1  2.2212  2.2212  7.40  0.022
Residual Error  10  2.9997  0.3000
Total           11  5.2209
```

Regression Analysis: MT versus coeff .2

```
The regression equation is
MT = 0.019 + 0.696 coeff .2


Predictor     Coef  SE Coef     T      P
Constant    0.0191   0.8530  0.02  0.983
coeff .2    0.6956   0.1958  3.55  0.005


S = 0.480467   R-Sq   55.8%   R-Sq(adj)   51.4%


Analysis of Variance

Source          DF      SS      MS      F      P
Regression       1  2.9124  2.9124  12.62  0.005
Residual Error  10  2.3085  0.2308
Total           11  5.2209
```

Regression Analysis: MT versus coeff .3

The regression equation is
MT = 0.237 + 0.733 coeff .3

Predictor	Coef	SE Coef	T	P
Constant	-0.2368	0.7192	-0.33	0.749
coeff .3	0.7329	0.1602	4.57	0.001

S = 0.410846   R-Sq = 67 7%   R-Sq(adj) = 64.4%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	3.5330	3.5330	20.93	0.001
Residual Error	10	1.6879	0.1688		
Total	11	5.2209			

Regression Analysis: MT versus coeff .4

The regression equation is
MT = 0.370 + 0.741 coeff .4

Predictor	Coef	SE Coef	T	P
Constant	-0.3701	0.5853	-0.63	0.541
coeff .4	0.7412	0.1265	5.86	0.000

S = 0.343286   R-Sq   77.4%   R-Sq(adj) = 75.2%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	4.0424	4.0424	34.30	0.000
Residual Error	10	1.1785	0.1178		
Total	11	5.2209			

Regression Analysis: MT versus coeff .5

The regression equation is
MT = - 0.404 + 0.728 coeff .5

Predictor	Coef	SE Coef	T	P
Constant	-0.4044	0.4628	-0.87	0.403
coeff .5	0.72790	0.09717	7 49	0.000

S = 0.281015   R-Sq - 84.9%   R-Sq(adj) - 83.4%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	4.4312	4.4312	56.11	0.000
Residual Error	10	0.7897	0.0790		
Total	11	5.2209			

Regression Analysis: MT versus coeff. .5676

The regression equation is
MT   - 0.386 + 0.711 .5676 coefficient

Predictor	Coef	SE Coef	T	P
Constant	-0.3862	0.3897	-0.99	0.345
.5676 coefficient	0.71065	0.08024	8.86	0.000

S = 0.242961   R-Sq = 88.7%   R-Sq(adj) = 87.6%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	4.6306	4.6306	78.44	0.000
Residual Error	10	0.5903	0.0590		
Total	11	5.2209			

Regression Analysis: MT versus ID w/ coeff 0.6

The regression equation is
MT =   0.369 + 0.701 coeff 0.6

Predictor	Coef	SE Coef	T	P
Constant	-0.3686	0.3577	-1.03	0.327
coeff 0.6	0.70077	0.07298	9.60	0.000

S = 0.226024   R-Sq = 90.2%   R-Sq(adj) = 89.2%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	4.7100	4.7100	92.20	0.000
Residual Error	10	0.5109	0.0511		
Total	11	5.2209			

Regression Analysis: MT versus coeff .7

The regression equation is
MT - - 0.288 + 0.666 coeff 7

Predictor	Coef	SE Coef	T	P
Constant	-0.2881	0.2724	-1.06	0.315
coeff 7	0.66605	0.05402	12.33	0.000

S = 0.179505   R-Sq = 93.8%   R-Sq(adj) = 93.2%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	4.8987	4.8987	152.03	0.000
Residual Error	10	0.3222	0.0322		
Total	11	5.2209			

Regression Analysis: MT versus ID w/ coeff 0.8

The regression equation is
MT = 0.183 + 0.628 coeff 0.8

Predictor	Coef	SE Coef	T	P
Constant	-0.1825	0.2070	-0.88	0.399
coeff 0.8	0.62817	0.03993	15.73	0.000

S = 0.142410   R-Sq = 96.1%   R-Sq(adj) - 95.7%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	5.0181	5.0181	247 43	0.000
Residual Error	10	0.2028	0.0203		
Total	11	5.2209			

Regression Analysis: MT versus coeff. .9

The regression equation is
MT = 0.065 + 0.590 coeff. .9

Predictor	Coef	SE Coef	T	P
Constant	-0.0653	0.1615	-0.40	0.694
coeff. .9	0.58995	0.03031	19.46	0.000

S = 0.115891   R-Sq = 97.4%   R-Sq(adj) = 97.2%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	5.0866	5.0866	378.73	0.000
Residual Error	10	0.1343	0.0134		
Total	11	5.2209			

Regression Analysis: MT versus ID w/ coeff 1

The regression equation is
MT = 0.055 + 0.553 coeff 1

Predictor	Coef	SE Coef	T	P
Constant	0.0549	0.1351	0.41	0.693
coeff 1	0.55304	0.02470	22.39	0.000

S = 0.101064   R-Sq = 98.0%   R-Sq(adj) = 97.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	5.1188	5.1188	501.15	0.000
Residual Error	10	0.1021	0.0102		
Total	11	5.2209			

Regression Analysis: MT versus coeff 1.1

The regression equation is
MT = 0.173 + 0.518 coeff 1.1

Predictor	Coef	SE Coef	T	P
Constant	0.1729	0.1255	1.38	0.198
coeff 1.1	0.51830	0.02235	23.19	0.000

S = 0.0976310   R-Sq = 98.2%   R-Sq(adj) = 98.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	5.1256	5.1256	537 73	0.000
Residual Error	10	0.0953	0.0095		
Total	11	5.2209			

Unusual Observations

Obs	coeff 1.1	MT	Fit	SE Fit	Residual	St Resid
9	6.53	3.3778	3.5588	0.0368	-0.1811	-2.00R

R denotes an observation with a large standardized residual.

Regression Analysis: MT versus ID w/ coeff 1.2

The regression equation is
MT = 0.286 + 0.486 coeff 1.2

Predictor	Coef	SE Coef	T	P
Constant	0.2857	0.1274	2.24	0.049
coeff 1.2	0.48609	0.02211	21.99	0.000

S = 0.102869   R-Sq = 98.0%   R-Sq(adj) = 97.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	5.1151	5.1151	483.38	0.000
Residual Error	10	0.1058	0.0106		
Total	11	5.2209			

Unusual Observations

Obs	coeff 1.2	MT	Fit	SE Fit	Residual	St Resid
9	6.76	3.3778	3.5732	0.0393	-0.1954	-2.06R

R denotes an observation with a large standardized residual.

Regression Analysis: MT versus coeff. 1.3

The regression equation is
MT = 0.392 + 0.457 coeff. 1.3

Predictor	Coef	SE Coef	T	P
Constant	0.3919	0.1351	2.90	0.016
coeff. 1.3	0.45651	0.02288	19.96	0.000

S = 0.113091   R-Sq = 97.6%   R-Sq(adj) = 97.3%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	5.0930	5.0930	398.22	0.000
Residual Error	10	0.1279	0.0128		
Total	11	5.2209			

Regression Analysis: MT versus ID w/ coeff 1.4

The regression equation is
MT = 0.491 + 0.429 coeff 1.4

Predictor	Coef	SE Coef	T	P
Constant	0.4909	0.1450	3.39	0.007
coeff 1.4	0.42946	0.02395	17.93	0.000

S = 0.125490   R-Sq = 97.0%   R-Sq(adj) = 96.7%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	5.0634	5.0634	321.53	0.000
Residual Error	10	0.1575	0.0157		
Total	11	5.2209			

Regression Analysis: MT versus coeff 1.5

The regression equation is
MT = 0.583 + 0.405 coeff 1.5

Predictor	Coef	SE Coef	T	P
Constant	0.5827	0.1550	3.76	0.004
coeff 1.5	0.40481	0.02499	16.20	0.000

S = 0.138459   R-Sq = 96.3%   R-Sq(adj) = 96.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	5.0292	5.0292	262.34	0.000
Residual Error	10	0.1917	0.0192		
Total	11	5.2209			

Unusual Observations

Obs	coeff 1.5	MT	Fit	SE Fit	Residual	St Resid
6	6.53	2.9593	3.2252	0.0421	-0.2660	-2.02R

R denotes an observation with a large standardized residual.

Regression Analysis: MT versus ID w/ coeff 1.6

The regression equation is
MT = 0.667 + 0.382 coeff 1.6

Predictor	Coef	SE Coef	T	P
Constant	0.6675	0.1643	4.06	0.002
coeff 1.6	0.38234	0.02587	14.78	0.000

S = 0.151193   R-Sq = 95.6%   R-Sq(adj) = 95.2%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	4.9923	4.9923	218.39	0.000
Residual Error	10	0.2286	0.0229		
Total	11	5.2209			

Unusual Observations

Obs	coeff 1.6	MT	Fit	SE Fit	Residual	St Resid
6	6.76	2.9593	3.2514	0.0466	-0.2921	-2.03R

R denotes an observation with a large standardized residual.

Regression Analysis: MT versus coeff 1.7

The regression equation is
MT = 0.746 + 0.362 coeff 1.7

Predictor	Coef	SE Coef	T	P
Constant	0.7457	0.1726	4.32	0.002
coeff 1.7	0.36186	0.02655	13.63	0.000

S = 0.163326   R-Sq = 94.9%   R-Sq(adj) = 94.4%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	4.9541	4.9541	185.72	0.000
Residual Error	10	0.2668	0.0267		
Total	11	5.2209			

Unusual Observations

Obs	coeff 1.7	MT	Fit	SE Fit	Residual	St Resid
6	6.99	2.9593	3.2745	0.0510	-0.3153	-2.03R

R denotes an observation with a large standardized residual.

Regression Analysis: MT versus coeff 1.8

The regression equation is
MT   0.818 + 0.343 coeff 1.8

Predictor	Coef	SE Coef	T	P
Constant	0.8178	0.1799	4.55	0.001
coeff 1.8	0.34316	0.02704	12.69	0.000

S = 0.174711   R-Sq   94.2%   R-Sq(adj) = 93.6%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	4.9157	4.9157	161.04	0.000
Residual Error	10	0.3052	0.0305		
Total	11	5.2209			

Unusual Observations

Obs	coeff 1.8	MT	Fit	SE Fit	Residual	St Resid
6	7.22	2.9593	3.2950	0.0553	-0.3358	-2.03R

R denotes an observation with a large standardized residual.

Regression Analysis: MT versus coeff 1.9

The regression equation is
MT = 0.884 + 0.326 coeff 1.9

Predictor	Coef	SE Coef	T	P
Constant	0.8844	0.1861	4.75	0.001
coeff 1.9	0.32608	0.02736	11.92	0.000

S = 0.185311   R-Sq = 93.4%   R-Sq(adj) = 92.8%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	4.8775	4.8775	142.03	0.000
Residual Error	10	0.3434	0.0343		
Total	11	5.2209			

Unusual Observations

Obs	coeff 1.9	MT	Fit	SE Fit	Residual	St Resid
6	7.45	2.9593	3.3133	0.0593	-0.3541	-2.02R

R denotes an observation with a large standardized residual.

Regression Analysis: MT versus coeff 2

The regression equation is
MT = 0.946 + 0.310 coeff 2

Predictor	Coef	SE Coef	T	P
Constant	0.9459	0.1914	4.94	0.001
coeff 2	0.31043	0.02754	11.27	0.000

S = 0.195145   R-Sq = 92.7%   R-Sq(adj) = 92.0%

Analysis of Variance

Source	DF	SS	MS	F	P
Regression	1	4.8401	4.8401	127.10	0.000
Residual Error	10	0.3808	0.0381		
Total	11	5.2209			

Unusual Observations

Obs	coeff 2	MT	Fit	SE Fit	Residual	St Resid
6	7.68	2.9593	3.3297	0.0631	-0.3705	-2.01R

R denotes an observation with a large standardized residual.

1.6 Fitts' Original Study

General Linear Model: Time versus Width, Amplitude, Stylus

Factor	Type	Levels	Values
Width	fixed	4	0.25, 0.50, 1.00, 2.00
Amplitude	fixed	4	2, 4, 8, 16
Stylus	fixed	2	1, 2

Analysis of Variance for Time, using Adjusted SS for Tests

Source	DF	Seq SS	Adj SS	Adj MS	***F***	***P***
Width	3	0.402718	0.402718	0.134239	***1605.52***	***0.000***
Amplitude	3	0.409662	0.409662	0.136554	***1633.20***	***0.000***
Weight	1	0.003698	0.003698	0.003698	***44.23***	***0.000***
Error	9	0.000753	0.000753	0.000084		
Total	31	0.832532				

S = 0.00914391 **R-Sq = 99.91% R-Sq(adj) = 99.69%**

2.1 Subject #1

Baseline

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
1	Trial 23	20	10	1.25	Right	3.21	5.000	1
1	Trial 6	10	5	1.25	Left	2.69	4.000	1
1	Trial 26	20	10	2.375	Right	3.66	4.074	1
1	Trial 22	20	5	2.375	Left	2.69	4.074	1
1	Trial 16	20	1	1.25	Left	2.03	5.000	1
1	Trial 1	10	1	1.25	Right	1.82	4.000	1
1	Trial 3	10	1	2.375	Right	1.44	3.074	1
1	Trial 14	10	10	2.375	Both	2.5	3.074	1
1	Trial 7	10	5	2.375	Right	2.16	3.074	1
1	Trial 13	10	10	2.375	Left	2.44	3.074	1
1	Trial 11	10	10	1.25	Both	2.78	4.000	1
1	Trial 27	20	10	2.375	Left	3.22	4.074	1
1	Trial 28	20	10	2.375	Both	2.81	4.074	1
1	Trial 15	20	1	1.25	Right	1.63	5.000	1
1	Trial 17	20	1	2.375	Right	1.94	4.074	1
1	Trial 20	20	5	1.25	Left	3.75	5.000	1
1	Trial 5	10	5	1.25	Right	2.31	4.000	1
1	Trial 25	20	10	1.25	Both	4.07	5.000	1
1	Trial 4	10	1	2.375	Left	1.71	3.074	1
1	Trial 19	20	5	1.25	Right	2.88	5.000	1
1	Trial 21	20	5	2.375	Right	2.43	4.074	1
1	Trial 24	20	10	1.25	Left	3.24	5.000	1
1	Trial 12	10	10	2.375	Right	2.56	3.074	1
1	Trial 10	10	10	1.25	Left	2.69	4.000	1
1	Trial 8	10	5	2.375	Left	2.37	3.074	1
1	Trial 2	10	1	1.25	Left	1.87	4.000	1
1	Trial 18	20	1	2.375	Left	2.38	4.074	1
1	Trial 9	10	10	1.25	Right	2.75	4.000	1

3-Dimensional

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
1	Trial 53	20	10	1.25	Both	3.07	5.000	2
1	Trial 47	20	5	1.25	Right	3.2	5.000	2
1	Trial 49	20	5	2.375	Right	2.78	4.074	2
1	Trial 54	20	10	2.375	Right	2.72	4.074	2
1	Trial 36	10	5	2.375	Left	2.28	3.074	2
1	Trial 33	10	5	1.25	Right	2.65	4.000	2
1	Trial 44	20	1	1.25	Left	2.47	5.000	2
1	Trial 42	10	10	2.375	Both	2.22	3.074	2
1	Trial 46	20	1	2.375	Left	1.88	4.074	2
1	Trial 29	10	1	1.25	Right	1.91	4.000	2
1	Trial 48	20	5	1.25	Left	2.88	5.000	2
1	Trial 40	10	10	2.375	Right	2.5	3.074	2
1	Trial 39	10	10	1.25	Both	2.35	4.000	2
1	Trial 50	20	5	2.375	Left	2.56	4.074	2
1	Trial 37	10	10	1.25	Right	2.72	4.000	2
1	Trial 41	10	10	2.375	Left	2.5	3.074	2
1	Trial 31	10	1	2.375	Right	1.22	3.074	2
1	Trial 55	20	10	2.375	Left	2.85	4.074	2
1	Trial 34	10	5	1.25	Left	2.84	4.000	2
1	Trial 43	20	1	1.25	Right	2.31	5.000	2
1	Trial 30	10	1	1.25	Left	1.94	4.000	2
1	Trial 32	10	1	2.375	Left	1.56	3.074	2
1	Trial 45	20	1	2.375	Right	1.78	4.074	2
1	Trial 51	20	10	1.25	Right	3.12	5.000	2
1	Trial 56	20	10	2.375	Both	2.9	4.074	2
1	Trial 35	10	5	2.375	Right	2.25	3.074	2
1	Trial 52	20	10	1.25	Left	3.38	5.000	2
1	Trial 38	10	10	1.25	Left	2.78	4.000	2

2.2 Subject #2

Baseline

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
2	Trial 5	10	5	1.25	Right	3.84	4.000	1
2	Trial 7	10	5	2.375	Right	3.25	3.074	1
2	Trial 17	20	1	2.375	Right	2.75	4.074	1
2	Trial 25	20	10	1.25	Both	4.56	5.000	1
2	Trial 9	10	10	1.25	Right	3.38	4.000	1
2	Trial 12	10	10	2.375	Right	2.97	3.074	1
2	Trial 4	10	1	2.375	Left	2.37	3.074	1
2	Trial 8	10	5	2.375	Left	3.06	3.074	1
2	Trial 15	20	1	1.25	Right	2.85	5.000	1
2	Trial 27	20	10	2.375	Left	4.41	4.074	1
2	Trial 16	20	1	1.25	Left	3.94	5.000	1
2	Trial 24	20	10	1.25	Left	4.9	5.000	1
2	Trial 11	10	10	1.25	Both	3.06	4.000	1
2	Trial 22	20	5	2.375	Left	3.44	4.074	1
2	Trial 21	20	5	2.375	Right	3.28	4.074	1
2	Trial 10	10	10	1.25	Left	3.19	4.000	1
2	Trial 13	10	10	2.375	Left	2.78	3.074	1
2	Trial 28	20	10	2.375	Both	3.53	4.074	1
2	Trial 26	20	10	2.375	Right	3.44	4.074	1
2	Trial 6	10	5	1.25	Left	3	4.000	1
2	Trial 23	20	10	1.25	Right	3.78	5.000	1
2	Trial 3	10	1	2.375	Right	1.68	3.074	1
2	Trial 20	20	5	1.25	Left	3.47	5.000	1
2	Trial 1	10	1	1.25	Right	1.85	4.000	1
2	Trial 18	20	1	2.375	Left	2.19	4.074	1
2	Trial 2	10	1	1.25	Left	2	4.000	1
2	Trial 14	10	10	2.375	Both	2.56	3.074	1
2	Trial 19	20	5	1.25	Right	3.47	5.000	1

3-Dimensional

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
2	Trial 50	20	5	2.375	Left	3.28	4.074	2
2	Trial 53	20	10	1.25	Both	3.94	5.000	2
2	Trial 41	10	10	2.375	Left	3.07	3.074	2
2	Trial 51	20	10	1.25	Right	3.84	5.000	2
2	Trial 29	10	1	1.25	Right	2.16	4.000	2
2	Trial 46	20	1	2.375	Left	2.22	4.074	2
2	Trial 39	10	10	1.25	Both	2.84	4.000	2
2	Trial 33	10	5	1.25	Right	3.19	4.000	2
2	Trial 45	20	1	2.375	Right	2.09	4.074	2
2	Trial 35	10	5	2.375	Right	2.38	3.074	2
2	Trial 43	20	1	1.25	Right	2.47	5.000	2
2	Trial 54	20	10	2.375	Right	3.81	4.074	2
2	Trial 40	10	10	2.375	Right	3.12	3.074	2
2	Trial 37	10	10	1.25	Right	3.25	4.000	2
2	Trial 34	10	5	1.25	Left	3.44	4.000	2
2	Trial 42	10	10	2.375	Both	2.78	3.074	2
2	Trial 56	20	10	2.375	Both	3.25	4.074	2
2	Trial 32	10	1	2.375	Left	1.91	3.074	2
2	Trial 31	10	1	2.375	Right	1.75	3.074	2
2	Trial 30	10	1	1.25	Left	2.13	4.000	2
2	Trial 36	10	5	2.375	Left	2.81	3.074	2
2	Trial 49	20	5	2.375	Right	3.18	4.074	2
2	Trial 55	20	10	2.375	Left	3.41	4.074	2
2	Trial 48	20	5	1.25	Left	4.32	5.000	2
2	Trial 38	10	10	1.25	Left	3.16	4.000	2
2	Trial 44	20	1	1.25	Left	2.72	5.000	2
2	Trial 47	20	5	1.25	Right	3.34	5.000	2
2	Trial 52	20	10	1.25	Left	4.07	5.000	2

2.3 Subject #3

Baseline

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
3	Trial 2	10	1	1.25	Left	2.94	4.000	1
3	Trial 10	10	10	1.25	Left	5.06	4.000	1
3	Trial 7	10	5	2.375	Right	3.72	3.074	1
3	Trial 4	10	1	2.375	Left	1.97	3.074	1
3	Trial 17	20	1	2.375	Right	2.72	4.074	1
3	Trial 11	10	10	1.25	Both	3.43	4.000	1
3	Trial 5	10	5	1.25	Right	3.84	4.000	1
3	Trial 20	20	5	1.25	Left	4.03	5.000	1
3	Trial 27	20	10	2.375	Left	3.94	4.074	1
3	Trial 23	20	10	1.25	Right	5.75	5.000	1
3	Trial 19	20	5	1.25	Right	4	5.000	1
3	Trial 18	20	1	2.375	Left	2.37	4.074	1
3	Trial 21	20	5	2.375	Right	3.21	4.074	1
3	Trial 9	10	10	1.25	Right	3.25	4.000	1
3	Trial 22	20	5	2.375	Left	3.25	4.074	1
3	Trial 26	20	10	2.375	Right	3.97	4.074	1
3	Trial 13	10	10	2.375	Left	2.72	3.074	1
3	Trial 14	10	10	2.375	Both	2.65	3.074	1
3	Trial 3	10	1	2.375	Right	1.91	3.074	1
3	Trial 8	10	5	2.375	Left	2.5	3.074	1
3	Trial 1	10	1	1.25	Right	2.09	4.000	1
3	Trial 28	20	10	2.375	Both	4.22	4.074	1
3	Trial 24	20	10	1.25	Left	3.94	5.000	1
3	Trial 6	10	5	1.25	Left	2.78	4.000	1
3	Trial 15	20	1	1.25	Right	2.56	5.000	1
3	Trial 12	10	10	2.375	Right	3.37	3.074	1
3	Trial 16	20	1	1.25	Left	4.31	5.000	1
3	Trial 25	20	10	1.25	Both	4.22	5.000	1

3-Dimensional

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
3	Trial 39	10	10	1.25	Both	3.84	4.000	2
3	Trial 41	10	10	2.375	Left	3.29	3.074	2
3	Trial 31	10	1	2.375	Right	1.94	3.074	2
3	Trial 48	20	5	1.25	Left	3.72	5.000	2
3	Trial 50	20	5	2.375	Left	3.35	4.074	2
3	Trial 54	20	10	2.375	Right	4.53	4.074	2
3	Trial 45	20	1	2.375	Right	2.34	4.074	2
3	Trial 38	10	10	1.25	Left	3.5	4.000	2
3	Trial 32	10	1	2.375	Left	1.56	3.074	2
3	Trial 47	20	5	1.25	Right	3.75	5.000	2
3	Trial 40	10	10	2.375	Right	3.47	3.074	2
3	Trial 44	20	1	1.25	Left	2.81	5.000	2
3	Trial 52	20	10	1.25	Left	4.22	5.000	2
3	Trial 53	20	10	1.25	Both	4.19	5.000	2
3	Trial 33	10	5	1.25	Right	4.07	4.000	2
3	Trial 35	10	5	2.375	Right	2.81	3.074	2
3	Trial 30	10	1	1.25	Left	2.19	4.000	2
3	Trial 36	10	5	2.375	Left	2.88	3.074	2
3	Trial 49	20	5	2.375	Right	3.28	4.074	2
3	Trial 46	20	1	2.375	Left	2.54	4.074	2
3	Trial 42	10	10	2.375	Both	3.03	3.074	2
3	Trial 51	20	10	1.25	Right	4.68	5.000	2
3	Trial 55	20	10	2.375	Left	4.03	4.074	2
3	Trial 56	20	10	2.375	Both	3.75	4.074	2
3	Trial 29	10	1	1.25	Right	2.4	4.000	2
3	Trial 43	20	1	1.25	Right	2.78	5.000	2
3	Trial 37	10	10	1.25	Right	3.84	4.000	2
3	Trial 34	10	5	1.25	Left	2.97	4.000	2

2.4 Subject #4

Baseline

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
4	Trial 27	20	10	2.375	Left	4.85	4.074	1
4	Trial 2	10	1	1.25	Left	2.81	4.000	1
4	Trial 15	20	1	1.25	Right	3.4	5.000	1
4	Trial 3	10	1	2.375	Right	1.97	3.074	1
4	Trial 10	10	10	1.25	Left	4.63	4.000	1
4	Trial 1	10	1	1.25	Right	2.38	4.000	1
4	Trial 18	20	1	2.375	Left	3.4	4.074	1
4	Trial 12	10	10	2.375	Right	2.61	3.074	1
4	Trial 21	20	5	2.375	Right	4	4.074	1
4	Trial 9	10	10	1.25	Right	4.34	4.000	1
4	Trial 19	20	5	1.25	Right	4.31	5.000	1
4	Trial 16	20	1	1.25	Left	3.5	5.000	1
4	Trial 26	20	10	2.375	Right	4.38	4.074	1
4	Trial 6	10	5	1.25	Left	4.03	4.000	1
4	Trial 22	20	5	2.375	Left	4.15	4.074	1
4	Trial 25	20	10	1.25	Both	4.91	5.000	1
4	Trial 7	10	5	2.375	Right	3.07	3.074	1
4	Trial 4	10	1	2.375	Left	2.22	3.074	1
4	Trial 24	20	10	1.25	Left	5.56	5.000	1
4	Trial 13	10	10	2.375	Left	3.63	3.074	1
4	Trial 14	10	10	2.375	Both	3.28	3.074	1
4	Trial 8	10	5	2.375	Left	3.03	3.074	1
4	Trial 11	10	10	1.25	Both	3.96	4.000	1
4	Trial 23	20	10	1.25	Right	4.6	5.000	1
4	Trial 5	10	5	1.25	Right	3.1	4.000	1
4	Trial 17	20	1	2.375	Right	2.38	4.074	1
4	Trial 20	20	5	1.25	Left	4.1	5.000	1
4	Trial 28	20	10	2.375	Both	3.69	4.074	1

3-Dimensional

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
4	Trial 39	10	10	1.25	Both	3.92	4.000	2
4	Trial 46	20	1	2.375	Left	3.03	4.074	2
4	Trial 50	20	5	2.375	Left	3.81	4.074	2
4	Trial 51	20	10	1.25	Right	4.85	5.000	2
4	Trial 38	10	10	1.25	Left	3.69	4.000	2
4	Trial 34	10	5	1.25	Left	3.41	4.000	2
4	Trial 43	20	1	1.25	Right	2.75	5.000	2
4	Trial 55	20	10	2.375	Left	5.03	4.074	2
4	Trial 36	10	5	2.375	Left	3.25	3.074	2
4	Trial 53	20	10	1.25	Both	4.07	5.000	2
4	Trial 56	20	10	2.375	Both	4.22	4.074	2
4	Trial 32	10	1	2.375	Left	2.07	3.074	2
4	Trial 29	10	1	1.25	Right	2.06	4.000	2
4	Trial 44	20	1	1.25	Left	2.9	5.000	2
4	Trial 48	20	5	1.25	Left	4	5.000	2
4	Trial 37	10	10	1.25	Right	3.72	4.000	2
4	Trial 54	20	10	2.375	Right	4.29	4.074	2
4	Trial 31	10	1	2.375	Right	1.72	3.074	2
4	Trial 30	10	1	1.25	Left	2.31	4.000	2
4	Trial 41	10	10	2.375	Left	3.28	3.074	2
4	Trial 33	10	5	1.25	Right	3.85	4.000	2
4	Trial 40	10	10	2.375	Right	3.28	3.074	2
4	Trial 45	20	1	2.375	Right	3	4.074	2
4	Trial 47	20	5	1.25	Right	4.04	5.000	2
4	Trial 35	10	5	2.375	Right	2.97	3.074	2
4	Trial 52	20	10	1.25	Left	5.31	5.000	2
4	Trial 42	10	10	2.375	Both	3.1	3.074	2
4	Trial 49	20	5	2.375	Right	3.81	4.074	2

2.5 Subject #5

Baseline

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
5	Trial 20	20	5	1.25	Left	4.56	5.000	1
5	Trial 17	20	1	2.375	Right	2.09	4.074	1
5	Trial 14	10	10	2.375	Both	2.78	3.074	1
5	Trial 6	10	5	1.25	Left	6.12	4.000	1
5	Trial 4	10	1	2.375	Left	1.84	3.074	1
5	Trial 7	10	5	2.375	Right	2.75	3.074	1
5	Trial 11	10	10	1.25	Both	3.66	4.000	1
5	Trial 28	20	10	2.375	Both	3.53	4.074	1
5	Trial 5	10	5	1.25	Right	2.75	4.000	1
5	Trial 18	20	1	2.375	Left	2.12	4.074	1
5	Trial 24	20	10	1.25	Left	4.28	5.000	1
5	Trial 21	20	5	2.375	Right	3	4.074	1
5	Trial 1	10	1	1.25	Right	1.81	4.000	1
5	Trial 25	20	10	1.25	Both	4.38	5.000	1
5	Trial 19	20	5	1.25	Right	3.85	5.000	1
5	Trial 2	10	1	1.25	Left	2.19	4.000	1
5	Trial 15	20	1	1.25	Right	2.75	5.000	1
5	Trial 16	20	1	1.25	Left	2.93	5.000	1
5	Trial 10	10	10	1.25	Left	3.79	4.000	1
5	Trial 13	10	10	2.375	Left	2.87	3.074	1
5	Trial 9	10	10	1.25	Right	3.53	4.000	1
5	Trial 23	20	10	1.25	Right	3.6	5.000	1
5	Trial 3	10	1	2.375	Right	1.44	3.074	1
5	Trial 27	20	10	2.375	Left	3.31	4.074	1
5	Trial 8	10	5	2.375	Left	3.07	3.074	1
5	Trial 26	20	10	2.375	Right	3.87	4.074	1
5	Trial 22	20	5	2.375	Left	3.6	4.074	1
5	Trial 12	10	10	2.375	Right	2.94	3.074	1

3-Dimensional

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
5	Trial 47	20	5	1.25	Right	3.66	5.000	2
5	Trial 51	20	10	1.25	Right	3.97	5.000	2
5	Trial 36	10	5	2.375	Left	2.82	3.074	2
5	Trial 30	10	1	1.25	Left	2.25	4.000	2
5	Trial 53	20	10	1.25	Both	4.07	5.000	2
5	Trial 35	10	5	2.375	Right	2.78	3.074	2
5	Trial 42	10	10	2.375	Both	3.18	3.074	2
5	Trial 32	10	1	2.375	Left	1.63	3.074	2
5	Trial 46	20	1	2.375	Left	2.53	4.074	2
5	Trial 43	20	1	1.25	Right	2.47	5.000	2
5	Trial 55	20	10	2.375	Left	3.97	4.074	2
5	Trial 29	10	1	1.25	Right	1.72	4.000	2
5	Trial 39	10	10	1.25	Both	3.44	4.000	2
5	Trial 44	20	1	1.25	Left	2.66	5.000	2
5	Trial 33	10	5	1.25	Right	3.28	4.000	2
5	Trial 52	20	10	1.25	Left	4.31	5.000	2
5	Trial 54	20	10	2.375	Right	3.78	4.074	2
5	Trial 48	20	5	1.25	Left	3.78	5.000	2
5	Trial 31	10	1	2.375	Right	1.37	3.074	2
5	Trial 37	10	10	1.25	Right	3.65	4.000	2
5	Trial 38	10	10	1.25	Left	3.75	4.000	2
5	Trial 45	20	1	2.375	Right	1.84	4.074	2
5	Trial 50	20	5	2.375	Left	3.32	4.074	2
5	Trial 40	10	10	2.375	Right	3.16	3.074	2
5	Trial 41	10	10	2.375	Left	3.19	3.074	2
5	Trial 56	20	10	2.375	Both	3.53	4.074	2
5	Trial 49	20	5	2.375	Right	3.13	4.074	2
5	Trial 34	10	5	1.25	Left	3.21	4.000	2

2.6 Subject #6

Baseline

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
6	Trial 14	10	10	2.375	Both	5.16	3.074	1
6	Trial 28	20	10	2.375	Both	4.46	4.074	1
6	Trial 23	20	10	1.25	Right	5.15	5.000	1
6	Trial 19	20	5	1.25	Right	4.56	5.000	1
6	Trial 11	10	10	1.25	Both	3.87	4.000	1
6	Trial 27	20	10	2.375	Left	4.56	4.074	1
6	Trial 15	20	1	1.25	Right	3.57	5.000	1
6	Trial 21	20	5	2.375	Right	4.37	4.074	1
6	Trial 10	10	10	1.25	Left	4.09	4.000	1
6	Trial 1	10	1	1.25	Right	3.09	4.000	1
6	Trial 5	10	5	1.25	Right	3.75	4.000	1
6	Trial 8	10	5	2.375	Left	3.57	3.074	1
6	Trial 13	10	10	2.375	Left	3.91	3.074	1
6	Trial 20	20	5	1.25	Left	4.47	5.000	1
6	Trial 26	20	10	2.375	Right	4.19	4.074	1
6	Trial 18	20	1	2.375	Left	3.09	4.074	1
6	Trial 7	10	5	2.375	Right	2.94	3.074	1
6	Trial 9	10	10	1.25	Right	3.53	4.000	1
6	Trial 17	20	1	2.375	Right	2.78	4.074	1
6	Trial 12	10	10	2.375	Right	3.31	3.074	1
6	Trial 22	20	5	2.375	Left	3.69	4.074	1
6	Trial 4	10	1	2.375	Left	2.06	3.074	1
6	Trial 24	20	10	1.25	Left	4.21	5.000	1
6	Trial 3	10	1	2.375	Right	1.93	3.074	1
6	Trial 16	20	1	1.25	Left	2.97	5.000	1
6	Trial 6	10	5	1.25	Left	3.19	4.000	1
6	Trial 25	20	10	1.25	Both	4.25	5.000	1
6	Trial 2	10	1	1.25	Left	2.34	4.000	1

3-Dimensional

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
6	Trial 30	10	1	1.25	Left	2.37	4.000	2
6	Trial 46	20	1	2.375	Left	2.47	4.074	2
6	Trial 55	20	10	2.375	Left	3.88	4.074	2
6	Trial 29	10	1	1.25	Right	2.43	4.000	2
6	Trial 50	20	5	2.375	Left	3.56	4.074	2
6	Trial 43	20	1	1.25	Right	2.62	5.000	2
6	Trial 35	10	5	2.375	Right	2.57	3.074	2
6	Trial 48	20	5	1.25	Left	3.96	5.000	2
6	Trial 40	10	10	2.375	Right	3.35	3.074	2
6	Trial 52	20	10	1.25	Left	4.44	5.000	2
6	Trial 56	20	10	2.375	Both	3.53	4.074	2
6	Trial 37	10	10	1.25	Right	3.24	4.000	2
6	Trial 36	10	5	2.375	Left	2.84	3.074	2
6	Trial 53	20	10	1.25	Both	3.31	5.000	2
6	Trial 44	20	1	1.25	Left	2.72	5.000	2
6	Trial 54	20	10	2.375	Right	3.71	4.074	2
6	Trial 39	10	10	1.25	Both	3.22	4.000	2
6	Trial 31	10	1	2.375	Right	1.63	3.074	2
6	Trial 33	10	5	1.25	Right	3.06	4.000	2
6	Trial 38	10	10	1.25	Left	3.5	4.000	2
6	Trial 41	10	10	2.375	Left	3.28	3.074	2
6	Trial 42	10	10	2.375	Both	2.94	3.074	2
6	Trial 49	20	5	2.375	Right	3.09	4.074	2
6	Trial 34	10	5	1.25	Left	3.16	4.000	2
6	Trial 32	10	1	2.375	Left	1.72	3.074	2
6	Trial 47	20	5	1.25	Right	3.91	5.000	2
6	Trial 45	20	1	2.375	Right	2.34	4.074	2
6	Trial 51	20	10	1.25	Right	4.22	5.000	2

2.7 Subject #7

Baseline

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
7	Trial 20	20	5	1.25	Left	3.53	5.000	1
7	Trial 18	20	1	2.375	Left	2.87	4.074	1
7	Trial 25	20	10	1.25	Both	3.63	5.000	1
7	Trial 26	20	10	2.375	Right	3.41	4.074	1
7	Trial 12	10	10	2.375	Right	2.69	3.074	1
7	Trial 11	10	10	1.25	Both	2.72	4.000	1
7	Trial 1	10	1	1.25	Right	1.81	4.000	1
7	Trial 14	10	10	2.375	Both	2.5	3.074	1
7	Trial 19	20	5	1.25	Right	3.06	5.000	1
7	Trial 8	10	5	2.375	Left	2.78	3.074	1
7	Trial 28	20	10	2.375	Both	2.97	4.074	1
7	Trial 6	10	5	1.25	Left	2.81	4.000	1
7	Trial 2	10	1	1.25	Left	1.78	4.000	1
7	Trial 16	20	1	1.25	Left	2	5.000	1
7	Trial 7	10	5	2.375	Right	2.34	3.074	1
7	Trial 13	10	10	2.375	Left	2.75	3.074	1
7	Trial 27	20	10	2.375	Left	3.34	4.074	1
7	Trial 3	10	1	2.375	Right	1.37	3.074	1
7	Trial 21	20	5	2.375	Right	2.75	4.074	1
7	Trial 17	20	1	2.375	Right	1.69	4.074	1
7	Trial 22	20	5	2.375	Left	3	4.074	1
7	Trial 4	10	1	2.375	Left	1.34	3.074	1
7	Trial 10	10	10	1.25	Left	3.44	4.000	1
7	Trial 23	20	10	1.25	Right	3.75	5.000	1
7	Trial 24	20	10	1.25	Left	3.94	5.000	1
7	Trial 9	10	10	1.25	Right	2.91	4.000	1
7	Trial 5	10	5	1.25	Right	2.59	4.000	1
7	Trial 15	20	1	1.25	Right	1.75	5.000	1

3-Dimensional

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
7	Trial 41	10	10	2.375	Left	2.56	3.074	2
7	Trial 43	20	1	1.25	Right	2.31	5.000	2
7	Trial 29	10	1	1.25	Right	1.81	4.000	2
7	Trial 50	20	5	2.375	Left	2.59	4.074	2
7	Trial 53	20	10	1.25	Both	3.94	5.000	2
7	Trial 55	20	10	2.375	Left	3.62	4.074	2
7	Trial 40	10	10	2.375	Right	2.75	3.074	2
7	Trial 33	10	5	1.25	Right	2.59	4.000	2
7	Trial 38	10	10	1.25	Left	3.1	4.000	2
7	Trial 37	10	10	1.25	Right	2.93	4.000	2
7	Trial 34	10	5	1.25	Left	2.59	4.000	2
7	Trial 46	20	1	2.375	Left	1.81	4.074	2
7	Trial 32	10	1	2.375	Left	1.34	3.074	2
7	Trial 42	10	10	2.375	Both	2.44	3.074	2
7	Trial 44	20	1	1.25	Left	2.03	5.000	2
7	Trial 52	20	10	1.25	Left	3.78	5.000	2
7	Trial 47	20	5	1.25	Right	3.35	5.000	2
7	Trial 31	10	1	2.375	Right	1.25	3.074	2
7	Trial 36	10	5	2.375	Left	2.41	3.074	2
7	Trial 39	10	10	1.25	Both	2.9	4.000	2
7	Trial 45	20	1	2.375	Right	1.56	4.074	2
7	Trial 51	20	10	1.25	Right	3.59	5.000	2
7	Trial 56	20	10	2.375	Both	3.31	4.074	2
7	Trial 35	10	5	2.375	Right	2.43	3.074	2
7	Trial 48	20	5	1.25	Left	2.94	5.000	2
7	Trial 54	20	10	2.375	Right	2.97	4.074	2
7	Trial 30	10	1	1.25	Left	1.6	4.000	2
7	Trial 49	20	5	2.375	Right	2.81	4.074	2

2.8 Subject #8

Baseline

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
8	Trial 25	20	10	1.25	Both	6.03	5.000	1
8	Trial 7	10	5	2.375	Right	3.69	3.074	1
8	Trial 22	20	5	2.375	Left	4.82	4.074	1
8	Trial 28	20	10	2.375	Both	4.69	4.074	1
8	Trial 1	10	1	1.25	Right	3.81	4.000	1
8	Trial 21	20	5	2.375	Right	4.44	4.074	1
8	Trial 12	10	10	2.375	Right	4.1	3.074	1
8	Trial 2	10	1	1.25	Left	3.81	4.000	1
8	Trial 17	20	1	2.375	Right	3.6	4.074	1
8	Trial 5	10	5	1.25	Right	3.94	4.000	1
8	Trial 8	10	5	2.375	Left	3.78	3.074	1
8	Trial 15	20	1	1.25	Right	3.81	5.000	1
8	Trial 23	20	10	1.25	Right	4.88	5.000	1
8	Trial 27	20	10	2.375	Left	4.53	4.074	1
8	Trial 19	20	5	1.25	Right	4.28	5.000	1
8	Trial 3	10	1	2.375	Right	2.69	3.074	1
8	Trial 16	20	1	1.25	Left	3.66	5.000	1
8	Trial 26	20	10	2.375	Right	4.22	4.074	1
8	Trial 10	10	10	1.25	Left	4.69	4.000	1
8	Trial 14	10	10	2.375	Both	3.68	3.074	1
8	Trial 4	10	1	2.375	Left	2.35	3.074	1
8	Trial 24	20	10	1.25	Left	5.31	5.000	1
8	Trial 6	10	5	1.25	Left	3.9	4.000	1
8	Trial 11	10	10	1.25	Both	4	4.000	1
8	Trial 9	10	10	1.25	Right	3.72	4.000	1
8	Trial 13	10	10	2.375	Left	3.66	3.074	1
8	Trial 20	20	5	1.25	Left	4.94	5.000	1
8	Trial 18	20	1	2.375	Left	2.69	4.074	1

3-Dimensional

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
8	Trial 29	10	1	1.25	Right	2.78	4.000	2
8	Trial 43	20	1	1.25	Right	3.06	5.000	2
8	Trial 33	10	5	1.25	Right	3.19	4.000	2
8	Trial 37	10	10	1.25	Right	3.85	4.000	2
8	Trial 51	20	10	1.25	Right	4.18	5.000	2
8	Trial 47	20	5	1.25	Right	3.69	5.000	2
8	Trial 45	20	1	2.375	Right	2.22	4.074	2
8	Trial 42	10	10	2.375	Both	3.25	3.074	2
8	Trial 34	10	5	1.25	Left	3.71	4.000	2
8	Trial 39	10	10	1.25	Both	3.63	4.000	2
8	Trial 44	20	1	1.25	Left	3.12	5.000	2
8	Trial 32	10	1	2.375	Left	2.12	3.074	2
8	Trial 56	20	10	2.375	Both	3.63	4.074	2
8	Trial 31	10	1	2.375	Right	1.56	3.074	2
8	Trial 35	10	5	2.375	Right	2.63	3.074	2
8	Trial 38	10	10	1.25	Left	3.28	4.000	2
8	Trial 41	10	10	2.375	Left	3.47	3.074	2
8	Trial 52	20	10	1.25	Left	5.18	5.000	2
8	Trial 48	20	5	1.25	Left	4.47	5.000	2
8	Trial 54	20	10	2.375	Right	3.96	4.074	2
8	Trial 50	20	5	2.375	Left	3.81	4.074	2
8	Trial 46	20	1	2.375	Left	2.63	4.074	2
8	Trial 49	20	5	2.375	Right	3.38	4.074	2
8	Trial 40	10	10	2.375	Right	3.1	3.074	2
8	Trial 53	20	10	1.25	Both	3.47	5.000	2
8	Trial 30	10	1	1.25	Left	2.56	4.000	2
8	Trial 36	10	5	2.375	Left	3.09	3.074	2
8	Trial 55	20	10	2.375	Left	3.88	4.074	2

2.9 Subject #9

Baseline

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
9	Trial 21	20	5	2.375	Right	3.94	4.074	1
9	Trial 8	10	5	2.375	Left	3.06	3.074	1
9	Trial 7	10	5	2.375	Right	2.62	3.074	1
9	Trial 22	20	5	2.375	Left	3.12	4.074	1
9	Trial 26	20	10	2.375	Right	3.35	4.074	1
9	Trial 12	10	10	2.375	Right	2.5	3.074	1
9	Trial 28	20	10	2.375	Both	2.82	4.074	1
9	Trial 10	10	10	1.25	Left	2.97	4.000	1
9	Trial 5	10	5	1.25	Right	2.57	4.000	1
9	Trial 16	20	1	1.25	Left	2.87	5.000	1
9	Trial 2	10	1	1.25	Left	2.18	4.000	1
9	Trial 24	20	10	1.25	Left	3.85	5.000	1
9	Trial 23	20	10	1.25	Right	3.81	5.000	1
9	Trial 25	20	10	1.25	Both	3.13	5.000	1
9	Trial 17	20	1	2.375	Right	2.16	4.074	1
9	Trial 18	20	1	2.375	Left	2.05	4.074	1
9	Trial 27	20	10	2.375	Left	3.4	4.074	1
9	Trial 14	10	10	2.375	Both	2.44	3.074	1
9	Trial 13	10	10	2.375	Left	2.62	3.074	1
9	Trial 15	20	1	1.25	Right	2.47	5.000	1
9	Trial 19	20	5	1.25	Right	3.19	5.000	1
9	Trial 6	10	5	1.25	Left	2.56	4.000	1
9	Trial 20	20	5	1.25	Left	3.12	5.000	1
9	Trial 1	10	1	1.25	Right	1.91	4.000	1
9	Trial 11	10	10	1.25	Both	2.53	4.000	1
9	Trial 9	10	10	1.25	Right	2.56	4.000	1
9	Trial 4	10	1	2.375	Left	1.75	3.074	1
9	Trial 3	10	1	2.375	Right	1.5	3.074	1

3-Dimensional

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
9	Trial 42	10	10	2.375	Both	2.47	3.074	2
9	Trial 31	10	1	2.375	Right	1.62	3.074	2
9	Trial 34	10	5	1.25	Left	2.62	4.000	2
9	Trial 46	20	1	2.375	Left	2.06	4.074	2
9	Trial 36	10	5	2.375	Left	2.4	3.074	2
9	Trial 55	20	10	2.375	Left	3.09	4.074	2
9	Trial 51	20	10	1.25	Right	3	5.000	2
9	Trial 52	20	10	1.25	Left	3.12	5.000	2
9	Trial 48	20	5	1.25	Left	2.79	5.000	2
9	Trial 43	20	1	1.25	Right	2.09	5.000	2
9	Trial 45	20	1	2.375	Right	1.75	4.074	2
9	Trial 38	10	10	1.25	Left	2.66	4.000	2
9	Trial 30	10	1	1.25	Left	1.94	4.000	2
9	Trial 29	10	1	1.25	Right	1.81	4.000	2
9	Trial 39	10	10	1.25	Both	2.42	4.000	2
9	Trial 37	10	10	1.25	Right	2.78	4.000	2
9	Trial 33	10	5	1.25	Right	2.38	4.000	2
9	Trial 50	20	5	2.375	Left	2.6	4.074	2
9	Trial 47	20	5	1.25	Right	2.57	5.000	2
9	Trial 54	20	10	2.375	Right	2.97	4.074	2
9	Trial 53	20	10	1.25	Both	2.59	5.000	2
9	Trial 35	10	5	2.375	Right	2.12	3.074	2
9	Trial 56	20	10	2.375	Both	2.46	4.074	2
9	Trial 49	20	5	2.375	Right	2.44	4.074	2
9	Trial 44	20	1	1.25	Left	2	5.000	2
9	Trial 40	10	10	2.375	Right	2.28	3.074	2
9	Trial 32	10	1	2.375	Left	1.66	3.074	2
9	Trial 41	10	10	2.375	Left	2.22	3.074	2

2.10 Subject #10

Baseline

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
10	Trial 24	20	10	1.25	Left	3.88	5.000	1
10	Trial 11	10	10	1.25	Both	2.47	4.000	1
10	Trial 25	20	10	1.25	Both	3.6	5.000	1
10	Trial 5	10	5	1.25	Right	2.38	4.000	1
10	Trial 27	20	10	2.375	Left	3.35	4.074	1
10	Trial 28	20	10	2.375	Both	3.25	4.074	1
10	Trial 12	10	10	2.375	Right	2.68	3.074	1
10	Trial 14	10	10	2.375	Both	2.47	3.074	1
10	Trial 15	20	1	1.25	Right	2.28	5.000	1
10	Trial 3	10	1	2.375	Right	1.41	3.074	1
10	Trial 9	10	10	1.25	Right	2.66	4.000	1
10	Trial 16	20	1	1.25	Left	3.18	5.000	1
10	Trial 10	10	10	1.25	Left	3.44	4.000	1
10	Trial 19	20	5	1.25	Right	3	5.000	1
10	Trial 4	10	1	2.375	Left	1.66	3.074	1
10	Trial 6	10	5	1.25	Left	2.63	4.000	1
10	Trial 17	20	1	2.375	Right	2	4.074	1
10	Trial 8	10	5	2.375	Left	2.94	3.074	1
10	Trial 21	20	5	2.375	Right	3.35	4.074	1
10	Trial 18	20	1	2.375	Left	2.18	4.074	1
10	Trial 1	10	1	1.25	Right	1.81	4.000	1
10	Trial 20	20	5	1.25	Left	3.29	5.000	1
10	Trial 13	10	10	2.375	Left	2.53	3.074	1
10	Trial 2	10	1	1.25	Left	2.38	4.000	1
10	Trial 22	20	5	2.375	Left	3.47	4.074	1
10	Trial 7	10	5	2.375	Right	2.72	3.074	1
10	Trial 26	20	10	2.375	Right	3.6	4.074	1
10	Trial 23	20	10	1.25	Right	3.41	5.000	1

3-Dimensional

Subject	Trial	Movement Amplitude (in.)	Probe Weight (~lbs.)	Target Width (in.)	Hand	Movement Time (sec.)	Index of Difficulty	Condition
10	Trial 40	10	10	2.375	Right	2.43	3.074	2
10	Trial 46	20	1	2.375	Left	2	4.074	2
10	Trial 36	10	5	2.375	Left	2.37	3.074	2
10	Trial 31	10	1	2.375	Right	1.47	3.074	2
10	Trial 35	10	5	2.375	Right	2.16	3.074	2
10	Trial 56	20	10	2.375	Both	3.09	4.074	2
10	Trial 52	20	10	1.25	Left	3.16	5.000	2
10	Trial 39	10	10	1.25	Both	2.78	4.000	2
10	Trial 30	10	1	1.25	Left	2	4.000	2
10	Trial 55	20	10	2.375	Left	3.09	4.074	2
10	Trial 47	20	5	1.25	Right	2.69	5.000	2
10	Trial 33	10	5	1.25	Right	2.4	4.000	2
10	Trial 32	10	1	2.375	Left	1.75	3.074	2
10	Trial 37	10	10	1.25	Right	2.4	4.000	2
10	Trial 42	10	10	2.375	Both	2.28	3.074	2
10	Trial 34	10	5	1.25	Left	2.72	4.000	2
10	Trial 48	20	5	1.25	Left	2.91	5.000	2
10	Trial 29	10	1	1.25	Right	1.88	4.000	2
10	Trial 54	20	10	2.375	Right	3.06	4.074	2
10	Trial 41	10	10	2.375	Left	2.43	3.074	2
10	Trial 49	20	5	2.375	Right	2.59	4.074	2
10	Trial 51	20	10	1.25	Right	3.03	5.000	2
10	Trial 45	20	1	2.375	Right	1.63	4.074	2
10	Trial 44	20	1	1.25	Left	2.63	5.000	2
10	Trial 50	20	5	2.375	Left	2.5	4.074	2
10	Trial 53	20	10	1.25	Both	3.32	5.000	2
10	Trial 38	10	10	1.25	Left	2.69	4.000	2
10	Trial 43	20	1	1.25	Right	2.12	5.000	2

2.11 Two-way Interaction

t-tests of the two way interaction

	Amplitude	
Weight	10	20
1	1.98	2.53
Std. Dev.	0.49	0.58
5	2.97	3.47
Std. Dev.	0.61	0.61
10	3.17	3.93
Std. Dev.	0.58	0.68

t-Test: Paired Two Sample for Means
Amp 10, Wt 5 vs Wt 10

	Variable 1	*Variable 2*
Mean	2.97225	3.1685
Variance	0.376486	0.335043
Observations	80	80
Pearson Correlation	0.623186	
Hypothesized Mean Difference	0	
df	79	
t Stat	-3.385214	
P(T<=t) one-tail	0.000555	
t Critical one-tail	1.664371	
P(T<=t) two-tail	0.00111	
t Critical two-tail	1.990452	

t-Test: Paired Two Sample for Means
Amp 20, Wt 5 vs Wt 10

	Variable 1	*Variable 2*
Mean	3.47125	3.926875
Variance	0.373474	0.465242
Observations	80	80
Pearson Correlation	0.756736	
Hypothesized Mean Difference	0	
df	79	
t Stat	-8.938978	
P(T<=t) one-tail	6.4E-14	
t Critical one-tail	1.664371	
P(T<=t) two-tail	1.28E-13	
t Critical two-tail	1.990452	

t-Test: Paired Two Sample for Means
Wt 1, Amp 10 vs Amp 20

	Variable 1	*Variable 2*
Mean	1.979875	2.533375
Variance	0.239394	0.337099
Observations	80	80
Pearson Correlation	0.770574	
Hypothesized Mean Difference	0	
df	79	
t Stat	-13.29358	
P(T<=t) one-tail	3.79E-22	
t Critical one-tail	1.664371	
P(T<=t) two-tail	7.57E-22	
t Critical two-tail	1.990452	

t-Test: Paired Two Sample for Means
Wt 5, Amp 10 vs Amp 20

	Variable 1	*Variable 2*
Mean	2.97225	3.47125
Variance	0.376486	0.373474
Observations	80	80
Pearson Correlation	0.739659	
Hypothesized Mean Difference	0	
df	79	
t Stat	-10.10068	
P(T<=t) one-tail	3.52E-16	
t Critical one-tail	1.664371	
P(T<=t) two-tail	7.05E-16	
t Critical two-tail	1.990452	

t-Test: Paired Two Sample for Means
Wt 10, Amp 10 vs Amp 20

	Variable 1	*Variable 2*
Mean	3.1685	3.926875
Variance	0.335043	0.465242
Observations	80	80
Pearson Correlation	0.703855	
Hypothesized Mean Difference	0	
df	79	
t Stat	-13.71782	
P(T<=t) one-tail	6.64E-23	
t Critical one-tail	1.664371	
P(T<=t) two-tail	1.33E-22	
t Critical two-tail	1.990452	

2.12 Three-way Interaction
t-tests of the three way interaction

Dominant

	width	
weight	1.25	2.375
1	2.45	1.93
Std. Dev.	0.66	0.52
5	3.26	2.96
Std. Dev.	0.61	0.58
10	3.62	3.29
Std. Dev.	0.69	0.59

different
no diff

Non-dominant

	width	
weight	1.25	2.375
1	2.52	2.14
Std. Dev.	0.57	0.47
5	3.54	3.12
Std. Dev.	0.76	0.55
10	3.87	3.41
Std. Dev.	0.83	0.70

t-Test: Paired Two Sample for Means
one pound, 1.25 width

	Variable 1	*Variable 2*
Mean	2.44525	2.5155
Variance	0.435108	0.319497
Observations	40	40
Pearson Correlation	-0.224066	
Hypothesized Mean Difference	0	
df	39	
t Stat	-0.46279	
P(T<=t) one-tail	0.323043	
t Critical one-tail	1.684875	
P(T<=t) two-tail	0.646087	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
one pound, 2.375 width

	Variable 1	*Variable 2*
Mean	1.9265	2.13925
Variance	0.275018	0.221228
Observations	40	40
Pearson Correlation	0.29327	
Hypothesized Mean Difference	0	
df	39	
t Stat	-2.269312	
P(T<=t) one-tail	0.014429	
t Critical one-tail	1.684875	
P(T<=t) two-tail	0.028858	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
ten pounds, 1.25 width

	Variable 1	*Variable 2*
Mean	3.61575	3.8745
Variance	0.482158	0.690446
Observations	40	40
Pearson Correlation	0.059708	
Hypothesized Mean Difference	0	
df	39	
t Stat	-1.557701	
P(T<=t) one-tail	0.063691	
t Critical one-tail	1.684875	
P(T<=t) two-tail	0.127383	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
ten pounds, 2.375 width

	Variable 1	*Variable 2*
Mean	3.2925	3.408
Variance	0.34564	0.491627
Observations	40	40
Pearson Correlation	0.278734	
Hypothesized Mean Difference	0	
df	39	
t Stat	-0.93724	
P(T<=t) one-tail	0.177202	
t Critical one-tail	1.684875	
P(T<=t) two-tail	0.354403	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
five pounds, 1.25 width

	Variable 1	*Variable 2*
Mean	3.25925	3.53925
Variance	0.370658	0.576202
Observations	40	40
Pearson Correlation	0.076371	
Hypothesized Mean Difference	0	
df	39	
t Stat	-1.891771	
P(T<=t) one-tail	0.032982	
t Critical one-tail	1.684875	
P(T<=t) two-tail	0.065964	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
five pounds, 2.375 width

	Variable 1	*Variable 2*
Mean	2.9645	3.124
Variance	0.342102	0.303066
Observations	40	40
Pearson Correlation	0.146195	
Hypothesized Mean Difference	0	
df	39	
t Stat	-1.358961	
P(T<=t) one-tail	0.090983	
t Critical one-tail	1.684875	
P(T<=t) two-tail	0.181967	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
dominant, one pound

	Variable 1	Variable 2
Mean	2.44525	1.9265
Variance	0.435108	0.275018
Observations	40	40
Pearson Correlation	0.783518	
Hypothesized Mean Difference	0	
df	39	
t Stat	8.003242	
P(T<=t) one-tail	4.69E-10	
t Critical one-tail	1.684875	
P(T<=t) two-tail	9.37E-10	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
dominant, 5 pound

	Variable 1	Variable 2
Mean	3.25925	2.9645
Variance	0.370658	0.342102
Observations	40	40
Pearson Correlation	0.831762	
Hypothesized Mean Difference	0	
df	39	
t Stat	5.372658	
P(T<=t) one-tail	1.92E-06	
t Critical one-tail	1.684875	
P(T<=t) two-tail	3.84E-06	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
non-dominant, one pound

	Variable 1	Variable 2
Mean	2.5155	2.13925
Variance	0.319497	0.221228
Observations	40	40
Pearson Correlation	0.601296	
Hypothesized Mean Difference	0	
df	39	
t Stat	5.061822	
P(T<=t) one-tail	5.15E-06	
t Critical one-tail	1.684875	
P(T<=t) two-tail	1.03E-05	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
non-dominant, five pound

	Variable 1	Variable 2
Mean	3.53925	3.124
Variance	0.576202	0.303066
Observations	40	40
Pearson Correlation	0.641524	
Hypothesized Mean Difference	0	
df	39	
t Stat	4.483609	
P(T<=t) one-tail	3.14E-05	
t Critical one-tail	1.684875	
P(T<=t) two-tail	6.29E-05	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
dominant, 10 pound

	Variable 1	Variable 2
Mean	3.61575	3.2925
Variance	0.482158	0.34564
Observations	40	40
Pearson Correlation	0.703329	
Hypothesized Mean Difference	0	
df	39	
t Stat	4.060053	
P(T<=t) one-tail	0.000114	
t Critical one-tail	1.684875	
P(T<=t) two-tail	0.000229	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
non-dominant, ten pound

	Variable 1	Variable 2
Mean	3.8745	3.408
Variance	0.690446	0.491627
Observations	40	40
Pearson Correlation	0.868226	
Hypothesized Mean Difference	0	
df	39	
t Stat	7.147643	
P(T<=t) one-tail	6.72E-09	
t Critical one-tail	1.684875	
P(T<=t) two-tail	1.34E-08	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
Dominant, 1.25, 1lb vs. 5 lb

	Variable 1	Variable 2
Mean	2.44525	3.25925
Variance	0.435108	0.370658
Observations	40	40
Pearson Correlation	0.756084	
Hypothesized Mean Difference	0	
df	39	
t Stat	-11.55537	
P(T<=t) one-tail	1.83E-14	
t Critical one-tail	1.684875	
P(T<=t) two-tail	3.66E-14	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
Dominant, 1.25, 1lb vs. 10lb

	Variable 1	Variable 2
Mean	2.44525	3.61575
Variance	0.435108	0.482158
Observations	40	40
Pearson Correlation	0.68709	
Hypothesized Mean Difference	0	
df	39	
t Stat	-13.79804	
P(T<=t) one-tail	6.85E-17	
t Critical one-tail	1.684875	
P(T<=t) two-tail	1.37E-16	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
ND, 1.25, 1lb vs. 5lb

	Variable 1	*Variable 2*
Mean	2.5155	3.53925
Variance	0.319497	0.576202
Observations	40	40
Pearson Correlation	0.485146	
Hypothesized Mean Difference	0	
df	39	
t Stat	-9.351528	
P(T<=t) one-tail	8.25E-12	
t Critical one-tail	1.684875	
P(T<=t) two-tail	1.65E-11	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
Dominant, 1.25, 5lb vs. 10 lb

	Variable 1	*Variable 2*
Mean	3.25925	3.61575
Variance	0.370658	0.482158
Observations	40	40
Pearson Correlation	0.760595	
Hypothesized Mean Difference	0	
df	39	
t Stat	-4.923261	
P(T<=t) one-tail	7.98E-06	
t Critical one-tail	1.684875	
P(T<=t) two-tail	1.6E-05	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
ND, 1.25, 5lb vs 10lb

	Variable 1	*Variable 2*
Mean	3.53925	3.8745
Variance	0.576202	0.690446
Observations	40	40
Pearson Correlation	0.61754	
Hypothesized Mean Difference	0	
df	39	
t Stat	-3.03636	
P(T<=t) one-tail	0.002127	
t Critical one-tail	1.684875	
P(T<=t) two-tail	0.004253	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
Dominant, 2.375, 1lb vs 10lb

	Variable 1	*Variable 2*
Mean	1.9265	3.2925
Variance	0.275018	0.34564
Observations	40	40
Pearson Correlation	0.793477	
Hypothesized Mean Difference	0	
df	39	
t Stat	-23.83519	
P(T<=t) one-tail	3.7E-25	
t Critical one-tail	1.684875	
P(T<=t) two-tail	7.4E-25	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
ND, 1.25, 1lb vs. 10lb

	Variable 1	*Variable 2*
Mean	2.5155	3.8745
Variance	0.319497	0.690446
Observations	40	40
Pearson Correlation	0.761273	
Hypothesized Mean Difference	0	
df	39	
t Stat	-15.8291	
P(T<=t) one-tail	7.15E-19	
t Critical one-tail	1.684875	
P(T<=t) two-tail	1.43E-18	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
Dominant, 2.375, 1lb vs. 5lb

	Variable 1	*Variable 2*
Mean	1.9265	2.9645
Variance	0.275018	0.342102
Observations	40	40
Pearson Correlation	0.836656	
Hypothesized Mean Difference	0	
df	39	
t Stat	-20.37032	
P(T<=t) one-tail	1.08E-22	
t Critical one-tail	1.684875	
P(T<=t) two-tail	2.17E-22	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
ND, 2.375, 1lb vs. 5lb

	Variable 1	*Variable 2*
Mean	2.13925	3.124
Variance	0.221228	0.303066
Observations	40	40
Pearson Correlation	0.700796	
Hypothesized Mean Difference	0	
df	39	
t Stat	-15.50382	
P(T<=t) one-tail	1.44E-18	
t Critical one-tail	1.684875	
P(T<=t) two-tail	2.88E-18	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
ND, 2.375, 1lb. Vs 10lb

	Variable 1	*Variable 2*
Mean	2.13925	3.408
Variance	0.221228	0.491627
Observations	40	40
Pearson Correlation	0.804851	
Hypothesized Mean Difference	0	
df	39	
t Stat	-18.80968	
P(T<=t) one-tail	1.83E-21	
t Critical one-tail	1.684875	
P(T<=t) two-tail	3.67E-21	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
ND, 2.375, 5lb vs. 10lb

	Variable 1	Variable 2
Mean	3.124	3.408
Variance	0.303066	0.491627
Observations	40	40
Pearson Correlation	0.77326	
Hypothesized Mean Difference	0	
df	39	
t Stat	-4.039279	
P(T<=t) one-tail	0.000122	
t Critical one-tail	1.684875	
P(T<=t) two-tail	0.000243	
t Critical two-tail	2.022689	

t-Test: Paired Two Sample for Means
Dominant, 2.375, 5lb vs. 10lb

	Variable 1	Variable 2
Mean	2.9645	3.2925
Variance	0.342102	0.34564
Observations	40	40
Pearson Correlation	0.801276	
Hypothesized Mean Difference	0	
df	39	
t Stat	-5.611185	
P(T<=t) one-tail	8.98E-07	
t Critical one-tail	1.684875	
P(T<=t) two-tail	1.8E-06	
t Critical two-tail	2.022689	