

**DETERMINING THE HUMAN ABILITY TO JUDGE INERTIA  
DURING A DYNAMIC PUSHING TASK**

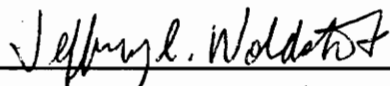
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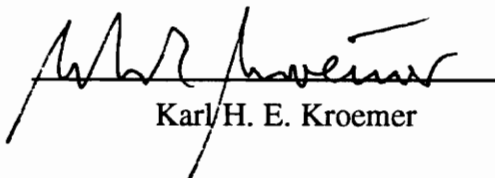
**Ralindo M. Pagulayan**

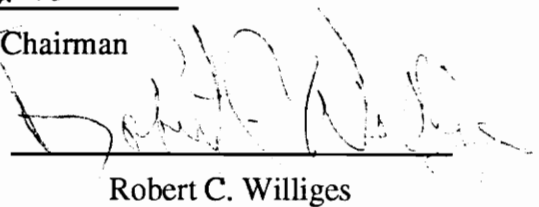
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APPROVED:

  
\_\_\_\_\_  
Jeffrey C. Woldstad, Chairman

  
\_\_\_\_\_  
Karl H. E. Kroemer

  
\_\_\_\_\_  
Robert C. Williges

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# **DETERMINING THE HUMAN ABILITY TO JUDGE INERTIA DURING A DYNAMIC PUSHING TASK**

by

Ralindo M. Pagulayan

Committee Chairman: Jeffrey C. Woldstad

Industrial and Systems Engineering

(ABSTRACT)

The purpose of this research was to study the human ability to perceive inertia and to investigate the relationship between individual sensitivity to mass discrimination and the accuracy of inertia judgment. The study involved two major experiments, a mass discrimination test to provide a measure of kinesthetic sensitivity and a push/aim task to measure inertia perception. The experimental apparatus allowed for the manipulation of an inertial load for both the mass discrimination test and the push/aim task.

The mass discrimination test was based on the method of constant stimuli and involved a standard stimulus of 30 kg and seven comparison stimuli ranging from 24.3 kg to 35.7 kg. It determined Weber fraction values which were used as a measure of sensitivity. The push/aim task simulated a dynamic horizontal pushing task and was restricted to an initial exertion causing the inertial load to travel to a target under its own momentum. Performance was measured by the errors associated with the accuracy of the aimed pushes. These errors were separated into an absolute component representing an overshoot or undershoot, and a relative measure of error representing variability of repeated trials about the absolute error.

Distance to the target (2 or 6 m), amount of load (25, 45, or 90 kg), and apparent size of the load (small or large) were manipulated in the dynamic pushing experiment. Hypothesis testing was used to determine whether performance exhibited a consistent overshooting or undershooting of the target. An ANCOVA was used to measure the effects of distance, amount of load, and apparent size on performance given a covariate of mass discrimination sensitivity. Since the ANCOVA showed no significant effect from the covariate, an ANOVA was used to analyze the effects of the independent variables on both measures of error.

The hypothesis tests revealed that absolute error in the push/aim task was significant by less than zero for the combined data set and at all levels of independent variables, indicating a consistent undershoot of the target. The ANCOVA results

indicated no significant effect from the covariate, mass discrimination. Correlation coefficients ( $R^2$ ) were calculated for the relation between sensitivity to mass discrimination and push/aim task performance with respect to absolute and relative error. These values were 0.004 for the absolute error and 0.008 for the relative error. The ANOVA results revealed that weight, distance, and the weight x distance interaction had significant effects on the absolute measure of error. Increasing the levels of either weight or distance resulted in significant increases in the amount of absolute error. Increasing the distance resulted in significant increases in the amount of relative error. The presence of a distance effect and the absence of a weight effect indicates the importance of rate of force over amount of force in the relative error associated with the push/aim task. Apparent size of the load did not have a significant effect on either absolute or relative error.

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# 1. INTRODUCTION

## 1.1 Rationale

At first glance, the use of material handling assist devices to aid in traditional lift and carry methods would appear to be only beneficial. These devices, which include overhead hoists, articulated arms, and floor-based cart systems, provide the vertical force necessary to lift, carry, or lower a load. They eliminate the static force exertions normally required to counteract the effects of gravity by removing the load's gravitational component. The operator only needs to provide a dynamic exertion large enough to overcome a small amount of static friction and the load's inertia to initiate movement and then provide another exertion to stop movement.

Manual material handling assist devices require operators to control an inertial load. An inertial load is defined as a mass put in motion by forces other than gravity (Greer, 1989). Essentially, inertia is the only significant resistant force because the assist devices remove the gravitational component of the load.

Many workers find the operation of material handling assist devices to be just as fatiguing as manually lifting and carrying the load (Woldstad and Chaffin, 1990). The cause of the fatigue can be traced to the dynamic exertions associated with the pushing and pulling of the devices (dynamic pushing and pulling tasks). An operator would be expected to apply an initial push exertion just large enough to allow the load to travel to its destination. Woldstad, Langolf, and Chaffin (1988) simulated the operation of material handling assist devices and found subjects exerted dynamic forces significantly higher than necessary during the initial push of the load. Some subjects exerted forces greater than accepted standards of safety.

The issue to be addressed in this thesis involves the dynamic exertions utilized to initiate movement of inertial loads. The theory of rapid-aimed movement theory will be used to describe the behavior associated with pushing inertial loads. A rapid-aimed movement is a movement made toward a target in a quick and accurate manner (Meyer, D.E., Abrams, R.A., Kornblum, S., Wright, C.E., and Smith, J.E.K., 1988). The operation of material handling assist devices is a form of a rapid-aimed movement because it essentially involves a rapid aimed push toward a specific destination. Rapid-aimed movement theory predicts decreased accuracy of the initial push when movement velocity requirements are increased. Possible sources of increased velocity requirements include longer distances to the target or greater amounts of load.

Inappropriate dynamic exertions may also be caused by subject misperceptions concerning the appropriate level of force to exert against inertial loads. The size-weight illusion may play a role in the misperception. This illusion occurs when a larger object seems lighter than a smaller object of equal mass (Charpentier, 1891). The size-weight illusion could affect loads which are large compared to their mass. More specifically, it would cause subjects to overestimate the weight of loads which are large compared to their mass and exert an inappropriately large force.

Misperceptions of the inertial load may also be due to a flawed perception of inertia. Several studies have looked at inertia perception and have concluded humans consistently underestimate the amount of inertial mass encountered and have a reduced ability to discriminate between different inertial mass levels (Rees and Copeland, 1960; Crawford and Kama, 1961; Ross and Reschke, 1982; Ross and Brodie, 1984; Ross and Brodie, 1987). The studies, however, have been limited to loads under 7 kg with the majority of focus on loads in the range of 0.05 kg. It remains unclear whether the poorer performance was due to an unfamiliarity with the properties of inertia or to an actual difference in the physiological mechanisms involved with the judgment of inertia.

This thesis investigated subjects' ability to perceive inertia by examining error associated with the dynamic pushing task and changes in this error when the amount of load, the apparent size of the load, and the distance to the target was manipulated. In addition, the effect of subjects' ability to perceive inertia on error was studied by coupling an individual's mass discrimination sensitivity to performance in the pushing task.

The information generated by this thesis should be immediately applicable to improved guidelines concerning the design and use of material handling assist devices. It is also hoped that this information can provide further theoretical insight into the human perception of inertia.

## 1.2 Experimental Approach and Objectives

The main objective of this study was to determine how accurately humans judge inertia by studying the behavior associated with the dynamic pushing task for weights in the range of 25 to 90 kg (50 - 200 lbs.). In addition, the relationship between individual sensitivity to mass discrimination and the ability to accurately judge inertia was also investigated. The experimental set-up simulated inertial loads and the dynamic pushing task by minimizing frictional resistance to horizontal movement and removing the load's gravitational component in a floor-based cart system.

This study involved two major experiments, a mass discrimination test to gauge individual sensitivity and a push/aim task which simulated the dynamic pushing task.

### 1.2.1 Mass Discrimination Test

The mass discrimination test was performed to determine the sensitivity of individual subjects to differences in mass. It is important to note that this test studied inertial mass, not weight. A floor-based cart system was used to generate an inertial mass. Individual subject sensitivity was measured in difference limens (DL's) which were determined based on the method of constant stimuli as described by Gescheider (1985).

### 1.2.2 Push/Aim Task

The push/aim task simulated the dynamic pushing task used to initiate movement in material handling assist devices. Inertia judgment was gauged by measuring how accurately subjects pushed an inertial load to a target. The push was defined as the initial exertion causing the load to travel to the target under its own momentum. Errors associated with the accuracy of the aimed pushes were separated into an absolute component representing a consistent undershoot or overshoot, and a relative component representing variability of the absolute error. In addition, the effects of the weight of the load, the distance to the target, and the apparent size of the load on the error associated with the push were studied.

### 1.2.3 Experimental Hypotheses

The following hypotheses were examined.

- H<sub>1</sub>: Performance of the push/aim task will exhibit significant error and, this error will be either a consistent overshoot of the target or a consistent undershoot of the target.
- H<sub>2</sub>: Varying the weight of the load to be pushed will have a significant effect on the accuracy of the push/aim task with respect to both absolute and relative error.
- H<sub>3</sub>: Varying the distance to the target will have a significant effect on the accuracy of the push/aim task with respect to both absolute and relative error.
- H<sub>4</sub>: Varying the apparent size of the load to be pushed will have a significant effect on the absolute error of the push but will have no significant effect on the relative error.
- H<sub>5</sub>: A significant linear correlation will be found to exist between subject sensitivity to mass discrimination and performance on the push/aim task as measured by absolute and relative error.

It is the assertion of this thesis that a consistent overshoot or undershoot (H<sub>1</sub>) would indicate both the presence and effect of inertia misjudgment. The effects of varying

load weight and target distance ( $H_2$  and  $H_3$ ) would then provide a clearer description of how the inertia perception changes when varying stimulus intensity. A significant effect from varying the load size ( $H_4$ ) would suggest the influence of the size-weight illusion on inertia perception. Finally, the existence of a significant linear correlation between discrimination and push/aim task performance ( $H_5$ ) would infer a possible link between kinesthetic sensitivity and the ability to perceive inertia.

## **2. LITERATURE REVIEW**

### **2.1 Overview**

This chapter summarizes the literature with respect to dynamic pushing tasks, rapid-aimed movements, and the perception of force, weight, and mass (inertia). The dynamic pushing task will be discussed first, with emphasis on the initial accelerative phase. Next, rapid-aimed movement theories will be covered, again emphasizing aspects associated with the initial accelerative phase of the movement. Finally, this chapter will cover issues of perception, specifically, the perception of force, weight, and mass (inertia). Possible causes of misperceptions of force, weight, and mass will be investigated.

### **2.2 Dynamic Push and Pull Tasks**

Dynamic pushing and pulling studies grew out of concern over the safety of material handling assist devices, such as overhead hoists, articulated arms, and floor-based cart systems. These devices eliminate the static requirements associated with lifting, carrying, and lowering the load by mechanically supporting the load against gravity. Dynamic force exertions against an inertial load to initiate and stop movement are the only significant forces required from the operator. The safety issue associated with material handling assist devices is the tradeoff between how fast the operator chooses to move the load and the subsequent biomechanical stress caused by the movement. Simply put, the faster the load is moved, the larger the resistant force created by the load's inertia. The studies by Woldstad et al. (1988) and Woldstad and Chaffin (1990) studied this tradeoff.

### 2.2.1 Woldstad, Langolf, and Chaffin (1988) Study

Woldstad et al. (1988) simulated the operation of material handling assist devices in a laboratory setting. Here, subjects pushed a hoist system in the horizontal plane from a fixed starting position to a target position as quickly as possible. The distance traveled, target size, system friction, and amount of load were all controllable and varied. The minimal system friction level best simulated an inertial load situation. The task itself represented a form of a rapid-aimed movement.

The study suggested that subjects performed the task in two distinct stages. In Woodworth's terms (Woodworth, 1899), these stages can be described as an initial ballistic phase followed by a current-control phase (Woldstad et al., 1988). The initial ballistic phase was believed to be preprogrammed prior to the actual movement and appeared to be based upon the subjects' evaluation of the load to be transported, the friction of the system, and the distance to be traveled. The apparent objective of this stage was to provide an initial acceleration large enough for the load to travel the entire distance to the target. In addition, the force of the initial acceleration seemed to be scaled to insure the final velocity of the load fell within some predefined range when the ballistic phase ended.

The current-control phase was associated with the active deceleration of the load. In this phase, subjects evaluated the success of the initial impulse and then applied a decelerative force accordingly to stop the load at the target.

Woldstad et al. (1988) concluded that the dynamic forces chosen by the subjects were not especially dangerous in the specific conditions of the experiment. However, they stressed that relatively minor changes in the environment (hand position, friction of the

floor surface) increased low back stress to dangerous levels. The pulling task was deemed especially stressful to subjects. They discovered when the load increased, the forces involved in decelerating the load increased at a faster rate than those involved in accelerating the load. This effect may have been due to an increasing over-acceleration associated with increasing the load. Subjects also tended to exhibit large errors in judging the amount of force needed to decelerate the load, especially in novel situations. This situation is especially dangerous to the operator and again, may be a function of an initial over-acceleration.

### 2.2.2 Woldstad and Chaffin (1990) Study

In a later paper, Woldstad and Chaffin (1990) developed more specific insights regarding individual behavioral trends in the earlier Woldstad et al. (1988) study. They identified three general patterns of behavior in the subject population: one characterized by extreme behavior during acceleration, another characterized by extreme behavior during deceleration, and a third in which subjects exhibited relatively moderate accelerations and decelerations. Subjects utilizing either of the extreme patterns of behavior were able to produce lower movement times, but at the expense of much higher force outputs.

Woldstad and Chaffin (1990) concluded the subjects did not perform the task in a biomechanically rational or optimal manner. Contrary to the earlier 1988 study, they found the peak acceleration and deceleration forces exhibited by subjects, in many cases, actually exceeded accepted standards of safe force exertions. The fact that the high level of force exertion was found to be relatively unaffected by variations in the external conditions of the task, coupled with the limited motivation to provide excess effort in the

experiment, implied human operators were not inclined to perform dynamic tasks in a safe manner. The authors suggested behavior associated with dynamic performance might be inherently different than other types of performance since higher levels of risk are tolerated in dynamic tasks.

The studies on the dynamic pushing and pulling tasks indicate humans exhibit potentially dangerous levels of exertion during the operation of mechanically supported loads. Given the opportunity to choose the dynamic forces required to move inertial loads, subjects tend to provide overly high exertions. An especially important aspect of the task is the initial acceleration or dynamic pushing of the load. Not only does a greater acceleration cause a higher velocity and a resulting large exertion, but it also results in an increase in the amount of effort required to decelerate and stop the load. A flawed perception of inertia may be the root cause of the selection of overly high dynamic forces to initiate movement of inertial loads.

The task designed by Woldstad et al. (1988) was a form of a rapid-aimed movement where the initial acceleration of the load represented the initial-impulse phase of the rapid-aimed movement. For this reason, basic theory concerning rapid-aimed movements, particularly the initial-impulse phase, will be reviewed.

### 2.3 Rapid-Aimed Movements

A rapid-aimed movement is an aimed movement made within some time constraint. The basic tenet of rapid-aimed movement theory is the speed-accuracy tradeoff: as movement speed increases, the accuracy of the movement decreases; conversely, as spatial accuracy increases, the movement speed decreases.

According to Woodworth (1899), an aimed movement begins with an "initial-impulse" phase followed by a "current-control" phase. The initial-impulse phase is preprogrammed and proceeds ballistically for its duration. The current-control phase occurs after completion of the initial-impulse phase and corrects any deviations from the intended path as the movement continues to its target. As mentioned earlier, the initial acceleration involved in the dynamic pushing task is analogous to the initial-impulse phase while the deceleration phase corresponds to the current-control phase. If errors associated with the initial-impulse phase relate to inappropriate initial accelerations in the dynamic pushing task, then rapid-aimed movement theory gives possible explanations of how the error in dynamic pushing behaves under certain conditions such as changing movement velocity or distance to target.

Research concerning the cause of the speed-accuracy tradeoff in aimed movements can be separated into two opposing theoretical camps. One group holds that variability in the current-control phase of the movement causes the loss of accuracy in the speed-accuracy tradeoff. The opposing camp believes neuromotor noise is the primary source of variability which directly affects the accuracy of the initial-impulse phase (Meyer, Smith, Kornblum, Abrams, and Wright, 1990).

### 2.3.1 Earlier Studies

Searle and Taylor (1948) and Brown and Slater-Hammel (1949) performed early studies appearing to confirm the initial-impulse phase as the primary source of variability in rapid-aimed movements (Meyer, et al., 1990). Searle and Taylor (1948) found variable error to increase with velocity during the initial-impulse phase while Brown and Slater-Hammel (1949) discovered the duration of the initial-impulse phase increased as spatial

accuracy demands increased. Fitts (1954), in a direct extension of Brown and Slater-Hammel's work, developed a mathematical relationship describing the behavior of rapid-aimed movements (Meyer, et al., 1990). The equation he developed:

$$T = A + B \log_2(2D/W) \quad (2.1),$$

where T is the duration of the movement; D, the distance to the target; W, the width of the target; and A and B, constants, is known as Fitts' law. Fitts also believed noise in the motor system decreased the accuracy of the initial-impulse phase as movement speed increased causing the speed-accuracy tradeoff of rapid-aimed movements.

### 2.3.2 Impulse Variability Model

Schmidt, Zelaznik, Hawkins, Frank, and Quinn (1979) introduced the impulse variability model to explain the behavior associated with rapid-aimed movements. It was based upon the following assumptions:

1. Initial acceleration is generated by a pulse of force with selected amplitude (f), which controls the level of the force, and time (t), which controls the duration of the force.
2. Following the acceleration impulse, the limb continues moving in free fall (like a projectile shot from a gun) until it strikes somewhere near its target.
3. The parameters (f) and (t) are programmed to have target values (F) and (T), but may fluctuate randomly about (F) and (T) due to noise in the motor system.
4. The variability in (f) and (t) due to motor system noise follows Weber's law.

$$S_f = k_f F \quad (2.2)$$

$$S_t = k_t T \quad (2.3)$$

(In other words, the standard deviation increases proportionately with the desired magnitude of the parameters. The resulting effect is movements traveling long distances at high velocities are more variable than short, low velocity movements.)

Meyer, Smith, and Wright (1982) questioned the validity of this model. They felt the model should have included effects of the current-control phase on aimed movements. Also, they found the development of the model to be flawed. A misapplication of physical laws, an oversimplification of movement dynamics, and a violation of probability theory are described in detail by Meyer, Smith, and Wright (1982).

### 2.3.3 Symmetric Impulse Variability Model

In response to the inaccuracies of the impulse variability model, Meyer, et al. (1982) developed the symmetric impulse variability model. The most significant difference between this model and the impulse variability model is the family of curves generated by the newer model describing the force-time relationship. The basic assumptions of the newer model, however, mirror those of the impulse variability model. Specifically, the subject produces an aimed movement by generating a force pulse whose magnitude and duration depend on both a force parameter ( $f$ ) and a time parameter ( $t$ ). And, both parameters ( $f$ ) and ( $t$ ) are random variables whose standard deviations increase proportionately with the means ( $F$ ) and ( $T$ ).

#### 2.3.4 Force Variability

The aimed dynamic pushing task involves the initial impulse phase of rapid-aimed movements. The Schmidt, et al. (1979) impulse variability model and the Meyer, et al. (1982) symmetric impulse variability model predict that the variability of force in the initial impulse phase is proportional to the amount of force exerted and to the duration of the exertion (see equations 2.2 and 2.3). With respect to the dynamic pushing task, exertions involving higher velocities, heavier loads, or longer durations would be more variable than exertions involving lower velocities, lighter loads, or shorter durations.

Research by Carlton and Newell (1988) and Newell and Carlton (1985, 1988) specifically studied the behavior of force variability. They felt the rate of force exertion, a parameter not considered in earlier models explaining the relationship between force and force variability, played a significant role in the variability of force exertion. In fact, their work implied that force-time properties of the initial impulse, rather than peak force, determined the force variability (Newell and Carlton, 1988). In the dynamic pushing task, this implies that exertions which involve faster rates of force production (such as for the generation of higher velocities), would involve greater amounts of variability.

#### 2.3.5 Integration with Mass-Spring Model

To integrate force description models with biomechanical and neurophysiological explanations of motor behavior, Meyer, et al. (1982) described the symmetric impulse variability model in context with the mass-spring model.

In the mass-spring model, agonist and antagonist muscles are viewed as springs whose opposing tensions control the position of the limbs. Movement of a limb occurs when the stiffnesses of the muscles are adjusted forcing the muscles to change their resting lengths to achieve a new point of equilibrium where the new tensions levels balance.

Meyer, et al. (1982) defined two specific stages in movement occurring in the mass-spring model. The first is a phasic component, which is comparable to the initial-impulse phase of the rapid-aimed movement. It acts to adjust the stiffness of the muscles quickly at the start of a movement, jerking the limb toward its target. The second stage is known as the tonic component and corresponds to the current-control phase of the rapid-aimed movement. It sets the final stiffness of the muscles insuring the limb reaches its exact target location.

Previous studies of electromyogram (EMG) pulses during rapid-aimed movements support this description of the mass-spring model (Meyer, et al., 1982). These studies identified three distinct EMG pulses during rapid-aimed movements. The first pulse occurs just before movement of the limb, stimulating the agonists and continues until peak acceleration. The second pulse occurs just after the first burst, stimulating the antagonist and continues until peak deceleration. The third and final pulse occurs just before the movement reaches its peak deceleration and restimulates the agonist. The first two pulses represent the phasic component of a movement and the third represents the tonic component of the movement.

### 2.3.6 Stochastic Optimized Submovement Models

As mentioned earlier, conflicting evidence points to either the initial-impulse phase or the current-control phase as the primary cause of the tradeoff relationship between

speed and accuracy in rapid-aimed movements. Generally, models based on the idea of motor system noise (initial-impulse phase as the main source of variability) are derived from experimental studies that exhibit a linear speed-accuracy tradeoff. These studies most often utilize the time-matching task. In this experimental protocol, the subject matches the movements to a set cadence determined by the experimenter. Time and distance are fixed, while accuracy is measured. Conversely, a logarithmic speed-accuracy relationship holds when the time-minimization task is used. This protocol requires aimed movements to be made as quickly as possible to a fixed target. In this task, distance and accuracy are fixed and time is measured. Models based on the time minimization task generally point to the current-control phase as the main source of variability in a rapid-aimed movement.

The stochastic optimized submovement models attempted to consolidate the differing results and conclusions from prior rapid aimed movement research into one set of shared principles explaining both of the opposing schools of thought (Meyer, et al., 1990).

The optimized multiple submovement model proposed by Meyer, et al. (1990) is an example of a stochastic optimized submovement model. The basic idea of this model is as follows: A rapid-aimed movement is made up of a primary submovement followed by zero, one, two, or more secondary submovements. If the primary submovement hits the target, the entire aimed movement is completed; otherwise, secondary submovements occur until the target is finally hit.

The model assumes both the primary and secondary submovements are subject to naturally existing noise in the motor system and behave according to Weber's law. Specifically, the standard deviation of the accuracy of the submovements increases linearly as the velocity of the submovement increases. The durations and number of submovements are chosen to minimize the overall duration of the aimed movement. A

longer primary submovement provides greater spatial accuracy but at the expense of a higher overall duration. On the other hand, a shorter primary submovement is quicker, but less accurate, which subsequently requires more secondary submovements.

Figure 2.1 illustrates the speed-accuracy tradeoff relationships predicted by this model as a function of the overall number of submovements ( $n$ ) involved in the movement.  $D/W$  is the ratio of distance to the target ( $D$ ) to the width of the target ( $W$ ).

Notice a linear tradeoff holds when  $n = 1$ . This prediction seems to represent underlying motor processes and reflects behavior when time pressure is at a minimum. When  $n = \infty$ , the condition where time pressure is at a maximum, the curve closely approximates the Fitts' law relationship. It seems to represent the ideal solution for the time minimization task where movements must be completed as quickly as possible.

### 2.3.7 Summary

Rapid-aimed movement theory suggests increasing the velocity of the initial-impulse movement would increase the variability of the accuracy of the aimed movement. This idea can be extended to the situation of the aimed dynamic pushing task. It follows then, increasing the required velocity of the push by increasing the distance to the target or the load to be pushed would increase the chance or amount of error in the push.

## 2.4 Perception of Force

Another important aspect of the dynamic pushing task involves the perception of the load to be pushed. Misjudgments associated with the initial acceleration in dynamic

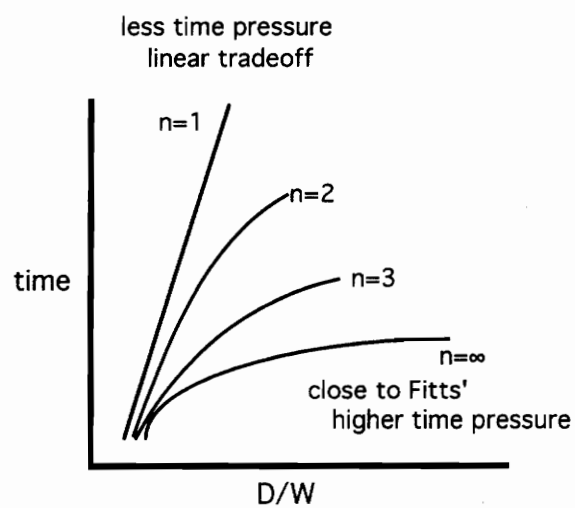


Figure 2.1. Speed-Accuracy Relationships as a Function of  $n$   
from Meyer, et. al. 1992

pushing may be primarily due to errors in the perception of the force exerted on the load, the judgment of the load's weight, or the judgment of the load's mass.

Current research divides into two theories of how the body perceives force (Jones, 1986). One supports a centrally mediated perception of force. This theory states that when a motor signal is sent to the motoneuron pool, a corresponding neural signal (a corollary discharge) is also sent to the sensory centers representing the magnitude of the efferent motor command (McCloskey, 1981). The perception of force is therefore based upon the magnitude of the motor signal sent to the muscle (via the corollary discharge).

The other school of thought argues for a peripherally mediated perception of force. Here, the force of contraction is sensed through afferent discharges from peripheral sensory receptors in the muscle (Jones, 1986). The role of sensing developed muscle tension lies primarily with the Golgi tendon organs (Åstrand and Rodahl, 1986).

Current theory purports two co-existing, yet independent, force perception systems. A centrally mediated system, which is based on corollary discharges of efferent commands, represents the primary system for the perception of force. A peripherally mediated system then functions to enhance or modify the perception of force (Jones, 1986).

Decoupling experiments support the view of two independent systems. These are experiments where the normal relationship between the efferent motor command and the afferent discharges arising from receptors in the muscles have been decoupled. Generally, these studies indicate that judgments of force are based primarily on the magnitude of the centrally generated motor command. At this point, the relationship between the motor command and perception of muscle force is not totally understood. Changes in the force perception correspond to changes in the motor command, but are not directly proportional. Muscular receptors (mainly the Golgi tendon organs), on the other hand, appear to play a

supplementary role in force perception. These sensory signals coincide with the movement and modify the perception of force (Jones, 1986).

The perception of force during fatigue also supports the likelihood of a centrally mediated force perception (Jones, 1986). A common experience is the feeling of increased effort to produce a consistent force as the muscle becomes increasingly fatigued. The sense of increased effort corresponds to an increased central efferent command to the fatigued muscle to maintain the constant force. The level of force exerted remains the same, yet the perception of force increases with the increased efferent command indicating the dependence of force perception on the centrally mediated system.

#### 2.4.1 Psychophysical Studies

Psychophysical studies define a relationship between the physical magnitude of an event and the corresponding mental experience of that event (Gescheider, 1985). With respect to the perceived magnitude of force, it has been found that the judgment of perceived force is a power function of the stimulus intensity (Jones, 1986). Pooling the results of psychophysical studies involving different muscle groups and a range of scaling methods yields a relationship in which the magnitude of apparent force grows as the 1.7 power of the actual force exerted. The exponent greater than unity indicates a positively accelerating power function.

Actual exponent values, however, vary across individual studies and range from 0.8 to 2.0 (Jones, 1986). The main source of this variability is attributed to the use of different experimental techniques in the different studies. Banister (1979) utilized a magnitude estimation technique to determine the relationship between apparent force and actual force exerted in an isometric contraction. Subjects were first asked to estimate their

maximum voluntary contraction (MVC) in an isometric pulling task. Subsequent exertions were then estimated as a ratio of their MVC. These trials were performed separately using the quadriceps and then the adductor pollicis. In both cases, the perceived effort grew exponentially with the actual force exerted, but in a negatively accelerating manner.

Cooper, Grimby, Jones, and Edwards (1979) also studied the perception-force relationship using the quadriceps and the adductor pollicis muscles. In one part of the study, they too, utilized a magnitude estimation technique. Subjects matched a specific force level and then defined it as a percentage of their MVC. The second part of the study utilized a magnitude production technique. In this situation, subjects were asked to produce an effort that represented a specific percentage of their MVC. The perception-force power curve derived from the magnitude estimation scenario yielded an exponent value of 0.7, a negatively accelerating power curve. The magnitude production technique, however, produced an exponent of 1.0, indicating a linear relationship between perception of force and actual force exerted.

Another example is the study by Stevens and Mack (1959). It clearly demonstrates the effect of varying the experimental technique on the resulting power function describing the perception-force relationship. In this study, all muscular exertions were performed on a handgrip dynamometer, but four separate experimental techniques were used to determine the perception-force relationship: ratio production, magnitude production, magnitude estimation, and category production.

The ratio production technique required subjects to exert two successive forces in a specific ratio with one another (e.g., 2 to 1, the second force half as much as the first). The magnitude production technique involved the subjects producing a force to match a given number value. Specifically, subjects made an arbitrary moderate exertion which was assigned some number value, for example, 10. The experimenter then requested an

exertion corresponding to another number, say 25, meaning an exertion two and a half times larger than the initial exertion. The magnitude estimation technique was also based on an arbitrary number assigned to an initial moderate exertion. The subjects were then asked to produce a specific level of exertion (the actual value being unknown to the subjects). When the specified level was attained, the subject was asked to assign a number value to the exertion based upon the initial exertion. Finally, in the category production technique, subjects exerted a "light" force which was defined as category 1, then a "heavy" force defined as category 7. Subjects were told to imagine seven equal categories to represent the possible exertions between categories 1 and 7. The perception trials then involved subjects making an exertion corresponding to a specific category.

The ratio production, magnitude production, and magnitude estimation techniques produced a positively accelerating power function for the perception-force curve. Both the ratio production and magnitude production techniques yielded power functions with a 2.0 exponent value, while the magnitude estimation technique produced a 1.7 exponent value. The category production technique, on the other hand, produced a logarithmic function. Contrary to the other three techniques, which exhibited positive accelerations in this study, the category production function increased with a negative acceleration to a specific asymptotic level.

#### 2.4.2 Summary

In conclusion, the literature supports a centrally mediated perception of force which can be modified by peripheral information from intramuscular sensors. Psychophysical studies of force perception indicate the magnitude of perceived force grows as a power function of the actual force. However, the shape of the power function

depends on the experimental technique used to gather the perception of force data. Exponent values have been found to range from 0.8 to 2.0.

## 2.5 Perception of Weight

The perception of weight is more likely to play a greater role than force perception in the dynamic pushing task. Misjudgments of the weight of the loads to be pushed may cause inappropriate applications of force. The perception of weight is actually a specific form of force perception; the sensory systems involved are essentially the same. However, weight perception, unlike force perception, is highly sensitive to peripheral sensory information. The perception of force depends primarily on corollaries of the efferent motor command and is affected mostly in a supplementary manner by peripheral sensory information. The perceived heaviness of an object, on the other hand, can be drastically affected by the object's physical properties, the manner in which it is lifted, or the order in which different objects are lifted (Jones, 1986).

### 2.5.1 Discrimination of Weight

The ability to discriminate between differences in weight is an important aspect of weight perception. It was once considered to be one of the primary components of the muscular sense and, therefore, was studied extensively (Jones, 1986).

Two general rules govern weight discrimination performance (Ross and Reschke, 1982). First, discrimination improves with an increase in the sources of sensory information or with an increase in the sensitivity of these sources. Along these lines,

experimental studies have shown that weight discrimination is most sensitive under conditions of voluntary muscle contractions (Jones, 1986) and is less sensitive in passive lifting situations, where the hand involved in lifting is physically supported, or during reflex-induced lifting (Brodie and Ross, 1984).

The improved sensitivity associated with active lifting versus passive or reflex-induced lifting suggests active lifting utilizes additional sources of sensory information. Jones (1986) hypothesized muscular receptors sensitive to dynamic activity aid in the discrimination of weight. These dynamic receptors operate during an active movement and provide additional sensory information. The addition of the afferent discharges from dynamic sensitive receptors to the efferent command signals normally associated with an active movement improves weight discrimination (Ross and Reschke, 1982).

The second rule states when subjects are well adapted to the range of weights being compared, discrimination is optimal. But, if the preadapted range of weights is much heavier or much lighter than the test object, discrimination deteriorates (Jones, 1986). Optimal discrimination also occurs when subjects are adapted to their own current body weight. For example, weighting the arm with a weighted cuff decreases sensitivity, but as the subject adapts to the new arm weight, sensitivity returns (Ross and Gregory, 1970).

### 2.5.2 Discrimination as a Function of Weight Intensity

Generally, discrimination sensitivity decreases with lower weight intensities until it reaches a relatively constant value around 150 g (Jones, 1986). Carlson, Drury, and Webber (1977) studied weights common in materials handling (10 - 20 kg) and found that beyond 3 kg sensitivity was optimal. However, Karwowski, Shumate, Pongpatana, and

Yates (1989) looked at discrimination during the lifting of boxes weighing 4 - 31.6 kg (8 - 64 lbs.) and found for weights over 14.8 kg (30 lbs.), difficulty in load differentiation increased as measured by the number of errors made in the experimental task.

Weber fractions offer a measure of discrimination sensitivity generalizeable to other discrimination tasks (lower fractions correspond to higher sensitivity). For weights between a few grams to three kilograms, a Weber fraction of between 0.06 and 0.10 is usually reported. As the stimulus increases to 3.0 kg (6.6 lbs.), the Weber fraction decreases but remains within the 0.06 to 0.10 range (Carlson, et al., 1977). Studies involving higher weight stimuli appear to be relatively scarce. Carlson, et al. (1977) studied weights of between 10 - 20 kg and found a Weber fraction of about 0.04 for the entire range of weights.

### 2.5.3 Absolute Estimates of Heaviness

The absolute judgment of apparent weight is another important aspect of weight perception. Humans exhibit a tendency toward what is known as mass constancy. It refers to the fact that an object will feel the same despite variations in the lifting of the object. For example, the weight of an object will appear to be the same whether it is lifted quickly or slowly or if it is lifted in the hand or attached to the wrist. Mass constancy occurs despite using different parts of the body, varying arm weight, varying of the distance of an object along a lever (Ross and Reschke, 1982) or varying the location of the weight along the arm (Nanthavanij and Deivanayagam, 1985).

Mass constancy generally prevails when the weight of the object remains the same and the variation lies in the manner of lifting (Ross and Reschke, 1982). Conversely, changes in an object's effective weight, for example, underwater (Ross, Rejman, and

Lennie, 1972), in a human centrifuge, or when the object can not be seen and weight must be judged through sense of effort or other non-visual cues (Ross and Reschke, 1982), reduces the effect of mass constancy.

With respect to direct estimation of the absolute value of weights, as weight becomes larger, the ability to accurately estimate weight deteriorates. In the Karwowski, et al. (1989) study, boxes of between 4 and 31.6 kg (6 - 64 lbs.) were lifted from the floor and lowered to a table. Overall, subjects tended to underestimate the true weight of the boxes. In addition, past 13.6 kg (30 lbs.), errors in estimating the load increased significantly. A linguistic scale (very light, light, less than medium, medium, more than medium, heavy, and very heavy) also yielded better results than simple numerical estimation. The study by Nanthavanij and Deivanayagam (1985) looked at the absolute estimation of weight in the 1.4 - 5.4 kg range (3 -12 lbs.) utilizing weight holding by the hand. They also found performance deteriorated as weight increased. However, contrary to the finding of Karwowski, et al. (1989), they found subjects tended to overestimate the weight of the object, as the weights became heavier.

#### 2.5.4 Size-Weight Illusion

As mentioned earlier, the physical properties of the object being judged greatly affect the perception of weight. The physical properties create an expectation of the weight of the object and if the expectation differs from the actual weight, an illusion occurs (Ross, 1969).

A significant weight illusion is the size-weight illusion. Given two objects of equal mass but different size, the larger object will be perceived lighter. Charpentier's

(1891) study was the first to identify this illusion when he found the larger of two spheres of equal mass was perceived lighter than the smaller sphere (Jones, 1986).

The size-weight illusion seems to be based on visual cues regarding the size of the object with respect to its weight. Volume and density are two major factors involved in this effect.

Researchers have extensively studied the effects of volume on the perceived heaviness of an object. If equal volumes are utilized for comparison, perceived heaviness increases as a power function of weight. However, at different constant volumes, a family of power curves is needed to describe the relationship with the exponent increasing as the volume increases (Jones, 1988). If the volume itself is varied during the estimates of heaviness, heaviness decreases as a logarithmic function of the volume (Jones, 1986). It is generally accepted that the magnitude of the size-weight illusion increases as the relative volume of the object increases. However, as the weight increases, the potency of the illusion decreases.

The effects of density have also been studied. If only volume is varied (weight and material constant), perceived weight is a linear function of the logarithm of density (Ross, 1969). In the same vein, Ross and DiLollo (1970) found an equivalent weight difference had a much greater effect on the perceived difference in heaviness for a pair of low density stimuli as compared to a pair of higher density stimuli. Finally, if the density itself is kept constant, a linear relationship between actual and perceived weight seems to apply (Ross, 1969).

The size-weight illusion generally occurs only in smaller weights (Bingham, Schmidt, and Rosenblum, 1989). Ross and DiLollo (1970) found a strong effect for weights between 0.1 kg and 0.3 kg, but a very weak one at weights over 0.7 kg.

### 2.5.5 Causes of the Size-Weight Illusion

There are currently two explanations as to the cause of the size-weight illusion, expectancy theory and intersensory information integration.

#### 2.5.5.1 Expectancy Theory

Expectancy theory can be described as follows. A person expects, from experience, the larger of two objects to be heavier. When the object is lifted according to this expectation, a greater force than otherwise needed is employed. The unexpectedly fast rate of lift causes the perception of the larger object weighing less (Jones, 1986).

Movement profile data and EMG data provide evidence for this theory. Movement profiles of subjects involved in lifting objects of equal weights but different volumes show a greater lift acceleration when the larger of the two objects is judged lighter. EMG studies of this type of task also support this view. They show a greater increase in muscle tension just before lifting for larger objects compared to smaller ones. Moreover, this phenomenon consistently occurs on trials where the size-weight illusion occurs.

#### 2.5.5.2 Intersensory Information Integration

Ross (1969) hypothesized a discrepancy between the expected sensory input based upon the efferent command and the actual sensory input received from the periphery caused the size-weight illusion. Jones (1986) furthered this theory by implicating corollary discharges. In normal conditions, the peripheral afferent discharges and central

efferent signals are appropriately matched for the weight of an object. Assuming muscular afferent discharges affect the scaling of the corollary discharges associated with the efferent motor command, Jones (1986) proposed the underestimation of weight was caused by an inappropriate adjustment of the corollary discharges with respect to the afferent discharges.

#### 2.5.6 Other Illusions

The color of an object as well as its composition have been shown in some instances to have a slight effect on the perception of weight. In those studies showing a significant effect, darker objects are perceived to be lighter than brighter objects, and metal containers are perceived to be lighter than wooden containers (Ross, 1969)

#### 2.5.7 Relationship between Discrimination and Absolute Estimates of Heaviness

The relationship between weight discrimination and the absolute judgment of weight is unclear. Separate neural mechanisms or pathways may be utilized by the two abilities (Ross and Reschke, 1982). It is accepted that optimal discrimination occurs at a non-illusory size-weight ratio (the ratio of size and weight where the size-weight illusion no longer occurs). It is unclear, however, why differential sensitivity is affected by misjudgments in the apparent weight of an object. Ross and Gregory (1970) offered the analogy of a Wheatstone bridge measuring system. They assume the size-weight illusion is based on a discrepancy between efferent command (anticipation) and the afferent feedback (visual information). Anticipation of the weight sets one of the ratio arms of the

bridge while the neighboring arm is set by the directly sensed weight from the limb.

When the anticipated and actual information are equivalent, the system balances without any special adjustment. However, if visual information is misleading, then the two ratio arms would be set differently from each other and the sensitivity of the bridge to differences in the signal will be reduced.

## 2.6 Perception of Mass

Whereas weight perception involves the combination of an objects inertial mass and the gravitational pull of the Earth upon the object, the judgment of mass occurs when the gravitational cues have been removed and only inertial cues are present. During mass perception, heaviness can only be perceived by accelerating an object and utilizing its inertial cues (Ross and Brodie, 1987). The issue of mass perception is, therefore, an issue of inertia perception.

Inertia itself refers to the property of an object that causes the object to resist changes in its condition or oppose applied forces. It is directly proportional to mass; more force is needed to overcome the inertia of an object of high mass than an object of smaller mass. When an object is put in motion by forces other than gravity, the object is referred to as inertial mass (Greer, 1989).

### 2.6.1 Mass Perception Studies

Mass perception occurs when the effects of gravity are nullified. This condition can be facilitated if an object is mechanically supported against the force of gravity and is

moved manually in the horizontal plane (Ross and Brodie, 1987). Examples include moving objects over a frictionless surface (e.g., air bearing table), sliding hockey pucks on ice, pushing objects supported by a pendulum (Ross and Reschke, 1982), or pushing objects suspended by strings (Ross and Brodie, 1987). Mass perception also occurs during weightless conditions in space or during the 0-G phase of parabolic flight.

#### 2.6.1.1 Air Bearing Table Studies

Rees and Copeland (1960) created a mass perception situation by pushing floating cylinders over an air bearing table. They investigated mass discrimination in the range of 1000 to 7000 g and found a Weber fraction for mass over twice as high as the Weber fraction for lifted weights.

Crawford and Kama (1961) used the same type of experimental setup (floating cylinders pushed over an air bearing table) in another study of mass perception. They studied performance in estimating the absolute value of masses in the range of 900 to 4600 g and found mass estimates were about half as large as the estimates of weight for the same objects.

#### 2.6.1.2 Weightlessness in Parabolic Flight

The weightless condition represents the truest mass perception situation since the effects of gravity are completely eliminated. In addition, tasks are not limited to horizontal movements since any movement of the object will involve only inertial movement.

The first studies involving weightlessness used the 0-G phases in parabolic flight. Ross and Reschke (1982) studied both magnitude estimation and mass discrimination in the 100 - 400 g range. With respect to magnitude estimation, estimates during 0-G were less than those under 1-G by a factor of about two. Furthermore, underestimation increased as the weight increased under the 0-G condition. The mass discrimination study looked at weights between 50 and 64 g and found difference limen (DL) values to be twice as high under 0-G than in 1-G.

#### 2.6.1.3 Prolonged Weightlessness

One of the problems with parabolic flight involved the short duration (only up to 25 seconds) of weightlessness offered by the parabolic flight method. The Spacelab I mission gave the opportunity to study mass perception under an extended period of time (up to 10 days). Ross and Brodie (1984) performed mass discrimination tests on weights between 50 and 64 g on the Spacelab I mission and found discrimination performance to be 1.84 times poorer under the 0-G condition.

During the subsequent D1 Spacelab mission, Ross, Schwartz, and Emmerson (1986, 1987) again looked at mass discrimination, but specifically studied the method of shaking used to judge mass. They again utilized weights of 50 - 64 g and found under 0-G, the short shaking method (short and rapid shakes) gave better performance than the long shaking method (long and slower shakes) although, both conditions still yielded worse performance under 0-G than in 1-G. The ratio of DL's in 0-G to 1-G was 1.87 for the long shake method and 1.17 for the short shake method.

#### 2.6.1.4 Suspended Cylinders

Ross and Brodie (1987) utilized cylinders of 50, 200, and 400 g suspended on strings to investigate discrimination performance in the mass perception situation. They also studied the method of judgment, specifically, the use of a firm grip versus a loose grip. Discrimination was best under weight judgment for all intensities, followed by the mass judgment/firm grip condition, and then the mass judgment/loose grip condition; except at the lowest intensity (50 g) where the mass-loose condition was better than the mass-firm condition. The Weber fraction for the mass-loose condition was about 0.12 for all intensities. For the mass-firm condition, it ranged from 0.14 at 50 g to 0.11 at 400 g.

#### 2.6.1.5 Summary

The results from previous studies concerning mass (inertia) perception can be summarized as follows. People judge inertial mass lighter than weight, generally by a factor of about two. Mass discrimination performance is poorer than weight discrimination. Most studies find mass discrimination, as measured by DL's or Weber fractions, to be worse by a factor of between 1.8 and 2.3 as compared to weight discrimination.

## 2.6.2 Explanations of Differences in Mass Performance

### 2.6.2.1 Why Mass is Perceived Lighter

In normal active lifting, people judge the heaviness of objects with both weight and inertial cues. Because people normally move objects at much lower accelerations than gravity ( $9.81 \text{ m/s}^2$ ), weight cues predominate. In the mass perception situation, objects will seem lighter since the weight cues are removed and only the inertial cues remain (Ross and Reschke, 1982)

A different argument suggests less force is used to accelerate a weightless object than to lift the same object against the force of gravity. In theory, this would cause the weightless object to appear lighter (Crawford and Kama, 1961). However, Ross and Brodie (1987) disputed the existence of a direct relationship between the applied force and the resulting sense of heaviness. Instead, they proposed a loss of the reactive force contributed by weight caused the difference between perceptions of mass and weight.

Ross et al. (1987) suggested sensory system errors affect the perception of mass. They offered the following scenario. On Earth, two systems are used to judge weight, a static pressure sensing system sensitive to weight and an active muscular system sensitive to both weight and mass. But under zero-G, only the active system operates and only mass can be sensed. The active system functions by monitoring and processing efferent command signals and the associated afferent information. Zero-G conditions could possibly cause imperfect monitoring of the command signals, incorrect scaling of afferent information from muscular sensors, or incorrect expectations of the efferent/afferent relationship resulting in misperceptions

### 2.6.2.2 Why Mass Discrimination is Poorer

An early explanation of why mass discrimination is poorer than weight discrimination was based on the fact that inertial mass feels lighter than weight (Rees and Copeland, 1960). The theory hypothesized mass discrimination was simply a case of weight discrimination at a lower stimulus. Knowing the Weber fraction increases with decreasing weight intensity, it would follow that mass discrimination would yield a higher Weber fraction, i.e., lesser sensitivity. Ross and Brodie (1987), however, discounted this idea by showing mass discrimination was worse than weight discrimination at both low masses and higher masses (up to 400 g).

Rees and Copeland (1960) and Crawford and Kama (1961) proposed a "suprathreshold" theory to explain the mass versus weight discrepancy. They suggested people judge weight by applying an increasing force until the object is lifted and then evaluate the "threshold" force needed to lift it. However, when judging inertial mass, no threshold force is needed to move the object (since the object accelerates in response to any applied force), so a "suprathreshold" procedure is utilized. Here, subjects apply a constant suprathreshold force and note the difference in achieved acceleration. The suprathreshold procedure was believed to be less reliable than the threshold procedure resulting in poorer discrimination. This explanation, however, is unlikely since the lifting of weights or moving of inertial masses in heaviness perception tasks are more likely preprogrammed movements (Ross and Brodie, 1987).

A loss of pressure information may cause the poorer discrimination of inertial mass. Downward pressure from gravity and a continuity of pressure information are both lost during the manipulation of inertial mass. Pressure exists only during acceleration or deceleration and stops when the hand stops or moves at a constant velocity. Pressure information related to inertial mass is intermittent, whereas for weight, the information is

continuous. The improved performance associated with increasing the acceleration or rapidity of shaking objects in mass perception (Ross et al., 1986, 1987; Crawford and Kama, 1961) may be related to the pressure information. The higher rate of shaking stimulates pressure receptors more vigorously and more frequently yielding more pressure information per unit of time (Ross, et al., 1987). Higher accelerations also provide more intense pressure stimulation which may raise the stimulus intensity of low masses to a level where the Weber fraction decreases (Ross and Brodie, 1987; Ross, et al., 1986, 1987).

Another possible explanation of the difference in mass and weight discrimination is based on the movements generally used in the two procedures. Upward movements, such as in lifting, produce finer discrimination than the sideways movements generally used in mass perception for weights of 50 g (Ross and Brodie, 1987). Upward movements utilize the entire arm and shoulder, while sideways movements use mainly the wrist and the forearm. Using the shoulder as a fulcrum yields better performance in the discrimination of weights between 20 and 1600 g compared to using the wrist as a fulcrum (Ross and Brodie, 1987).

### 2.6.3 No Difference Between Mass and Weight Perception

The previous mass perception studies suggest perception of inertial mass is qualitatively different from weight perception. In other words, the two perceptual abilities may utilize different mechanisms. Greer (1989) disagreed and argued the difference in perceptions is due to an actual difference in the sum of external forces acting upon the object.

Greer's experiment simulated three conditions: 1) a weight perception task where subjects moved an object up and down in the vertical plane; 2) a modified mass perception task where subjects moved an object back and forth in the horizontal plane, but against an external horizontal force equal to gravity; and 3) a true mass perception task where subjects moved an object back and forth in the horizontal plane with no opposing horizontal forces.

Greer determined Weber fractions for each condition and found they were the same for the weight perception task and the mass perception task modified to incur opposing forces equivalent to gravity. The true mass perception condition yielded the highest Weber fraction. The results indicated sensations of heaviness were simply a function of the sum of the external forces operating on the object, regardless of whether the forces were inertial or gravitational (Greer, 1989).

The study, however, focused only on discrimination and did not address absolute estimates of heaviness. Greer admits research should address why an object feels lighter when the magnitude of external forces acting on an object is reduced, and this study does not address this question.

Another situation not addressed by the Greer study involves the discrimination of the moment of inertia. The moment of inertia refers to an object's inertial resistance to rotational acceleration. While it is not equivalent to the inertia in the mass perception tasks discussed (translational acceleration), it is similar. Weber fractions for the moment of inertia are about 10 times that of lifted weights (Kreifeldt and Chuang, 1979). This difference suggests the sensing of inertia is indeed qualitatively different than the sensing of weight.

## 2.7 Summary of Literature

Previous studies of dynamic pushing indicate the existence of a great deal of misjudgment during the initial acceleration of the object. The error seems to affect the correct amount of force required to push an inertial mass to its destination. One possible explanation of this error may be related to the initial-impulse phase of a rapid-aimed movement. The pushing task in question is a form of the rapid-aimed movement and would be subject to the known behaviors associated with rapid-aimed movements. According to rapid-aimed movement theory, increasing the load or the distance to the target should increase error.

Error could also be related to the perception of the force exerted when the load is pushed or the perception of the weight of the load to be pushed. Misjudgments in either of these perceptions would result in an inappropriate application of force. The size-weight illusion is an example of a common misjudgment associated with the heaviness of an object.

The final perceptual ability discussed is mass perception. This concept is probably the best explanation of the misjudgments that occur during the dynamic pushing task. The perception of mass, by definition, is a perception of inertia. The literature with respect to mass discrimination is clear in one regard. Performance during mass estimation and mass discrimination is significantly poorer than performance during weight estimation and weight discrimination.

### **3. EXPERIMENTAL METHODS**

#### **3.1 Overview**

The study involved two separate experimental tasks, a mass discrimination test and a push/aim task. The mass discrimination test was based on the method of constant stimuli for weight discrimination described by Gescheider (1985) and was used to determine measures of individual subject sensitivity to differences in mass. The push/aim task simulated the dynamic pushing task in an aiming situation. Performance in this task was a function of the accuracy of the aimed push to a designated target.

#### **3.2 Subjects**

Twelve subjects, drawn from the university population without regard to sex, age, race, or physical strength participated in the experiment. The experiment averaged slightly more than two hours per subject. Subjects were compensated at a rate of \$5 per hour.

#### **3.3 Apparatus**

A modified floor-based cart system consisting of a cart assembly and a linear track system was constructed for this study. Figure 3.1 is a schematic of the trolley system. A pair of triangular-shaped aluminum rails, nine meters long, were placed parallel to each

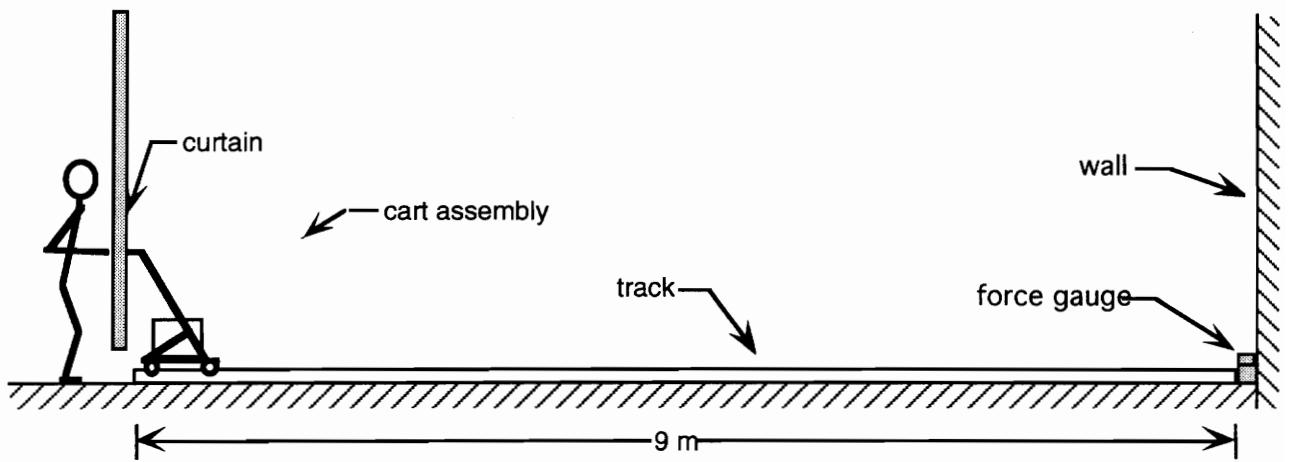


Figure 3.1 Schematic of Cart System

other on the floor of the Industrial Ergonomics Laboratory. Cross braces secured the aluminum rails together and also provided a means with which to adjust the height of the rails at several locations along the track system. The control of track height was needed because the floor of the Industrial Ergonomics laboratory was not level. Figure 3.2 shows the track system.

The cart assembly consisted of a four-wheeled cart and a box-shaped container used to house the weights. Low-friction wheels minimized frictional resistance against movement and allowed only two-way (back and forth), horizontal movement of the cart along the tracks. The cart was built with a handle at a height of about 1.3 m to allow for approximately chest high pushing of the load and a lower shelf surface to carry weights. Figure 3.3 is a drawing of the cart.

The box-shaped container used to hold the weights was either a  $0.39 \times 0.41 \times 0.31$  m<sup>3</sup> (wide x long x high) "small" size box or a  $0.56 \times 0.59 \times 0.55$  m<sup>3</sup> "large" size box. Both containers were made of cardboard and painted white. The purpose of these containers was to control the apparent size of the loads. Lead weights were placed into the weight containers allowing the total cart assembly weight to be varied between 25 and 90 kg. Subjects could not see the lead weights, only the box-shaped container holding the weights.

A curtain was hung from the ceiling between the subject's standing position and the cart to eliminate visual feedback concerning performance during the experiment.

It should be noted that available floor space in the Industrial Ergonomics Laboratory limited track length to 9 m causing concern that some overexertions would cause the trolley to travel farther than the 9 m provided. For this reason, a Chatillon push/pull gauge was positioned at the end of the tracks to measure the force of the trolley when (if) it reached the end of the tracks. By measuring the force of impact, the distance the trolley would have traveled could be estimated. (This situation never occurred).

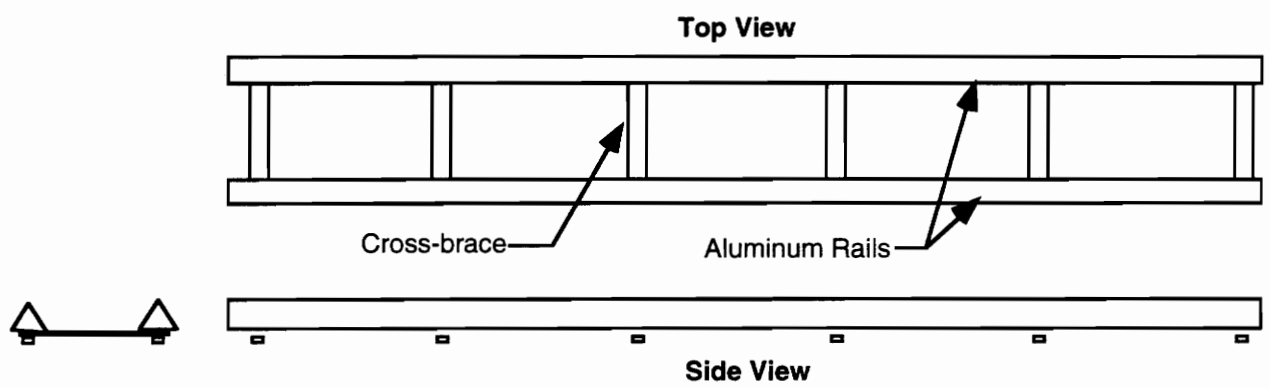


Figure 3.2 Track

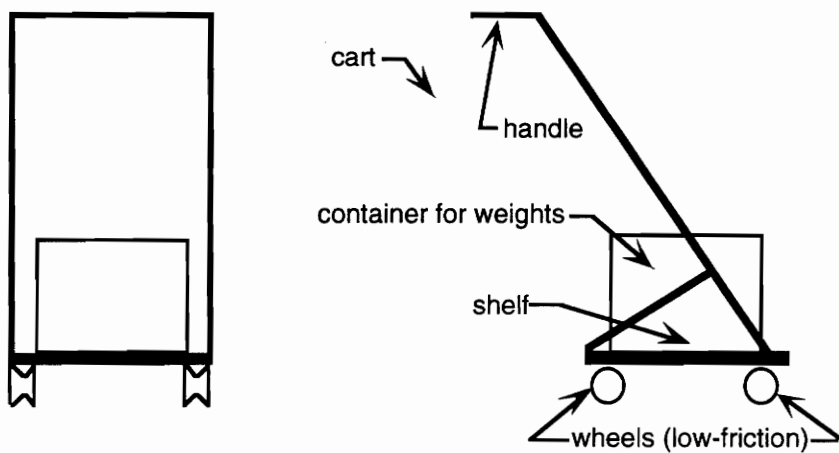


Figure 3.3 Cart

### 3.4 Mass Discrimination Test

A test of mass discrimination based upon the method of constant stimuli (Gescheider, 1985) was used to determine individual subject sensitivity.

#### 3.4.1 Experimental Design

Seven comparison stimuli (Co) were used with a standard stimulus (St) of 30 kg. This value was chosen because it was not a level utilized in the push/aim task; however, it was close to the range of values being tested in the push/aim task . The comparison stimuli (Co<sub>i</sub>) were valued (in kilograms) as follows.

$$Co_{-3} = 24.3, Co_{-2} = 26.2, Co_{-1} = 28.1, Co_0 = 30, Co_{+1} = 31.9, Co_{+2} = 33.8, Co_{+3} = 35.7$$

The extreme Co values (Co<sub>-3</sub>, Co<sub>+3</sub>) represented weights which would most likely never be mistaken as larger (Co<sub>-3</sub>) or smaller (Co<sub>+3</sub>) than the standard stimulus value. The intermediate Co values were then equally interspersed between the extreme Co values and the Co<sub>0</sub> value.

The possible treatment combinations were as follows:

|                    |                    |                     |                      |
|--------------------|--------------------|---------------------|----------------------|
| StCo <sub>-3</sub> | StCo <sub>+3</sub> | Co <sub>-3</sub> St | Co <sub>+1</sub> St  |
| StCo <sub>-2</sub> | StCo <sub>+2</sub> | Co <sub>-2</sub> St | Co <sub>+2</sub> St  |
| StCo <sub>-1</sub> | StCo <sub>+1</sub> | Co <sub>-1</sub> St | Co <sub>+3</sub> St, |
| StCo <sub>0</sub>  |                    | Co <sub>0</sub> St  |                      |

where  $StCo_i$  represented  $St$  presented before  $Co_i$  in the paired comparison and  $Co_iSt$  represented  $Co_i$  presented before  $St$  in the paired comparison. There were a total of 14 different treatment combinations with each combination presented three times for a total of 42 possible trials. Each subject performed all 42 trials in a random order.

### 3.4.2 Experimental Procedures

The mass discrimination test used the cart system. Each trial involved comparing the mass of two loads (a paired comparison). Before the trials began, the subject was blindfolded to eliminate visual information concerning the size of the loads being judged. At the start of each comparison, the cart system was loaded to a weight level of 24.3, 26.2, 28.1, 30, 31.9, 33.8, or 35.7 kg depending on the particular treatment combination. The subject was then asked to "test" the mass of the load by grasping the handle of the cart assembly with both hands and moving the cart back and forth to get a feeling for the mass of the load. The cart assembly was then reconfigured with another weight level (as dictated by the particular treatment combination) and the subject again "tested" the mass of the second load. Following the second "test," the subject indicated which load appeared to have more mass.

The process of "testing" the first load, the second load, and then choosing which load had greater mass represented a single trial. After every 10 trials or whenever requested, the subject was be given a one minute rest period.

Each subject was given additional instructions just prior to the first trial to control possible biasing effects caused by the experimental procedures and apparatus. First, subjects were instructed to ignore the sounds of the weights being placed onto the trolley. They were told that the loudness of the sounds did not correlate with the heaviness of the

weights. Secondly, subjects were instructed to base their weights judgments only on the "feel" of the weights and nothing else. This instruction was given to prevent the use of other techniques or "tricks" that would utilize other abilities, for example, making very small pushes and comparing the time or distance it takes for the load to come to rest. Finally, subjects were asked to remove their hands from the handle of the trolley while the weight level was reconfigured to eliminate any possible information about weights occurring from feeling weights being taken off or put on to the trolley.

### 3.5 Push/Aim Task

The push/aim task required the subject to push/shove objects of a particular weight and size to a target located a specific distance from the initial position of the object.

#### 3.5.1 Experimental Design

The push/aim task was a 3 x 2 x 2 within-subjects design. The independent variables included three levels of weight (25, 45, and 90 kg), two levels of distance to the target (2 m, 6 m), and two levels of apparent size of the load to be pushed ( $0.39 \times 0.41 \times 0.31$ ,  $0.56 \times 0.59 \times 0.55 \text{ m}^3$ ) creating 12 different treatment combinations. Each of these treatment combinations was presented four times for a total of 48 possible treatment combinations. Each subject performed each of the 48 treatment combinations. Figure 3.4 is a graphical representation of the experimental design. The order of presentation was based upon a known 12 x 12 Latin square design given by Fisher and Yates (1963). To accommodate the 48 treatment combinations for each of the twelve subjects, four 12 x 12

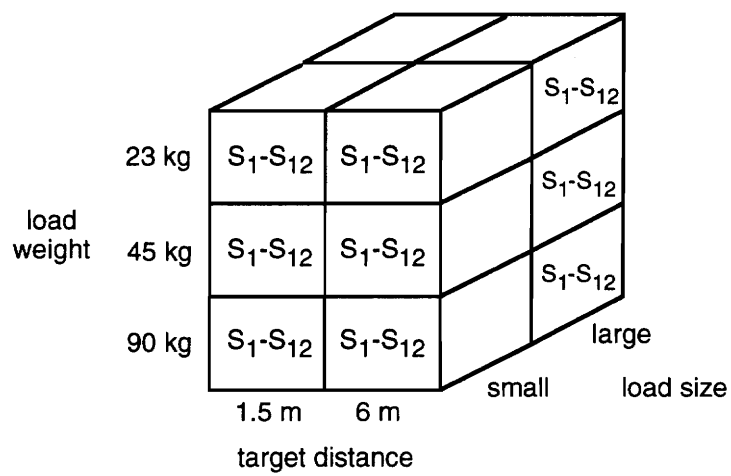


Figure 3.4 Experimental Design of Push/Aim Task

Latin squares were randomly generated according to the method described by Guenther (1964). The base Latin square given by Fisher and Yates (1963) and the four randomly generated Latin squares used in the study can be found in Appendix B.

The experimental design included two dependent measures, both associated with the accuracy of the aimed push; the absolute error of each aimed push and the relative error (i.e., variability) of the aimed pushes. For each trial, error was measured as the distance between the center of the target and the load's final resting position following an aimed push. The value for absolute error was then the average absolute error of the four trials associated with each treatment combination in the push/aim task. The relative error was the standard deviation of the four aimed pushes associated with each treatment combination.

### 3.5.2 Experimental Procedures

At the start of the push/aim task portion of the study, the experimenter gave a quick explanation and demonstration of the proper way to perform the push/aim task. Subjects were then given three practice pushes. During the practice pushes, the cart was unloaded, the target distance was six meters and subjects were allowed to watch the trolley travel to the target. The practice trials allowed the subject to attain proper footwork and, more importantly, gain a sense of how the trolley rolled down the track. Following the practice trials, subjects were given additional instructions aimed at eliminating potential biasing effects from the experimental procedures and apparatus. Specifically targeted was the potential use of sound for feedback; for example, judging the distance the cart traveled on how long they could hear the trolley roll down the tracks. Subjects were told to avoid making a judgment on distance traveled based on these sound cues. They were told such a

judgment would be erroneous because it was based on an unknown standard. Since subjects were never given feedback, they would not know if their standard was correct. It was stressed that subjects approach each push as if it were a separate and independent situation. The actual trials then proceeded as follows.

At the start of each trial, the trolley assembly was loaded to a level of 25, 45 or 90 kg. After loading the trolley, the curtain was opened allowing the subject to see the target, the trolley, and the box-shaped container holding the actual weights. Two containers were used, a  $0.40 \times 0.40 \times 0.40 \text{ m}^3$  "small" box and a  $0.64 \times 0.64 \times 0.64 \text{ m}^3$  "large" box. The larger box served to increase the apparent size of the load to be pushed while the smaller box decreased the apparent size. The specific ratio of volume of the large box to the small box was about four to one.

The subjects were asked to "test" the weight of the load to gauge its mass. This "test" involved subjects grasping the handles and pushing the load forward (approximately 15 cm) and pulling it back to the starting position a small number of times (1-3). Subjects were allowed to choose how fast and how many times they pushed and pulled the load during every "test." After testing the load's mass, subjects performed the aimed push. The push supplied an initial force to the load causing it to travel to the target under its own momentum. Before each push, subjects' feet were placed in a fixed position. The two feet were shoulder width apart with one foot forward and one foot back (see Figure 3.5). During the actual push, subjects were allowed to bring the rear foot forward in a "follow-through" motion. The allowance of a "follow-through" motion provided an effective weight transfer from the rear leg to the front leg. This motion was useful for the heaviest load level which required fairly high exertions for weaker subjects.

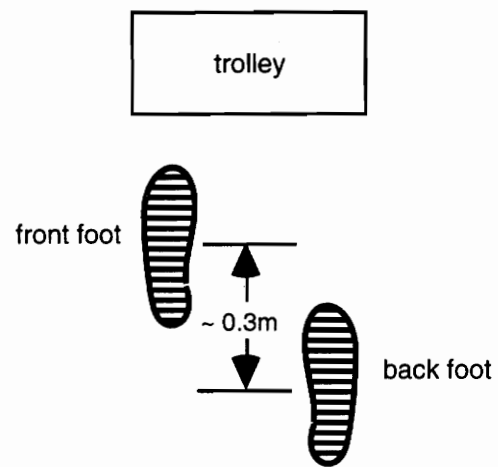


Figure 3.5 Feet Position during Push/Aim Task

The target itself was marked on the tracks by a 5 cm thick, black, horizontal line placed either 2 or 6 m away from the initial position of the load. Immediately after pushing the load, the curtain was closed to eliminate visual information to the subject concerning the accuracy of the aimed push.

Once the load came to a stop, the experimenter measured the distance between the center of the load and the center of the target. If the load stopped before the target position, a negative value was assigned to the measure of error. Likewise, a positive value was assigned if the load stopped past the target.

The next trial proceeded as soon as the experimental apparatus was configured for the next condition.

### 3.6 Experimental Protocol

The experiment was completed in two separate sessions over two separate days. The first session involved the mass discrimination test and the second session involved the push/aim task.

During the first session, the subject was given written information describing the entire study in general and an informed consent form. These forms can be found in the Appendix A. Once the informed consent form was signed, the experimenter verbally described the overall experiment and then gave detailed instructions on how to perform the mass discrimination test. After confirming the subject understood the task involved, actual trials began. This session lasted between 45 and 60 minutes. Once all trials were completed, the second session was scheduled and the subject left.

On the second day, the subject completed the push/aim portion of the experiment. The subject was given a general review of the overall study followed by detailed

instructions on how to perform the push/aim task. The subject then performed three practice pushes on the unloaded trolley. Following the practice trials, actual trials began. The second session lasted about 75 minutes.

After completing the push/aim experiment, the subject was thanked, debriefed, and paid. The total time for both sessions generally involved between two and two and a half hours.

## 4. RESULTS

### 4.1 Overview

The results are presented separately for the Weber fraction data, the absolute error data, and the relative error data. Weber fractions were determined for both the individual and group level as a measure of subject sensitivity. Push/aim task performance was based on absolute and relative measures of error. The absolute error was defined as the distance between the average final resting point of the center of the load and the center of the target for the four trials associated with each treatment combination of the push/aim task. The relative error was a measure of the variability of the aimed pushes from trial to trial and was defined as the sample standard deviation of the four aimed pushes associated with each treatment combination of the push/aim task. Statistical analyses involved simple hypothesis testing, analysis of covariance (ANCOVA), analysis of variance (ANOVA), and Newman-Keuls post-hoc comparison tests. Statistical significance was considered to exist at p-values less than 0.05.

### 4.2 Weber Fractions

Weber fractions were calculated to quantify the subjects' sensitivity to mass discrimination following the methods described in Gescheider (1985).

#### 4.2.1 Fit to Ogive Curve

Before calculating Weber fractions, the data (the proportion of responses where  $Co > St$ ) had to be shown to fit the S-shape or ogive curve typically associated with psychometric discrimination responses (Gescheider, 1985). Figure 4.1 shows the theoretical ogive curve.

According to Gescheider, transforming the proportion values into z-values and then graphing the resulting z-values versus the Co values yields a linear relationship if the original data was from an ogive curve. Table 4.1 shows the z-transformation for all of the data points. Figure 4.2 is the resulting graph for the data averaged over subjects. The data exhibited a strong linear relationship, as shown by the high  $R^2$  value (0.992) from the best-fit linear regression function. It was, therefore, concluded that Weber fractions could be calculated from the data.

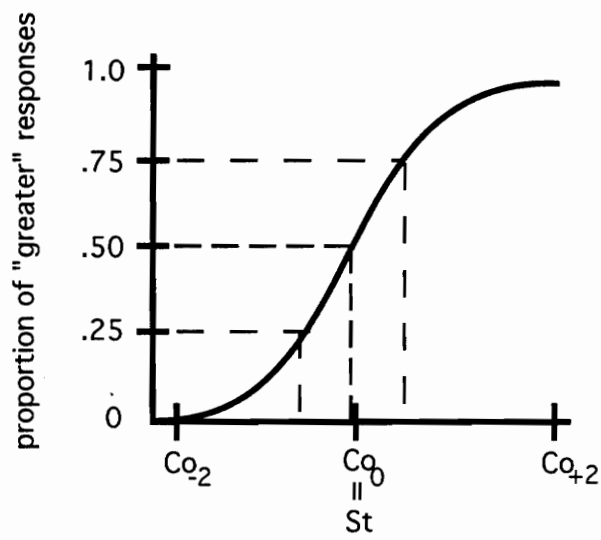


Figure 4.1. Typical Psychometric Function of Discrimination Responses  
adapted from Gescheider, 1985

Table 4.1 Proportion Values (in %) and Equivalent Z-Values

|       | Co-3 |        | Co-2 |        | Co-1 |        | Co0  |       | Co+1 |       | Co+2 |       | Co+3 |       |
|-------|------|--------|------|--------|------|--------|------|-------|------|-------|------|-------|------|-------|
|       | %    | z      | %    | z      | %    | z      | %    | z     | %    | z     | %    | z     | %    | z     |
| sub1  | 0    | -3.5   | 0    | -3.5   | 16.7 | -0.974 | 66.7 | 0.43  | 66.7 | 0.43  | 83.3 | 0.966 | 100  | 3.5   |
| sub2  | 0    | -3.5   | 0    | -3.5   | 33.3 | -0.44  | 66.7 | 0.43  | 83.3 | 0.966 | 83.3 | 0.966 | 100  | 3.5   |
| sub3  | 0    | -3.5   | 0    | -3.5   | 16.7 | -0.974 | 33.3 | -0.44 | 83.3 | 0.966 | 83.3 | 0.966 | 100  | 3.5   |
| sub4  | 0    | -3.5   | 50   | 0      | 16.7 | -0.974 | 33.3 | -0.44 | 33.3 | -0.44 | 83.3 | 0.966 | 100  | 3.5   |
| sub5  | 0    | -3.5   | 0    | -3.5   | 16.7 | -0.974 | 66.7 | 0.43  | 100  | 3.5   | 100  | 3.5   | 100  | 3.5   |
| sub6  | 16.7 | -0.974 | 0    | -3.5   | 33.3 | -0.44  | 33.3 | -0.44 | 83.3 | 0.966 | 100  | 3.5   | 83.3 | 0.966 |
| sub7  | 0    | -3.5   | 16.7 | -0.974 | 16.7 | -0.974 | 50   | 0     | 66.7 | 0.43  | 83.3 | 0.966 | 100  | 3.5   |
| sub8  | 16.7 | -0.974 | 0    | -3.5   | 33.3 | -0.44  | 50   | 0     | 50   | 0     | 100  | 3.5   | 83.3 | 0.966 |
| sub9  | 0    | -3.5   | 16.7 | -0.974 | 0    | -3.5   | 33.3 | -0.44 | 83.3 | 0.966 | 66.7 | 0.43  | 100  | 3.5   |
| sub10 | 0    | -3.5   | 0    | -3.5   | 33.3 | -0.44  | 50   | 0     | 83.3 | 0.966 | 100  | 3.5   | 100  | 3.5   |
| sub11 | 0    | -3.5   | 16.7 | -0.974 | 33.3 | -0.44  | 50   | 0     | 100  | 3.5   | 83.3 | 0.966 | 100  | 3.5   |
| sub12 | 0    | -3.5   | 0    | -3.5   | 0    | -3.5   | 50   | 0     | 83.3 | 0.966 | 83.3 | 0.966 | 100  | 3.5   |

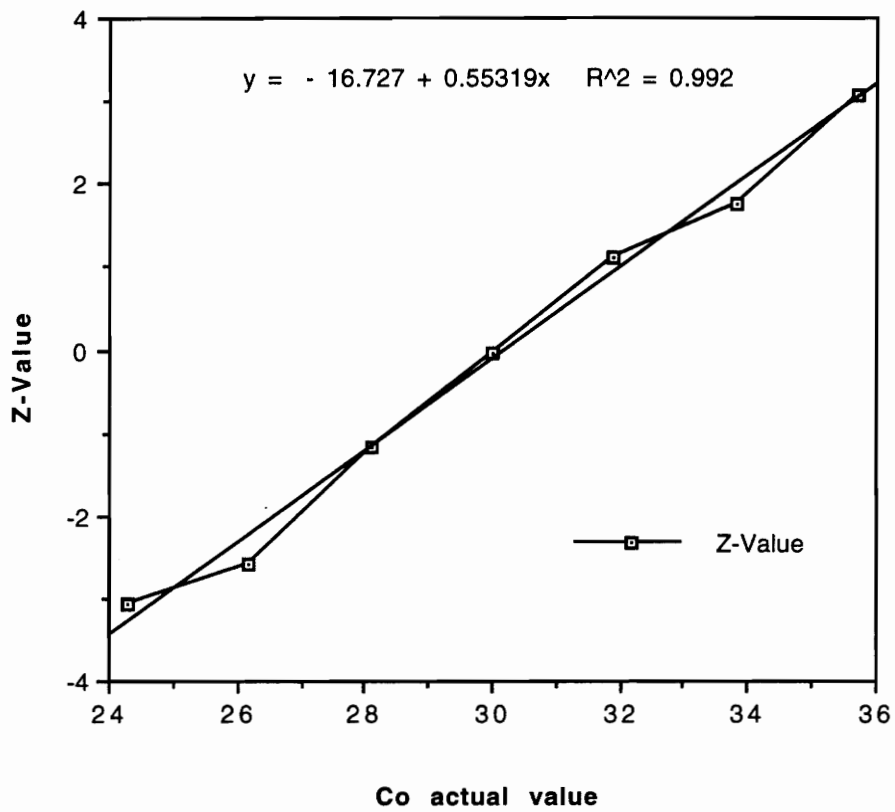


Figure 4.2 Graph of Co Value vs. Z-Value: Overall Subject Population

#### 4.2.2 Weber Fraction Calculation

Weber fractions were calculated using equation (4.1) where DL was the individual subject's difference limen value and PSE represented the point of subjective equality.

$$\text{Weber fraction} = \text{DL}/\text{PSE}, \quad (4.1)$$

Difference limen values were determined using equations (4.2), (4.3), and (4.4).

$$\text{DL}_u = \text{Co}(0.75) - \text{Co}(0.50) \quad (4.2)$$

$$\text{DL}_l = \text{Co}(0.50) - \text{Co}(0.25) \quad (4.3)$$

$$\text{DL} = (\text{DL}_u + \text{DL}_l)/2 \quad (4.4)$$

The Co(x) values were determined from a best-fit linear regression function for each individual subject similar to the one shown in Figure 4.1. For ease of calculation, the corresponding Co versus z-value graphs were used. The corresponding z-values were:

$$\text{Co}(0.75) = z(0.67) \quad (4.5)$$

$$\text{Co}(0.50) = z(0) \quad (4.6)$$

$$\text{Co}(0.25) = z(-0.67) \quad (4.7)$$

The Co value vs. z-value graphs for each individual, the corresponding best-fit functions, and the calculations used to determine the Weber fractions can be found in Appendix C. The Weber fraction for the entire subject population was 0.04 while individual Weber fractions ranged from 0.031 to 0.058. Table 4.2 summarizes the overall and individual Weber fraction values.

Table 4.2 Calculated Weber Fraction Values

| Subject | Weber Fraction |
|---------|----------------|
| 1       | 0.037          |
| 2       | 0.037          |
| 3       | 0.036          |
| 4       | 0.050          |
| 5       | 0.031          |
| 6       | 0.056          |
| 7       | 0.045          |
| 8       | 0.058          |
| 9       | 0.041          |
| 10      | 0.033          |
| 11      | 0.042          |
| 12      | 0.033          |
| overall | 0.040          |

### 4.3 Absolute Error

Two-tailed hypothesis tests were performed to determine if the absolute error was a consistent undershoot or overshoot. An ANCOVA was used to evaluate the effects of weight level, apparent size, and target distance given a covariate, subject sensitivity. A significant covariate effect would also indicate a significant correlation between subject sensitivity and absolute error. Since the covariate was not significant, the effects of weight level, apparent size, and target distance on the absolute error were evaluated with an ANOVA.

#### 4.3.1 Absolute Error Hypothesis Tests

Two-tailed hypothesis tests based on a one sample t-test method were used to determine if the absolute error associated with the aimed pushes was a consistent undershoot or overshoot. The null hypothesis was that absolute error was equal to zero ( $\mu = 0$ ) and the alternative hypothesis was that absolute error was not equal to zero ( $\mu \neq 0$ ). These hypothesis tests were performed for the combined data and then at each level of the independent variable (interactions were not considered). The tests revealed that absolute error was significant by less than zero for the combined data set and at all levels of the independent variables. Table 4.3 summarizes the hypothesis test results.

#### 4.3.2 Analysis of Covariance

An ANCOVA was used to evaluate the effects of the independent variables on the absolute error given a covariate of mass discrimination sensitivity, as measured by the Weber fraction. The ANCOVA is shown in Table 4.4. The overall effect of the Weber fraction values was not significant ( $p = 0.4268$ ) indicating no significant correlation between discrimination sensitivity and absolute error. Figure 4.3 is a plot of the absolute error versus Weber fraction. The best-fit line yielded a correlation coefficient ( $R^2$ ) of 0.004 between absolute error and Weber fraction values. The lack of a discernible pattern graphically reinforces the conclusion of no correlation. These results also indicate that an ANOVA would be an appropriate analysis for the absolute error since the effect of the covariate was not significant.

#### 4.3.3 Analysis of Variance

An ANOVA was used to evaluate the effects of weight, apparent size, and target distance on the absolute error. Table 4.5 is the ANOVA summary table based on the absolute error dependent measure. Note that the G-G column and the H-F column represent adjustments from the Greenhouse-Geisser and Hunyh-Feldt corrections for non-homogeneity of covariance, respectively.

The significant effects were weight ( $p = 0.0001$ ) and distance ( $p = 0.0001$ ). A significant interaction existed between weight and distance ( $p = 0.0475$ ). Newman-Keuls post-hoc tests were used to investigate the significance of different levels within the weight main effect and the weight x distance interaction. The weight effect is shown in Figure 4.4. The largest absolute error occurred at the 90 kg level. In Figure 4.4,

Table 4.3 Hypothesis Tests on Absolute Error ( $H_0: \mu = 0, H_A: \mu \neq 0$ )

|                                   | Mean   | DF  | t-Value | P-Value |
|-----------------------------------|--------|-----|---------|---------|
| Absolute Error, Combined          | -.876  | 575 | -22.464 | <.0001  |
| <u>Separated by Weight</u>        |        |     |         |         |
| Absolute Error, 25 kg             | -.743  | 191 | -10.520 | <.0001  |
| Absolute Error, 45 kg             | -.795  | 191 | -12.293 | <.0001  |
| Absolute Error, 90 kg             | -1.091 | 191 | -16.824 | <.0001  |
| <u>Separated by Distance</u>      |        |     |         |         |
| Absolute Error, m2                | -.109  | 287 | -3.887  | .0001   |
| Absolute Error, m6                | -1.643 | 287 | -47.313 | <.0001  |
| <u>Separated by Apparent Size</u> |        |     |         |         |
| Absolute Error, large             | -.881  | 287 | -16.285 | <.0001  |
| Absolute Error, small             | -.872  | 287 | -15.480 | <.0001  |

Table 4.4 ANCOVA Summary Table

Dependent Variable: Absolute Error

| Source                                             | df | Sum of Squares | Mean Square | F-value | p-value      |
|----------------------------------------------------|----|----------------|-------------|---------|--------------|
| <b>Weber Fraction</b>                              | 1  | .399           | .399        | .686    | <b>.4268</b> |
| Subject                                            | 10 | 5.814          | .581        |         |              |
| Weight                                             | 2  | .750           | .375        | 3.317   | .0570        |
| Weight * Weber Fraction                            | 2  | .326           | .163        | 1.441   | .2602        |
| Weight * Subject                                   | 20 | 2.261          | .113        |         |              |
| Distance                                           | 1  | 2.075          | 2.075       | 5.490   | .0411        |
| Distance * Weber Fraction                          | 1  | .192           | .192        | .507    | .4927        |
| Distance * Subject                                 | 10 | 3.779          | .378        |         |              |
| Apparent Size                                      | 1  | .048           | .048        | .988    | .3436        |
| Apparent Size * Weber Fraction                     | 1  | .055           | .055        | 1.143   | .3101        |
| Apparent Size * Subject                            | 10 | .485           | .048        |         |              |
| Weight * Distance                                  | 2  | .003           | .001        | .020    | .9801        |
| Weight * Distance * Weber Fraction                 | 2  | .008           | .004        | .057    | .9443        |
| Weight * Distance * Subject                        | 20 | 1.384          | .069        |         |              |
| Weight * Apparent Size                             | 2  | .131           | .066        | 1.285   | .2986        |
| Weight * Apparent Size * Weber Fraction            | 2  | .120           | .060        | 1.177   | .3287        |
| Weight * Apparent Size * Subject                   | 20 | 1.023          | .051        |         |              |
| Distance * Apparent Size                           | 1  | .023           | .023        | 1.120   | .3148        |
| Distance * Apparent Size * Weber Fraction          | 1  | .018           | .018        | .862    | .3751        |
| Distance * Apparent Size * Subject                 | 10 | .206           | .021        |         |              |
| Weight * Distance * Apparent Size                  | 2  | .042           | .021        | .771    | .4757        |
| Weight * Distance * Apparent Size * Weber Fraction | 2  | .036           | .018        | .659    | .5282        |
| Weight * Distance * Apparent Size * Subject        | 20 | .548           | .027        |         |              |

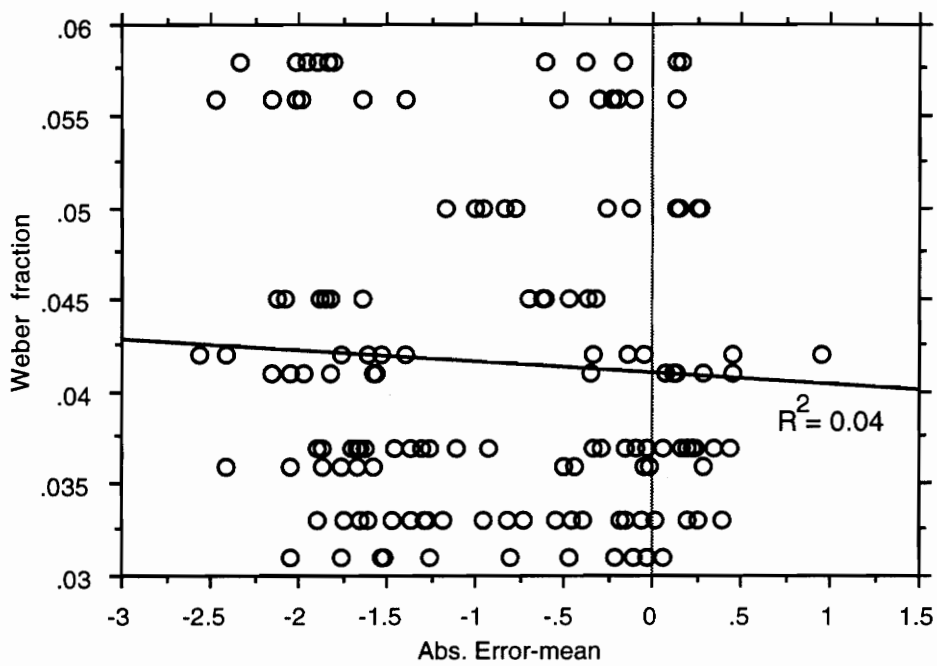


Figure 4.3 Scatterplot of Absolute Error vs. Weber Fraction

Table 4.5 ANOVA Summary Table

Dependent Value: Absolute Error

| Source                                      | df | Sum of Squares | Mean Square | F-value | p-value      | G-G   | H-F   |
|---------------------------------------------|----|----------------|-------------|---------|--------------|-------|-------|
| Subject                                     | 11 | 6.213          | .565        |         |              |       |       |
| <b>Weight</b>                               | 2  | 3.395          | 1.698       | 14.441  | <b>.0001</b> | .0015 | .0012 |
| Weight * Subject                            | 22 | 2.586          | .118        |         |              |       |       |
| <b>Distance</b>                             | 1  | 84.675         | 84.675      | 234.551 | <b>.0001</b> | .0001 | .0001 |
| Distance * Subject                          | 11 | 3.971          | .361        |         |              |       |       |
| Apparent Size                               | 1  | .003           | .003        | .067    | .8008        | .8008 | .8008 |
| Apparent Size * Subject                     | 11 | .540           | .049        |         |              |       |       |
| <b>Weight * Distance</b>                    | 2  | .444           | .222        | 3.510   | <b>.0475</b> | .0548 | .0475 |
| Weight * Distance * Subject                 | 22 | 1.392          | .063        |         |              |       |       |
| Weight * Apparent Size                      | 2  | .023           | .011        | .217    | .8069        | .7765 | .8069 |
| Weight * Apparent Size * Subject            | 22 | 1.144          | .052        |         |              |       |       |
| Distance * Apparent Size                    | 1  | .011           | .011        | .547    | .4748        | .4748 | .4748 |
| Distance * Apparent Size * Subject          | 11 | .224           | .020        |         |              |       |       |
| Weight * Distance * Apparent Size           | 2  | .066           | .033        | 1.247   | .3069        | .3048 | .3069 |
| Weight * Distance * Apparent Size * Subject | 22 | .584           | .027        |         |              |       |       |

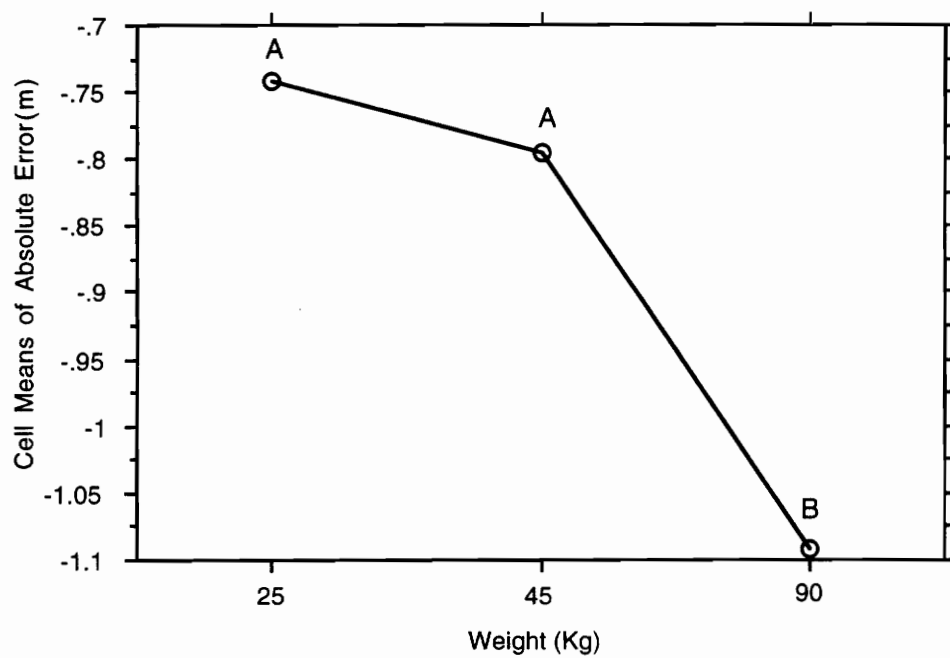


Figure 4.4 Plot of Weight Main Effect vs. Absolute Error Dependent Variable

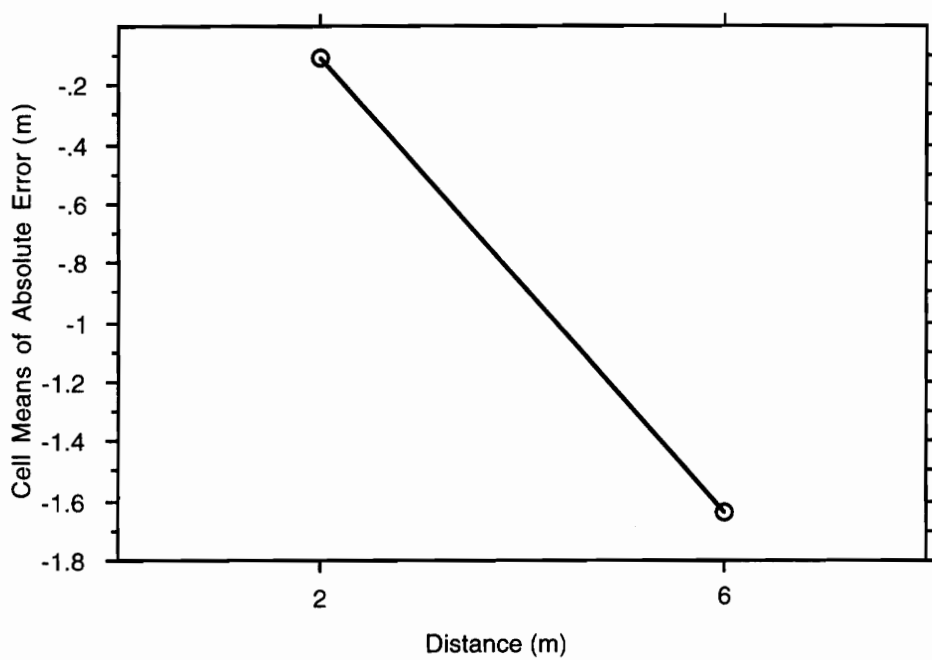


Figure 4.5 Plot of Distance Main Effect vs. Absolute Error Dependent Variable

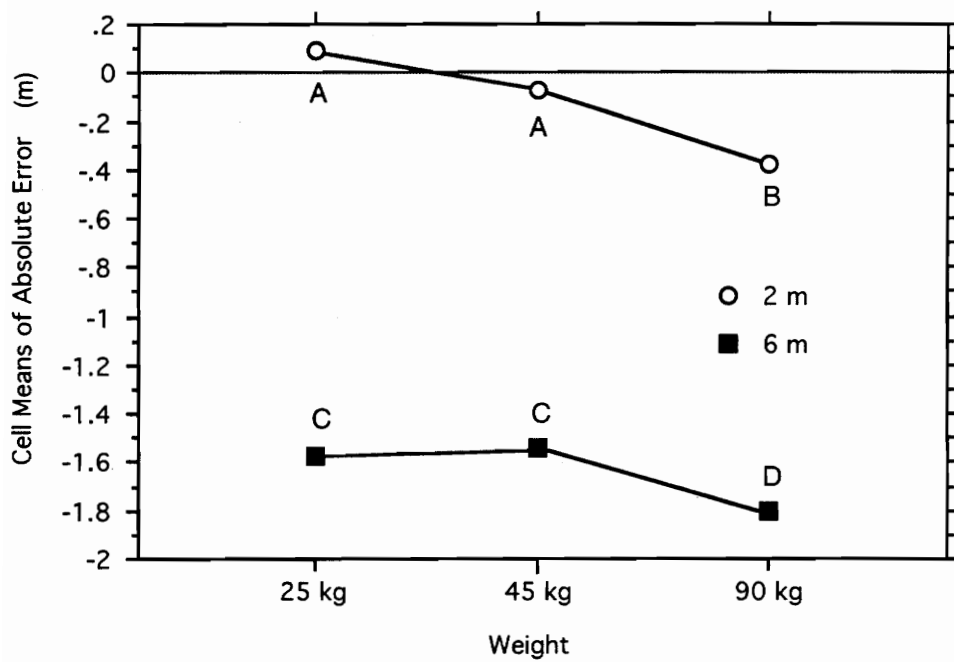


Figure 4.6 Interaction Plot of Weight x Distance  
Dependent Variable: Absolute Error

groupings labeled "A" were significantly different than groupings labeled "B." The 90 kg absolute error was significantly different than the absolute error associated with both the 25 kg and 45 kg levels. Errors at the 25 kg and 45 kg levels were not significantly different. The effect of distance is shown in Figure 4.5. The largest absolute error was found to occur at the 6 m level.

Figure 4.6 is the interaction plot for the weight by distance effect. Significantly different groupings are represented by different letters ("A", "B", "C", and "D"). At the 2 m level, the largest absolute error occurred at the 90 kg level followed by 45 kg, and then 25 kg. At the 6 m level, the largest absolute error again was associated with the 90 kg level; however, no significant difference was found between the 45 kg and 25 kg levels.

#### 4.4 Relative Error Data

One-tailed hypothesis tests were performed to determine if the relative error associated with the push/aim task was statistically significant. An ANCOVA was used to evaluate the effects of the independent variables on the dependent measure of relative error given a covariate of mass discrimination sensitivity, as measured by the Weber fraction. A significant covariate effect would also indicate a significant correlation between subject sensitivity and relative error. Since the covariate was not significant, the effects of weight level, apparent size, and target distance on the absolute error were evaluated with an ANOVA.

#### 4.4.1 Relative Error Hypothesis Tests

One-tailed hypothesis tests based on the one sample t-test were performed to determine if the relative error could be considered significantly different than zero. The null hypothesis was that relative error was equal to zero ( $\mu = 0$ ) and the alternative hypothesis was that relative error was greater than zero ( $\mu > 0$ ). The hypothesis tests were performed for the combined data and at each level of the independent variables (interactions were not considered). Relative error was significantly greater than zero for the combined data and also at each level of the independent variables. Table 4.6 summarizes the hypothesis test results.

#### 4.4.2 Analysis of Covariance

Overall, the Weber fraction effect was not significant ( $p = 0.2499$ ) indicating a lack of correlation between sensitivity and relative error. Table 4.7 is the ANCOVA summary table for the dependent variable of relative error. Figure 4.7 graphically shows the lack of correlation between relative error and Weber fraction values. The best-fit line yielded a correlation coefficient ( $R^2$ ) of 0.008 between absolute error and Weber fraction values. The lack of a discernible pattern graphically reinforces the conclusion of no correlation. These results also indicate that an ANOVA would be an appropriate analysis for the relative error since the effect of the covariate was not significant.

#### 4.4.3 Analysis of Variance

An ANOVA was used to evaluate the effects of weight, apparent size, and target distance on the relative error. Table 4.8 is the ANOVA summary table based on the relative error dependent measure.

For this analysis, only the main effect of distance was significant. Relative error was largest at the 6 m level as shown in Table 4.9.

Table 4.6 Hypothesis Tests on Relative Error ( $H_0: \mu = 0$ ,  $H_A: \mu > 0$ )

|                               | Mean | DF  | t-Value | P-Value |
|-------------------------------|------|-----|---------|---------|
| Relative Error, Total         | .378 | 143 | 20.476  | <.0001  |
| <u>Split by Weight</u>        |      |     |         |         |
| Relative Error, 25 kg         | .359 | 47  | 12.377  | <.0001  |
| Relative Error, 45 kg         | .369 | 47  | 10.961  | <.0001  |
| Relative Error, 90 kg         | .406 | 47  | 12.185  | <.0001  |
| <u>Split by Distance</u>      |      |     |         |         |
| Relative Error, m2            | .323 | 71  | 13.701  | <.0001  |
| Relative Error, m6            | .434 | 71  | 16.018  | <.0001  |
| <u>Split by Apparent Size</u> |      |     |         |         |
| Relative Error, large         | .356 | 71  | 15.533  | <.0001  |
| Relative Error, small         | .401 | 71  | 13.866  | <.0001  |

Table 4.7 ANCOVA Summary Table

Dependent Variable: Relative Error

| Source                                             | df | Sum of Squares | Mean Square | F-value | p-value      |
|----------------------------------------------------|----|----------------|-------------|---------|--------------|
| <b>Weber Fraction</b>                              | 1  | .054           | .054        | 1.492   | <b>.2499</b> |
| Subject                                            | 10 | .363           | .036        |         |              |
| Weight                                             | 2  | .054           | .027        | .557    | .5817        |
| Weight * Weber Fraction                            | 2  | .047           | .024        | .487    | .6214        |
| Weight * Subject                                   | 20 | .968           | .048        |         |              |
| Distance                                           | 1  | 3.604E-5       | 3.604E-5    | .001    | .9716        |
| Distance * Weber Fraction                          | 1  | .017           | .017        | .641    | .4421        |
| Distance * Subject                                 | 10 | .271           | .027        |         |              |
| Apparent Size                                      | 1  | .131           | .131        | 3.266   | .1009        |
| Apparent Size * Weber Fraction                     | 1  | .181           | .181        | 4.529   | .0592        |
| Apparent Size * Subject                            | 10 | .400           | .040        |         |              |
| Weight * Distance                                  | 2  | .205           | .102        | 2.051   | .1548        |
| Weight * Distance * Weber Fraction                 | 2  | .278           | .139        | 2.783   | .0859        |
| Weight * Distance * Subject                        | 20 | .999           | .050        |         |              |
| Weight * Apparent Size                             | 2  | .241           | .120        | 2.417   | .1148        |
| Weight * Apparent Size * Weber Fraction            | 2  | .269           | .134        | 2.694   | .0920        |
| Weight * Apparent Size * Subject                   | 20 | .997           | .050        |         |              |
| Distance * Apparent Size                           | 1  | .004           | .004        | .082    | .7801        |
| Distance * Apparent Size * Weber Fraction          | 1  | .002           | .002        | .037    | .8509        |
| Distance * Apparent Size * Subject                 | 10 | .476           | .048        |         |              |
| Weight * Distance * Apparent Size                  | 2  | .036           | .018        | .521    | .6017        |
| Weight * Distance * Apparent Size * Weber Fraction | 2  | .015           | .008        | .222    | .8026        |
| Weight * Distance * Apparent Size * Subject        | 20 | .688           | .034        |         |              |

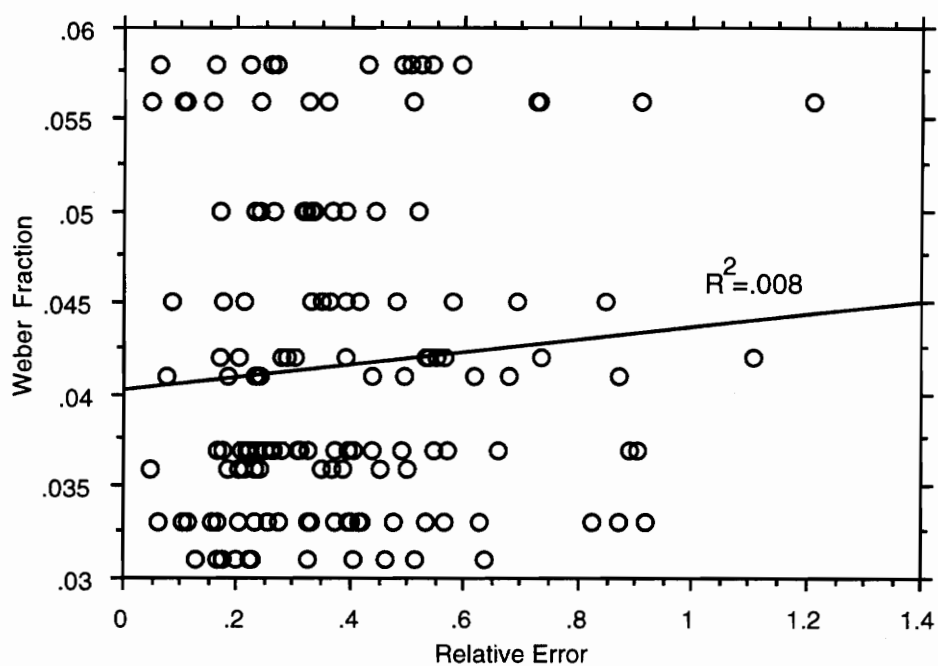


Figure 4.7 Scatterplot of Relative Error vs. Weber Fraction

Table 4.8 ANOVA Summary Table

Dependent Variable: Relative Error

| Source                                      | df | Sum of Squares | Mean Square | F-value | p-value      | G-G   | H-F   |
|---------------------------------------------|----|----------------|-------------|---------|--------------|-------|-------|
| Subject                                     | 11 | .417           | .038        |         |              |       |       |
| Weight                                      | 2  | .059           | .029        | .637    | .5381        | .5176 | .5381 |
| Weight * Subject                            | 22 | 1.015          | .046        |         |              |       |       |
| <b>Distance</b>                             | 1  | .442           | .442        | 16.858  | <b>.0017</b> | .0017 | .0017 |
| Distance * Subject                          | 11 | .288           | .026        |         |              |       |       |
| Apparent Size                               | 1  | .074           | .074        | 1.403   | .2611        | .2611 | .2611 |
| Apparent Size * Subject                     | 11 | .581           | .053        |         |              |       |       |
| Weight * Distance                           | 2  | .168           | .084        | 1.447   | .2568        | .2583 | .2569 |
| Weight * Distance * Subject                 | 22 | 1.277          | .058        |         |              |       |       |
| Weight * Apparent Size                      | 2  | .086           | .043        | .751    | .4835        | .4753 | .4835 |
| Weight * Apparent Size * Subject            | 22 | 1.266          | .058        |         |              |       |       |
| Distance * Apparent Size                    | 1  | .011           | .011        | .255    | .6237        | .6237 | .6237 |
| Distance * Apparent Size * Subject          | 11 | .478           | .043        |         |              |       |       |
| Weight * Distance * Apparent Size           | 2  | .160           | .080        | 2.504   | .1047        | .1178 | .1092 |
| Weight * Distance * Apparent Size * Subject | 22 | .704           | .032        |         |              |       |       |

Table 4.9 Least Squares Means of Relative Error  
Separated by Distance

|     | Mean | Std. Dev. | Std. Error |
|-----|------|-----------|------------|
| 2 m | .323 | .162      | .019       |
| 6 m | .434 | .162      | .019       |

## 5. DISCUSSION

### 5.1 Overview

The hypotheses initially proposed in the introduction are reiterated and examined based on the analyses of the Weber fraction data, absolute error data, and relative error data presented in the results section. The results of the analyses are then interpreted and discussed in detail. The section is closed with some basic recommendations and possibilities for further research.

### 5.2 Initial Hypotheses

*H<sub>1</sub>: Performance of the push/aim task will exhibit significant error and, this error will be either a consistent overshoot of the target or a consistent undershoot of the target.*

Performance of the push/aim task exhibited significant error with respect to both the absolute and relative measures of error. The absolute error analysis showed error to be a consistent undershooting of the target.

*H<sub>2</sub>: Varying the weight of the load to be pushed will have a significant effect on the accuracy of the push/aim task with respect to both absolute and relative error.*

Varying the weight of the load had a significant effect on the accuracy of the push/aim task with respect to the absolute measure of error. However, it did not have a significant effect on push/aim task performance as measured by relative error.

*H<sub>3</sub>: Varying the distance to the target will have a significant effect on the accuracy of the push/aim task with respect to both absolute and relative error.*

Varying the distance to the target had a significant effect on the accuracy of the push/aim task with respect to both absolute and relative error.

*H<sub>4</sub>: Varying the apparent size of the load to be pushed will have a significant effect on the absolute error of the push but will have no significant effect on the relative error.*

Varying the apparent size of the load did not have a significant effect on either the absolute or relative measures of error.

*H<sub>5</sub>: A significant linear correlation will be found to exist between subject sensitivity to mass discrimination and performance on the push/aim task as measured by absolute and relative error.*

A significant linear correlation was not found to exist between mass discrimination sensitivity and performance on the push/aim task as measured by absolute or relative error.

### 5.3 Weber Fractions

The Weber fraction for the combined subject population was 0.04; individually, it ranged from 0.031 to 0.058. These values are considered relatively low, which indicates a high degree of sensitivity for discrimination utilizing a horizontal push and pull motion against inertial loads. Weber fractions generally range from 0.06 to 0.10 for discrimination of lifted weights and up to twice these values for purely inertial masses (Carlson, et al., 1977; Rees and Copeland, 1960; and, Crawford and Kama, 1961). The higher sensitivity associated with this study is not unexpected since higher levels of load were utilized. It is generally accepted that as stimulus level increases, sensitivity increases, up to some asymptotic level (Jones, 1986). The loads used in this study (24 - 36 kg) may well be above the level where maximal sensitivity occurs.

Whether these results can be generalized to the pushing of inertial loads is uncertain. The loads cannot be considered purely inertial since some level of frictional resistance (rolling resistance) did exist. The main purpose of measuring the mass discrimination sensitivity was to identify a possible covariate with push/aim task performance. For this reason (among others such as time and cost limits), the study used only four trials per comparison. For a truly accurate measurement, hundreds of trials per comparison would have been ideal (Gescheider, 1985). The Weber fractions generated by this study should be considered only as rough estimates.

### 5.4 Absolute Error

#### 5.4.1 Overshoot or Undershoot

The hypothesis tests performed on the absolute error indicate that subjects consistently undershot the target, regardless of load level, target distance, or apparent size. In addition, the underestimation increased as the load increased. There are two possible explanations of the undershooting behavior. First, undershooting may be an inherent trend in human behavior. When faced with a pushing task based on inertial cues, humans initially apply less force than needed. This behavior may be a mental safety mechanism used to prevent injury from overexertion or to prevent the undesirable consequences which usually seem to accompany errors of overexertion (e.g., pushing a cart too fast or too far causing it to crash into someone or something; pushing a handle too hard and breaking it, etc.).

The second explanation is that undershooting is an artificial effect introduced by the experimental task or the experimental apparatus. The study performed by Woldstad et al. (1988) suggested isolating the initial push would indicate overestimations of the force required to push an inertial load. A possible explanation of the contradicting results generated by this study involves the experimental task. In the Woldstad et al. study, subjects never released the load after pushing it. Subjects, therefore, may have been more willing to provide greater initial exertions since they could easily correct for an overexertion by pulling back on the load. The push/aim task did not afford the opportunity to correct for an overexertion since subjects released the load immediately following the initial push. Without the ability to correct for possible overexertions, subjects may have compensated by erring on the conservative side. Another explanation might be that subjects actually underexert during the initial stage of the Woldstad et al. task, but immediately sense the underestimation of the force. Since they do not release the load, they adjust the exertion but overcompensate their correction.

The presence of frictional resistance in the experimental apparatus may have also contributed to the undershooting effect. Subjects were told the apparatus minimized

frictional resistance, a fact which was emphasized out of fear that they would not fully realize they were dealing with inertial loads. Subjects may have actually overestimated how much frictional resistance was removed. Anecdotal evidence supporting this possibility occurred during the practice pushes. Eleven out of the twelve subjects undershot the target on their first practice push by at least one meter. In addition, the majority continued to undershoot the target on the final two practice pushes. Subjects seemed to expect the cart to roll much longer than it actually did.

#### 5.4.2 Effects of Independent Variables on Absolute Error

The ANOVA based on the absolute error dependent measure identifies the main effects of weight and distance, and the interaction of weight and distance as significant. A simple interpretation of the weight effect is as mass increases, subjects increasingly undershoot the target. It appears that for a given increase in force requirement, the increase in force applied is less.

The effect of distance also indicates a decreasing ratio of applied force to required force for the task. Here, the longer distance increases the required force to reach the target. A longer undershoot associated with the longer distance is, therefore, expected.

A tendency toward safe behavior probably causes the increased undershooting. The larger force requirements require higher exertions and are, therefore, more dangerous. Although exertions must rise to meet the higher force requirements, the body responds by decreasing the ratio of force exerted to the actual force required.

The weight x distance interaction provides some insight into the relationship between the weight and distance effects. Weight and distance increase the force required in different ways. The basic equation,  $F = ma$  (force is equal to the product of mass and

acceleration), explains this difference. In the weight effect, larger force requirements are directly due to an increased load (i.e., mass). The distance effect affects the acceleration component in a more indirect manner. To reach a target at a greater distance, the trolley velocity must be increased, which in turn requires an increase in the acceleration requirement. The increased acceleration requirement then increases the force requirement.

The interaction shows that at the 2 m distance, the greatest absolute error occurs at the 90 kg level, followed by the 45 kg level, and then the 25 kg level, which is expected. At the 6 m distance, overall absolute error increases, as expected. However, the relationship between the weight levels changes. The greatest absolute error still occurs at 90 kg, but the absolute error at the 45 kg and 25 kg levels remain statistically the same.

One possible explanation for the change in relationship between absolute error and weight level may be related to the high levels of exertions required by the 90 kg level. Increasing the target distance to 6 m raises the required force exertions even more. At such high levels of force, an asymptotic level of absolute error may have been achieved. Greater differences in force requirements may be needed to create significant increases in error. Another possibility is that the effect of increasing distance is dominant over (or more important than) the effect of increasing weight. It further implies that absolute error is more dependent on acceleration or velocity requirements than on load level requirements.

The chance that the increasing undershoot associated with increasing load is not a natural behavior must also be considered. Again, frictional resistance in the experimental apparatus may play a role. Specifically, the rolling resistance of the trolley wheels is believed to increase with the load. Consider Figure 5.1.

The variables are defined as follows (Beer and Johnston, 1988):

$W$  = load

$P$  = force applied to wheel to keep it a constant speed

$R$  = resultant of the forces exerted by the ground on the wheel over the area which occurs at point B (this area is the contact area between the wheel and ground from deformation of both)

$O$  = center of wheel

$b$  = distance between  $O$  and  $B$ , known as the coefficient of rolling resistance

$r$  = radius of wheel

The relationship is defined in equation 5.1 (Beer and Johnston, 1988):

$$Pr = Wb \quad (5.1)$$

The trolley wheels were made of a plastic material and the rails of aluminum. With trolley weight ranging from 25 kg to 90 kg, a significant difference in the value of "b" due to differences in the deformation of the wheels and/or the aluminum tracks could be expected at the different weight levels. The higher "b" at the highest weight level would increase the rolling resistance. Subjects would be expected to account for the increased requirement of  $P$  as  $W$  increases; however, they may not account for the simultaneous increase of "b."

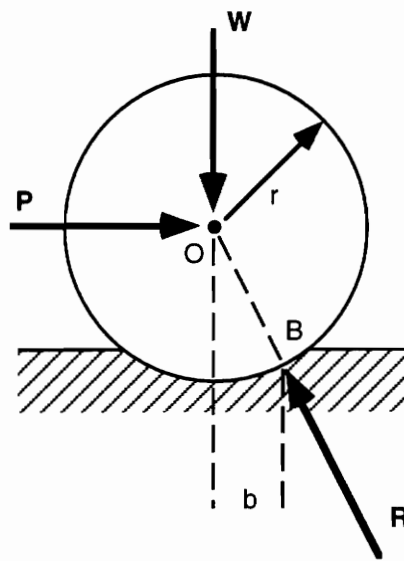


Figure 5.1 Rolling Resistance Diagram  
(from Beer and Johnston, 1988)

## 5.5 Relative Error

### 5.5.1 Significance of Relative Error

The basic hypothesis tests indicate relative error associated with the push/aim task was significant. In other words, using statistical significance as the criterion, subjects did not execute the push/aim task in an accurate manner with respect to relative error. The applicability of this information is fairly limited. The specific values generated can only be applied to the specific conditions involved in this study.

### 5.5.2 Effects of Independent Variables on Relative Error

The ANOVA based on the relative error dependent variable indicates a significant effect from distance. The increasing relative error associated with the higher distance seems indicative of rapid-aimed movement behavior. Rapid-aimed movement theory predicts an increasing variability as movement velocity increases which is what occurs in the experimental situation (Meyer, et al. 1990). The increased distance requires a higher velocity of movement and results in greater relative error.

It does not seem unreasonable to expect increased force requirements from higher loads to increase relative error, but the effect of weight was not significant. The presence of a distance effect and the absence of a weight effect indicates again the importance of acceleration or velocity rather than mass in the resulting error associated with the

push/aim task. More specifically, the rate of force production seems to have a greater influence than the level of force production on relative error in the push/aim task.

The interaction between weight and distance based on the relative error dependent measure is examined in Figure 5.1. Groupings are defined as follows: group "A" was not significantly different than group "B"; group "B" was not significantly different than group "C"; but, group "A" was significantly different than group "C." It might be expected that the interaction would be significant, but it was not. Studying the weight and distance interaction more closely reveals that weight has no effect on the amount of relative error at either distance level. The only significant increase in relative error seems to be associated with the longest distance level (2 m) and the largest weight level (90 kg).

## 5.6 Velocity or Acceleration?

The interpretations of both the absolute error and relative error have implicated either acceleration or velocity requirements as the major factor affecting push/aim task performance. The study by Woldstad et al. (1988) described earlier gives evidence supporting the importance of velocity. The experimenters developed movement profiles of the subjects pushing the hoist device used in the experimental task. The experimental task was similar to the push/aim task except their subjects did not release the hoist. Instead, they continued to hold and push the hoist as they walked to a specific target. The push/aim task is basically the initial portion of the Woldstad et al. task. The movement profiles showed a relatively constant phenomenon involving velocity. Subject movement behavior seemed to be geared to achieve some constant velocity level before the point of deceleration (to stop the hoist movement). The achievement of the constant velocity level

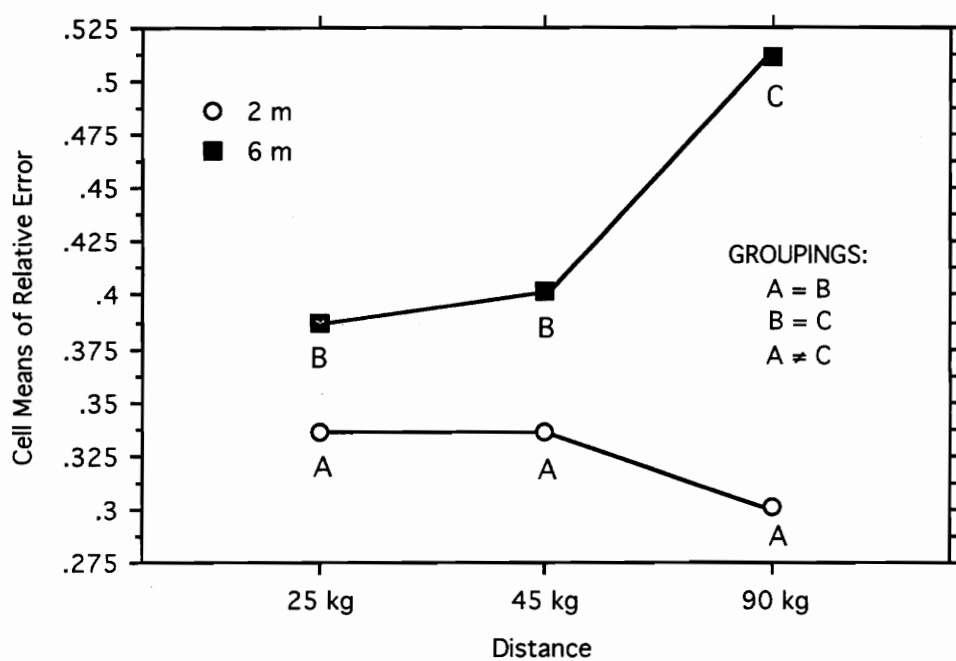


Figure 5.2 Interaction Plot of Weight x Distance

Dependent Variable: Relative Error

was unaffected by variations in frictional resistance, load level, or placement tolerance. The results of both the Woldstad et al. study and this study implicate the importance of velocity in the push/aim task.

## 5.7 Recommendations

Although the presence of frictional resistance may have contaminated the results with respect to "true" inertia perception, its existence probably increased the applicability of these results in the real world. The lift-assist devices discussed earlier fit into the situation of manipulating loads against reduced, but not removed, levels of frictional resistance.

- (i) Automate the initial push needed to generate movement in lift-assist devices by providing a mechanical impulse.

By mechanically providing the initial push, operators would be required only to maintain the device's momentum. It seems clear that the initial push of initial push of inertial loads is inaccurate. The best way to handle the problem is to eliminate it.

- (ii) Provide a brake.

Although the pull task was not studied, it seems appropriate to address the issue of stopping the device. Brake devices should utilize the hands or feet rather than the whole body (which stresses the back).

(iii) Inform operators of the unique situation (i.e., inertial loads) involved with manipulating lift-assist devices the best way to operate these devices.

Operators should be told that these lift devices incur a different set of problems than what is usually encountered in typical pushing situations. If they are aware of the potential dangers, it becomes easier to minimize dangerous behaviors. Furthermore, knowledge of why the problem exists may make operators more likely to follow suggested methods. For example, train operators to minimize their initial exertions and then slowly ramp up their exertion to an appropriate level. Explain to them that this is a good technique because the natural tendency is for people to push these objects too hard.

## 5.8 Further Research

The following list contains possible areas for further research.

(i) Utilize true inertial mass.

The question of true inertia judgment is still, technically, unanswered. The use of air-supported loads would better approach the true inertial situation.

(ii) Incorporate subjective measures.

It would be interesting to see if subjects are aware of their own performance. In other words, does a subject's own judgment of task performance correlate with actual performance.

iii) Adjust frictional resistance levels.

There may be some level of frictional resistance which optimizes performance in pushing tasks.

iv) Directly compare "push and release" to "push and maintain."

In other words, incorporate the push/aim task and the Woldstad et al. task (with special emphasis on the initial push) into one study with common subjects and see if opposing results are still generated.

v) Investigate velocity.

The importance of velocity should be studied. Could it be that human movement is based on achieving specific levels of velocity (as opposed to reaching a position in space, overcoming a resistant force, reaching a specific tension level, etc.)? Answers to this question could have interesting implications to the field of motor control.

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## **APPENDICES**

**APPENDIX A INSTRUCTIONS AND INFORMED CONSENT**

## **Dynamic Pushing Study Instructions for Experiment**

Thank you for participating in this study. It is being conducted by the Industrial Ergonomics Laboratory of the Human Factors Engineering Center at Virginia Tech. The experiment is being run by Rally Pagulayan as part of his Master's thesis work under the supervision of Dr. Jeff Woldstad, a professor in Industrial and Systems Engineering.

Two separate experiments make up this study, a mass discrimination test and a pushing/aiming test. You will complete the mass discrimination test today and then complete the pushing/aiming test on a separate day which will be scheduled following completion of today's session.

Both tests involve the manipulation of medium-sized loads on a floor-based trolley system. The trolley can move in a horizontal manner along a linear track system placed on the floor (i.e. back and forth). In addition, the trolley system has attempted to eliminate, as much as possible, any frictional resistance to the trolley's movement.

The mass discrimination test involves the comparison of two loads, one after another. You will be asked to indicate which load is greater. During these trials, you will be blindfolded to hide the size of the loads you will be testing. The experimenter will load the trolley to a specific weight level. Once the load is set, you will "test" the heaviness of the load. To "test" the load, you will grasp the handle of the trolley with both hands and move the trolley back and forth about six inches, one to five times. Effectively, you will be slowly shaking the trolley back and forth. The exact number of times you shake the load or the speed at which you shake it is up to you. After testing the first load, the experimenter will load the trolley to another specific weight level. You will "test" the second load and indicate to the experimenter which of the two loads seems greater. The process of testing the first load, the second load, and then indicating which is greater comprises a single trial. After 10 trials, you will be given a one minute break during which you may remove the blindfold. This session should last about 30 minutes.

The second session involves a pushing/aiming task. Basically, you will be shoving the trolley to a specified target. Specifically, you will supply an initial acceleration to the trolley so it can travel the rest of the way to the target under its own subsequent momentum. For each trial, the experimenter will load the trolley to a specific weight level and then ask you to "test" the load to gauge its heaviness. The "test" is identical to the one performed in the mass discrimination task. After testing the load, the experimenter will tell you which target you are aiming the trolley at. There are two possible targets, one 2.0 m away and another 6 m away. You are to try to get the center of the trolley to end up at the center of the target. After informing you of which target to shoot for, the experimenter will say "go" and you will shove the trolley (by the handle) to the target. During the push, your feet will be in a fixed position, shoulder width apart, one foot forward and one back. Following the push, you will then bring your rear foot forward in a "follow-through" motion. The goal is to have a transfer of weight from the rear leg to the front leg and then into the load. Immediately after you release the trolley, the experimenter will close the curtains positioned in front of the hoist system. This is done to eliminate visual feedback of how close the load comes to the target. The experimenter will record the accuracy of the push after and a new trial will begin. This session should last no more than one hour.

Both sessions should end up taking about 90 minutes. You will be paid at a rate of \$5 per hour and will receive payment after completing the second session.

Feel free to stop the experiment at any time to rest or to ask any questions. The weights involved in both sessions will range from 25 to 90 kg (50 - 200 lbs.) and a great amount of effort should not be involved. If, however, you feel you have strained yourself in anyway, or if you begin to feel any pain or abnormal discomfort, please inform the instructor immediately. If you need to withdraw from the experiment you will be paid for the time you have served in the experiment

The data from the experiment should be analyzed by the end of September, 1993. The results will be made available to you should you desire to review them. The research team members are:

Rally Pagulayan, Graduate Student, ISE  
Dr. Jeffrey Woldstad, Professor, ISE

If you have any questions or concerns about the way you have been treated during this experiment, please contact the chair of the institutional review board, research division at 231-6077.

Thank you again for your participation. We hope that you will enjoy your experience in this experiment.

# VIRGINIA POLYTECHNIC INSTITUTE AND STATE UNIVERSITY

## Informed Consent of Participants of Investigative Projects

Title of Project:           Determining the Human Ability to Judge Inertia during a Dynamic Pushing Task

Principle Investigator:       Ralindo M. Pagulayan

### **I. THE PURPOSE OF THIS RESEARCH/PROJECT**

You are invited to participate in a study about the ability of humans to judge inertial loads. This study involves experimentation for the purpose of determining how accurately typical humans apply acceleratory forces to loads when only inertial cues are present.

### **II. PROCEDURES**

The procedures to be used in this research are as follows: 1) You will be blindfolded and asked to slowly shake a load weighing between 24.3 and 35.7 kg (54 - 79 lbs.) back and forth in the horizontal plane. The load itself will be placed on a trolley. You will be allowed to remove the blindfold between each trial. 2) You will be asked to shove a load weighing between 25 and 90 kg (50 and 200 lbs.) to a target located either 2.0 or 6 m away from the starting position of the load. The trolley, which carries the load, travels on a track system and has been designed to eliminate as much frictional resistance to horizontal movement as possible. 3) The weights involved in the study should not require a strenuous effort. However, if you feel the load requires you to exceed your maximal safe effort, inform the experimenter immediately. You will not be asked by anyone associated with this experiment to exceed what you consider to be your maximum safe effort. The time and conditions required for you to participate in this project are a 30 minute session and a one-hour session, each completed on a separate day. The first session consists of 42 trials of slowly shaking the load back and forth. The second session consists of 48 aimed shoves to a target.

There are no foreseeable physical risks from participating in this study.

Safeguards that will be used to minimize your risk or discomfort are relatively low weight levels to be pushed against minimal frictional resistance (not more than 90 kg of load), relatively short distances to push the load (not more than 6 m), and your judgment of your maximum safe effort.

### **III. BENEFITS OF THIS PROJECT**

Your participation in the project will provide the following information that may be helpful. It addresses an area, the judgment of inertial loads, that has not been studied extensively. Previous studies have shown that the judgment of objects using only inertial cues is poorer than when both weight and inertial cues are utilized. However, most studies have concentrated on loads less than one pound. This study hopes to determine the type of error involved in the pushing of inertial loads for weights that would typically be found in industry.

No guarantee of benefits has been made to encourage you to participate.

You may receive a synopsis or summary of this research when completed. Please leave (or bring back) a self-addressed envelope.

**IV. EXTENT OF ANONYMITY AND CONFIDENTIALITY**

The results of this study will be kept strictly confidential. The information you provide will have your name removed and only a subject number will identify you during analyses and any written reports of the research.

**V. COMPENSATION**

Monetary

For participation in the project you will receive \$5 per hour for a total of \$7.50.

**VI. FREEDOM TO WITHDRAW**

You are free to withdraw from this study at any time without penalty. If you choose to withdraw, you will be compensated for the portion of the time of the study in which you participated.

There may be the following circumstances under which the investigator may determine that you should not continue as a subject of this project. These might include fatigue or discomfort. You will be compensated for the portion of the project completed.

**VII. APPROVAL OF RESEARCH**

This research project has been approved, as required, by the Institutional Review Board for projects involving human subjects at Virginia Polytechnic Institute and State University, by the Department of Industrial and Systems Engineering.

**VIII. SUBJECT'S RESPONSIBILITIES**

I know of no reason I cannot participate in this study. I have the following responsibility, to inform the experimenter if I feel overly fatigued or strained.

\_\_\_\_\_  
Signature

.....  
**IX. SUBJECT'S PERMISSION** (Tear off at dotted line and give to subject)

I have read and understand the informed consent and conditions of this project. I have had all my questions answered. I hereby acknowledge the above and give my voluntary consent for participation in this project.

If I participate, I may withdraw at any time without penalty. I agree to abide by the rules of this project.

Should I have any questions about this research or its conduct, I will contact:

|                                                      |          |
|------------------------------------------------------|----------|
| Ralindo M. Pagulayan, Principal Investigator         | 552-7506 |
| Dr. Jeffrey Woldstad, Faculty Advisor                | 231-4927 |
| Chair, Institutional Review Board, Research Division | 231-6077 |

**APPENDIX B LATIN SQUARES FOR PRESENTATION ORDER**

**Base Latin Square and Randomly Generated Latin Squares**

Table B.1 12 x 12 Latin Square from Fisher and Yates (1963)

|   |   |   |   |   |   |   |   |   |   |   |   |
|---|---|---|---|---|---|---|---|---|---|---|---|
| A | B | C | D | E | F | G | H | I | J | K | L |
| B | L | G | C | D | J | K | E | H | A | F | I |
| C | K | A | B | F | L | I | D | G | H | J | E |
| D | F | I | A | L | E | C | G | J | B | H | K |
| E | D | F | G | J | K | A | L | C | I | B | H |
| F | H | K | E | G | C | D | B | A | L | I | J |
| G | I | D | F | K | H | J | A | L | C | E | B |
| H | E | L | J | C | A | B | I | K | D | G | F |
| I | J | B | L | H | G | F | K | D | E | A | C |
| J | C | E | K | A | I | H | F | B | G | L | D |
| K | G | J | H | I | B | L | C | E | F | D | A |
| L | A | H | I | B | D | E | J | F | K | C | G |

Table B.2 Latin Square 1

| <u>1</u> | <u>2</u> | <u>3</u> | <u>4</u> | <u>5</u> | <u>6</u> | <u>7</u> | <u>8</u> | <u>9</u> | <u>10</u> | <u>11</u> | <u>12</u> |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|-----------|-----------|
| 6        | 3        | 12       | 10       | 4        | 1        | 11       | 5        | 8        | 7         | 9         | 2         |
| 9        | 7        | 10       | 4        | 1        | 5        | 2        | 12       | 6        | 11        | 8         | 3         |
| 2        | 6        | 5        | 3        | 9        | 11       | 12       | 1        | 4        | 10        | 7         | 8         |
| 3        | 1        | 8        | 6        | 10       | 7        | 4        | 9        | 11       | 5         | 2         | 12        |
| 10       | 12       | 7        | 8        | 5        | 6        | 1        | 11       | 9        | 2         | 3         | 4         |
| 11       | 8        | 2        | 12       | 7        | 10       | 6        | 3        | 1        | 9         | 4         | 5         |
| 8        | 2        | 11       | 5        | 3        | 4        | 9        | 7        | 12       | 1         | 10        | 6         |
| 7        | 5        | 1        | 11       | 6        | 8        | 10       | 4        | 2        | 3         | 12        | 9         |
| 4        | 11       | 9        | 2        | 8        | 3        | 5        | 6        | 7        | 12        | 1         | 10        |
| 5        | 4        | 3        | 1        | 12       | 9        | 8        | 2        | 10       | 6         | 11        | 7         |
| 1        | 10       | 6        | 9        | 2        | 12       | 7        | 8        | 3        | 4         | 5         | 11        |
| 12       | 9        | 4        | 7        | 11       | 2        | 3        | 10       | 5        | 8         | 6         | 1         |

Table B3 Latin Square 2

| <u>1</u> | <u>2</u> | <u>3</u> | <u>4</u> | <u>5</u> | <u>6</u> | <u>7</u> | <u>8</u> | <u>9</u> | <u>10</u> | <u>11</u> | <u>12</u> |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|-----------|-----------|
| 4        | 9        | 2        | 12       | 6        | 5        | 7        | 3        | 1        | 10        | 8         | 11        |
| 3        | 12       | 9        | 4        | 1        | 10       | 11       | 5        | 2        | 8         | 6         | 7         |
| 11       | 5        | 1        | 10       | 9        | 6        | 2        | 4        | 12       | 7         | 3         | 8         |
| 6        | 8        | 4        | 11       | 7        | 2        | 5        | 1        | 10       | 3         | 12        | 9         |
| 10       | 7        | 6        | 8        | 3        | 11       | 1        | 2        | 4        | 9         | 5         | 12        |
| 1        | 2        | 8        | 5        | 10       | 7        | 3        | 9        | 11       | 12        | 4         | 6         |
| 8        | 11       | 5        | 1        | 12       | 9        | 4        | 10       | 7        | 6         | 2         | 3         |
| 2        | 3        | 12       | 6        | 4        | 1        | 9        | 11       | 8        | 5         | 7         | 10        |
| 7        | 1        | 11       | 9        | 5        | 12       | 8        | 6        | 3        | 4         | 10        | 2         |
| 12       | 6        | 3        | 2        | 8        | 4        | 10       | 7        | 9        | 1         | 11        | 5         |
| 5        | 4        | 10       | 7        | 2        | 3        | 12       | 8        | 6        | 11        | 9         | 1         |
| 9        | 10       | 7        | 3        | 11       | 8        | 6        | 12       | 5        | 2         | 1         | 4         |

Table B4 Latin Square 3

| <u>1</u> | <u>2</u> | <u>3</u> | <u>4</u> | <u>5</u> | <u>6</u> | <u>7</u> | <u>8</u> | <u>9</u> | <u>10</u> | <u>11</u> | <u>12</u> |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|-----------|-----------|
| 9        | 10       | 8        | 3        | 1        | 6        | 4        | 5        | 11       | 7         | 12        | 2         |
| 1        | 2        | 3        | 5        | 7        | 11       | 6        | 12       | 10       | 9         | 8         | 4         |
| 2        | 12       | 4        | 9        | 10       | 7        | 5        | 11       | 3        | 8         | 6         | 1         |
| 11       | 5        | 7        | 1        | 8        | 2        | 10       | 6        | 12       | 3         | 4         | 9         |
| 12       | 7        | 2        | 6        | 9        | 10       | 8        | 1        | 4        | 5         | 11        | 3         |
| 5        | 4        | 1        | 8        | 6        | 3        | 12       | 9        | 2        | 11        | 7         | 10        |
| 7        | 3        | 12       | 4        | 11       | 8        | 1        | 2        | 5        | 10        | 9         | 6         |
| 6        | 11       | 5        | 10       | 12       | 4        | 9        | 7        | 1        | 2         | 3         | 8         |
| 8        | 6        | 11       | 12       | 4        | 5        | 3        | 10       | 9        | 1         | 2         | 7         |
| 10       | 8        | 9        | 2        | 5        | 12       | 7        | 3        | 6        | 4         | 1         | 11        |
| 3        | 9        | 6        | 7        | 2        | 1        | 11       | 4        | 8        | 12        | 10        | 5         |
| 4        | 1        | 10       | 11       | 3        | 9        | 2        | 8        | 7        | 6         | 5         | 12        |

Table B5 Latin Square 4

| <u>1</u> | <u>2</u> | <u>3</u> | <u>4</u> | <u>5</u> | <u>6</u> | <u>7</u> | <u>8</u> | <u>9</u> | <u>10</u> | <u>11</u> | <u>12</u> |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|-----------|-----------|
| 5        | 8        | 9        | 11       | 12       | 7        | 6        | 1        | 2        | 4         | 3         | 10        |
| 11       | 9        | 3        | 12       | 8        | 10       | 5        | 6        | 7        | 2         | 4         | 1         |
| 7        | 5        | 1        | 6        | 3        | 12       | 4        | 2        | 8        | 10        | 9         | 11        |
| 4        | 2        | 12       | 10       | 9        | 6        | 11       | 8        | 5        | 7         | 1         | 3         |
| 6        | 7        | 11       | 4        | 2        | 3        | 8        | 12       | 10       | 1         | 5         | 9         |
| 8        | 4        | 2        | 7        | 5        | 9        | 10       | 3        | 1        | 11        | 12        | 6         |
| 3        | 6        | 4        | 1        | 10       | 11       | 2        | 5        | 12       | 9         | 7         | 8         |
| 1        | 12       | 6        | 2        | 7        | 5        | 3        | 10       | 9        | 8         | 11        | 4         |
| 10       | 1        | 5        | 3        | 11       | 8        | 9        | 7        | 4        | 12        | 6         | 2         |
| 2        | 11       | 8        | 5        | 1        | 4        | 7        | 9        | 3        | 6         | 10        | 12        |
| 12       | 10       | 7        | 9        | 6        | 2        | 1        | 4        | 11       | 3         | 8         | 5         |
| 9        | 3        | 10       | 8        | 4        | 1        | 12       | 11       | 6        | 5         | 2         | 7         |

**APPENDIX C WEBER FRACTION CALCULATIONS**

Subject 1

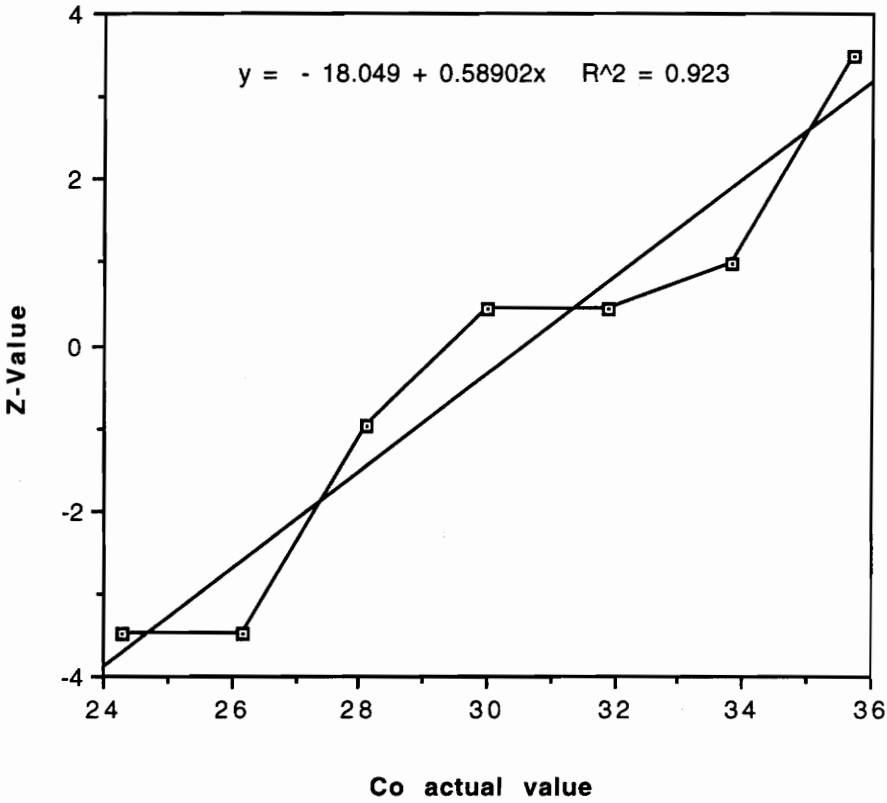


Figure C.1 Co Value vs. Z-Value Graph, Subject 1

## Subject 2

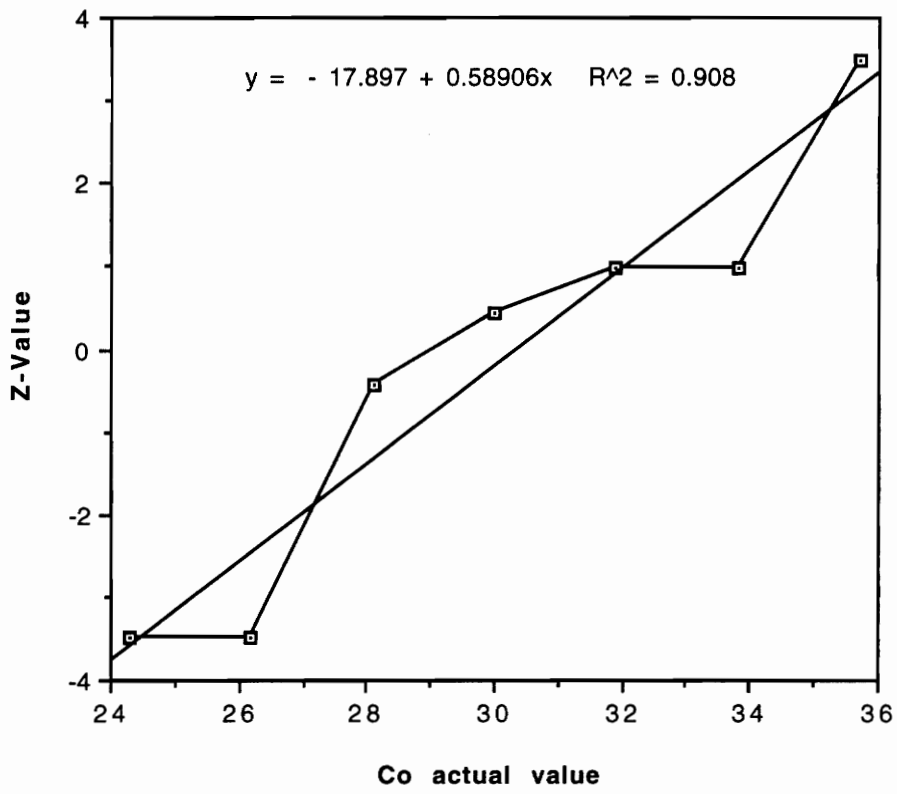


Figure C.2 Co Value vs. Z-Value Graph, Subject 2

**Subject 3**

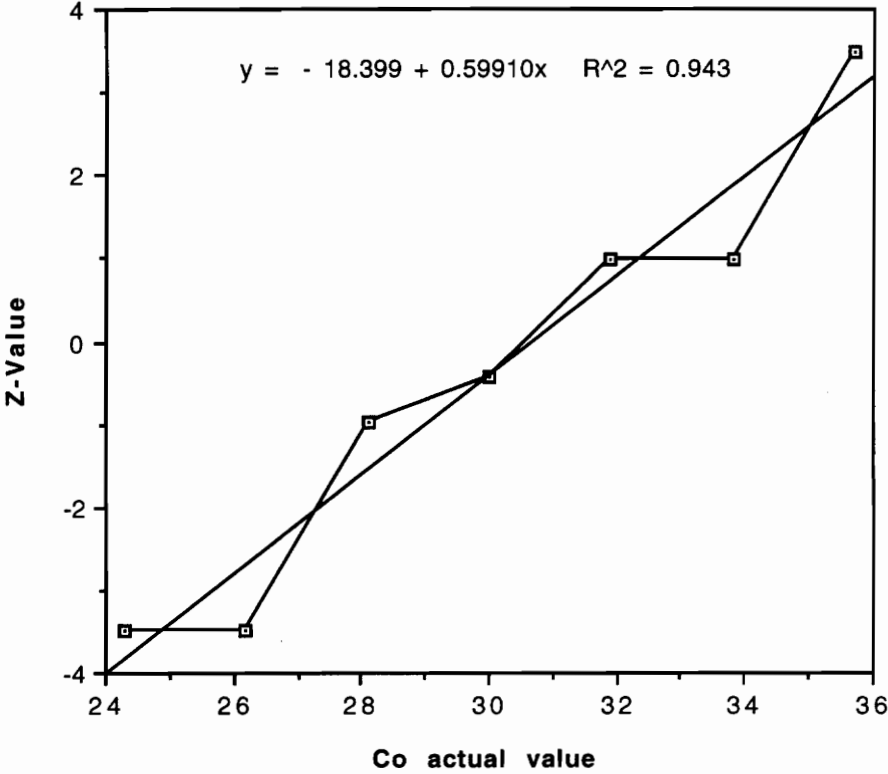


Figure C.3 Co Value vs. Z-Value Graph, Subject 3

**Subject 4**

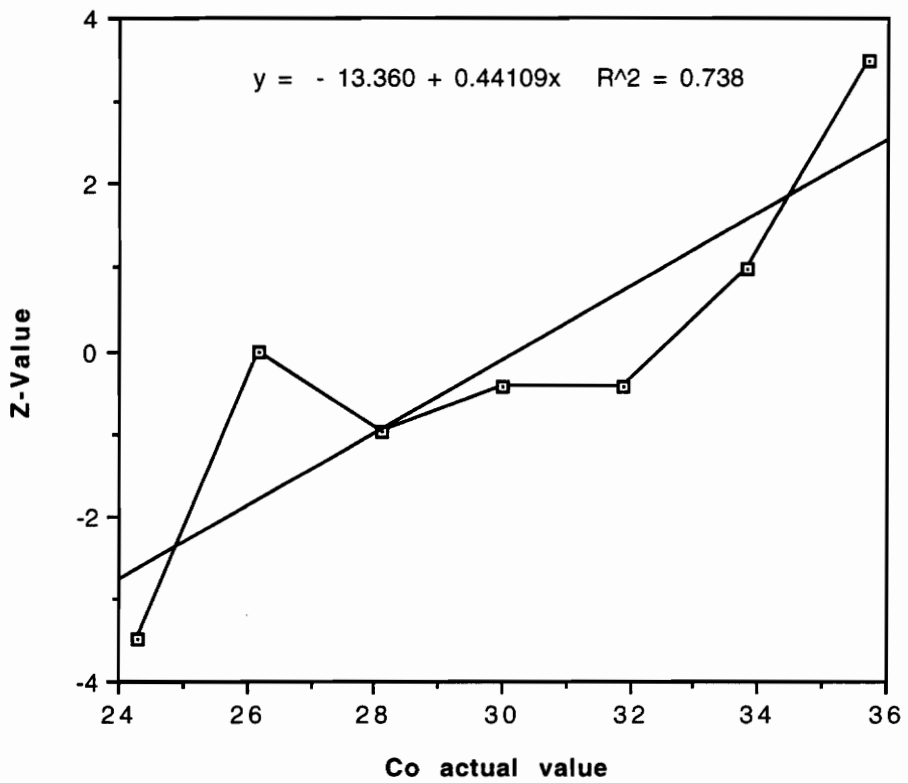


Figure C.4 Co Value vs. Z-Value Graph, Subject 4

### Subject 5

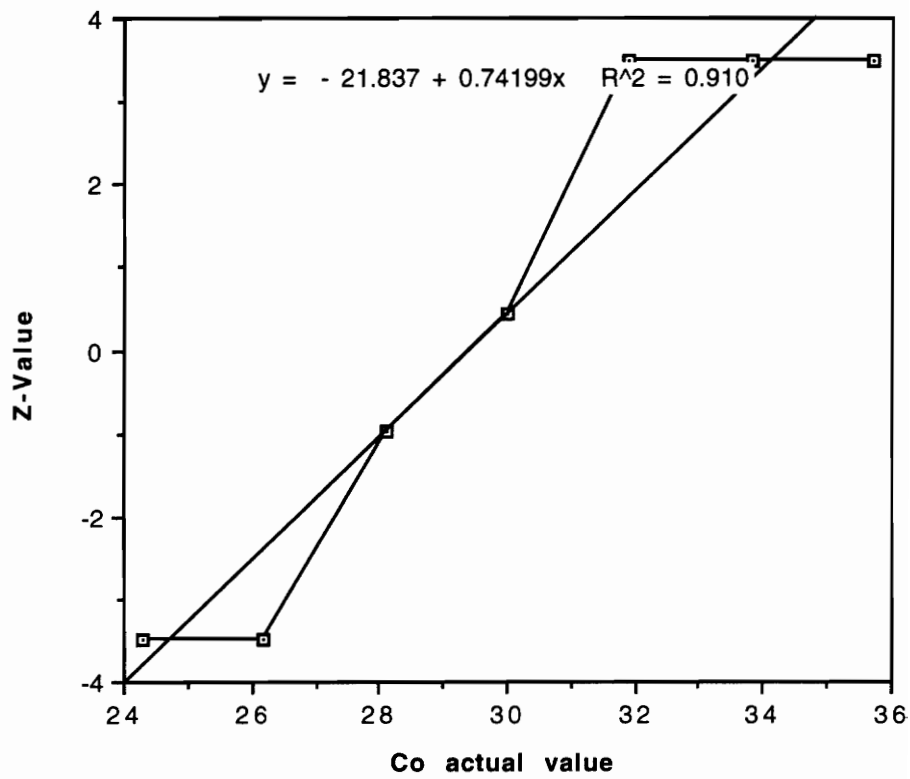


Figure C.5 Co Value vs. Z-Value Graph, Subject 5

**Subject 6**

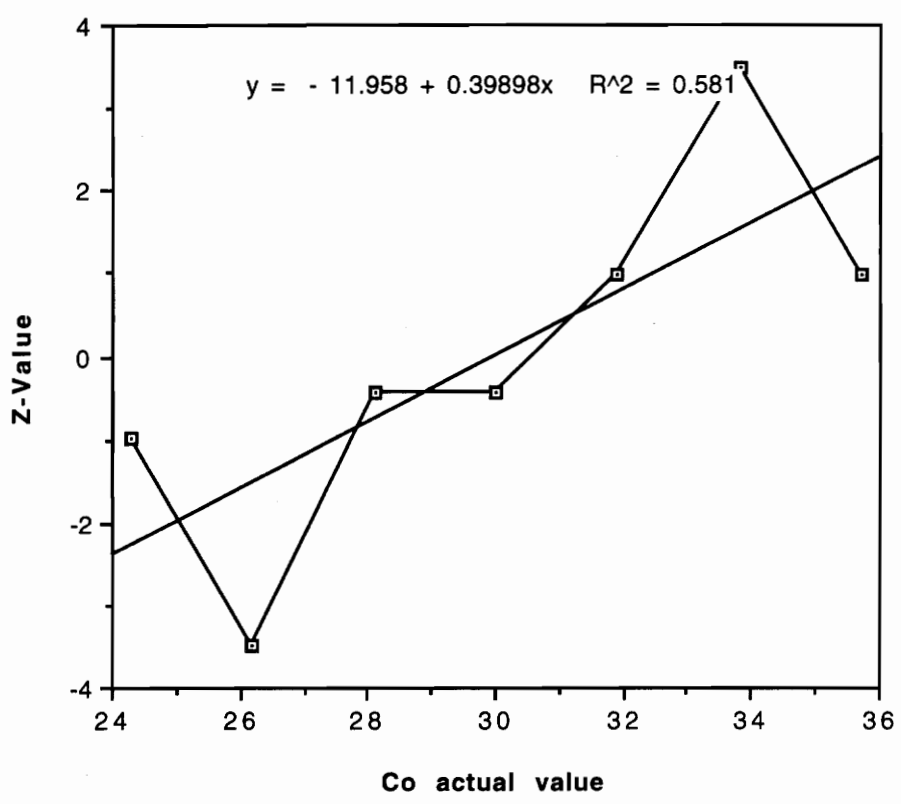


Figure C.6 Co Value vs. Z-Value Graph, Subject 6

### Subject 7

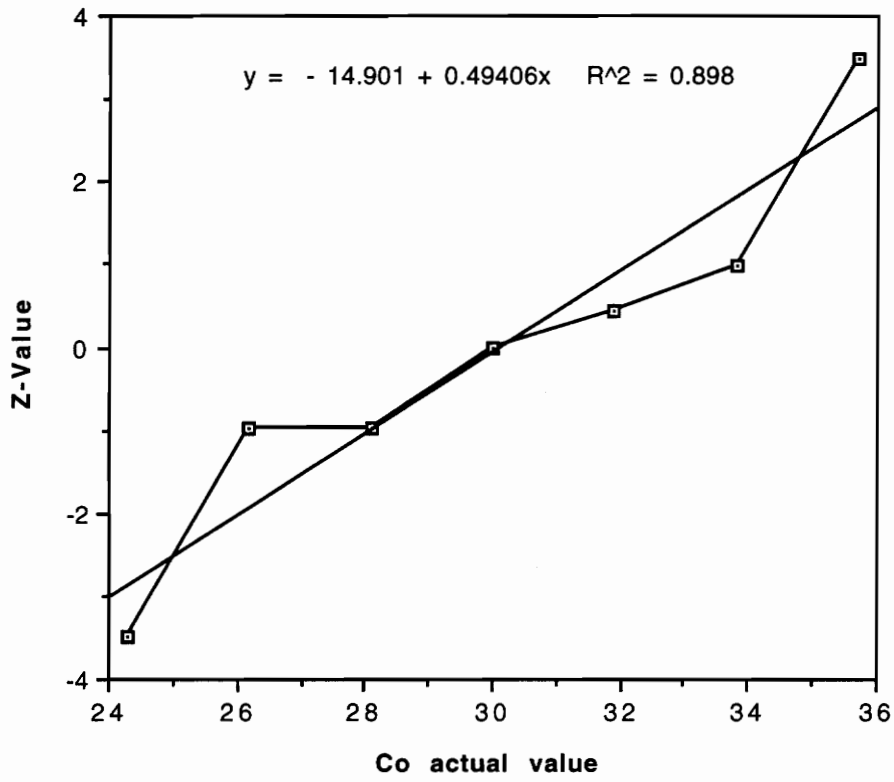


Figure C.7 Co Value vs. Z-Value Graph, Subject 7

Subject 8

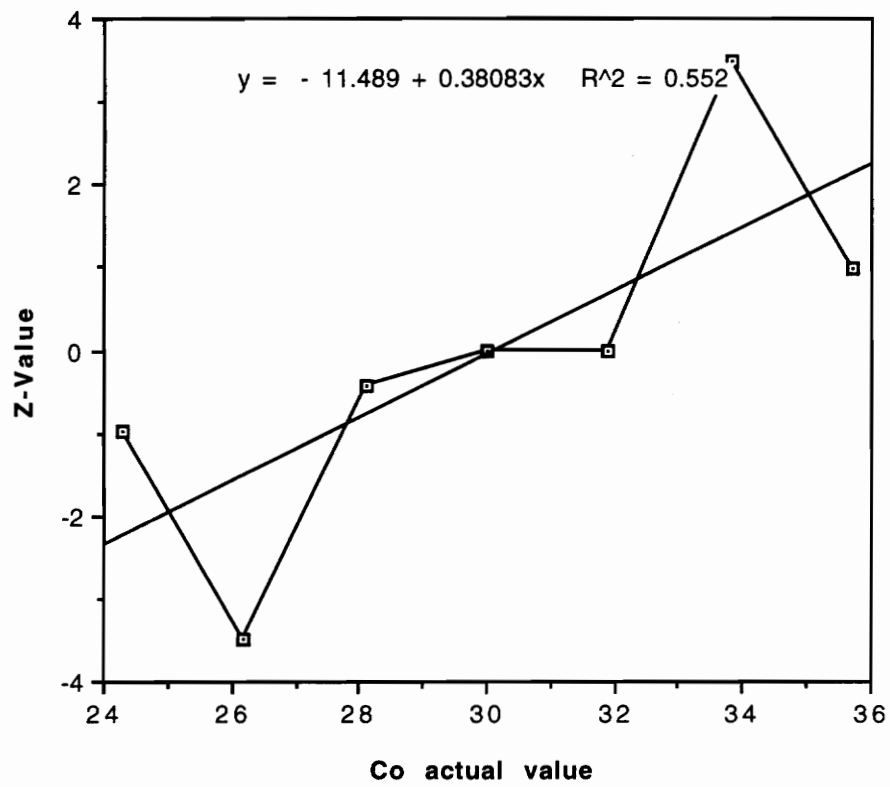


Figure C.8 Co Value vs. Z-Value Graph, Subject 8

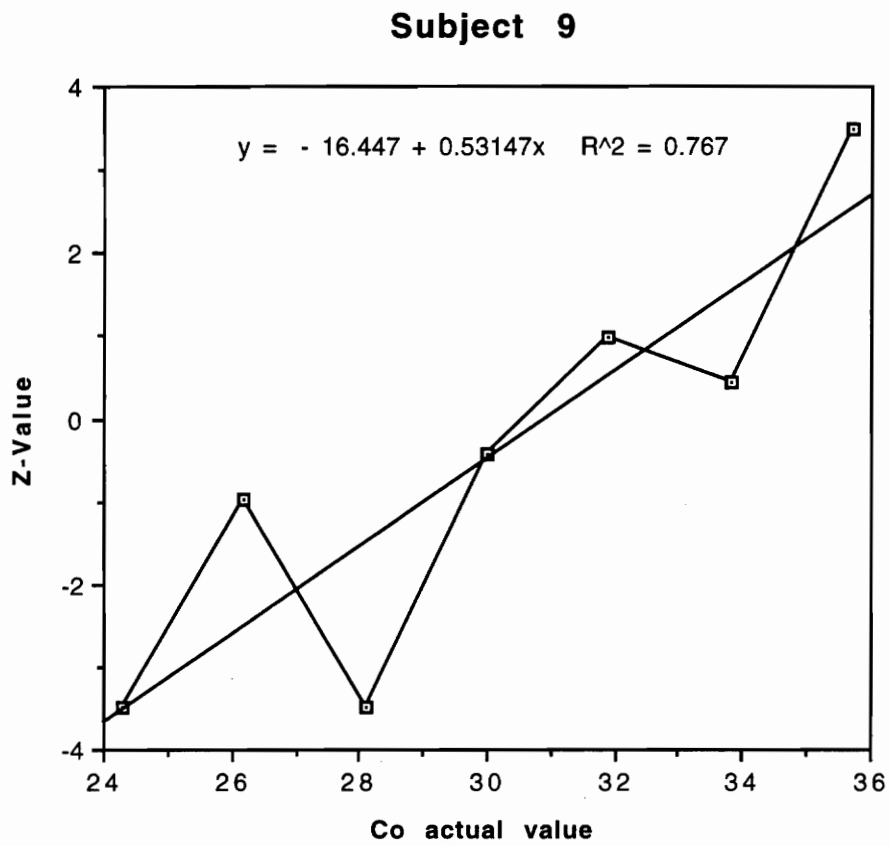


Figure C.9 Co Value vs. Z-Value Graph, Subject 9

### Subject 10

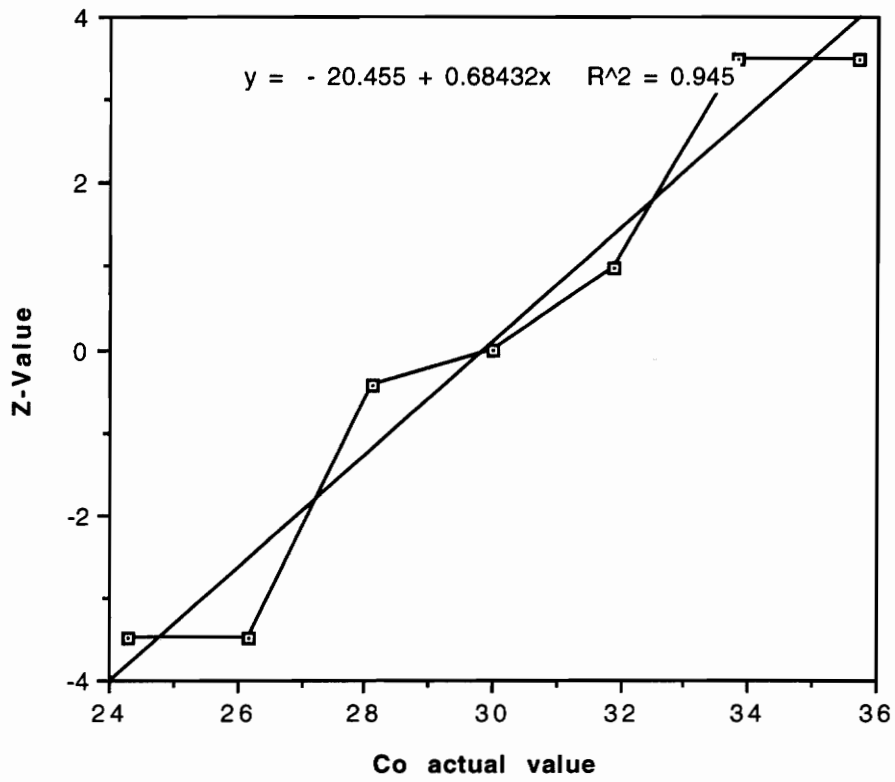


Figure C.10 Co Value vs. Z-Value Graph, Subject 10

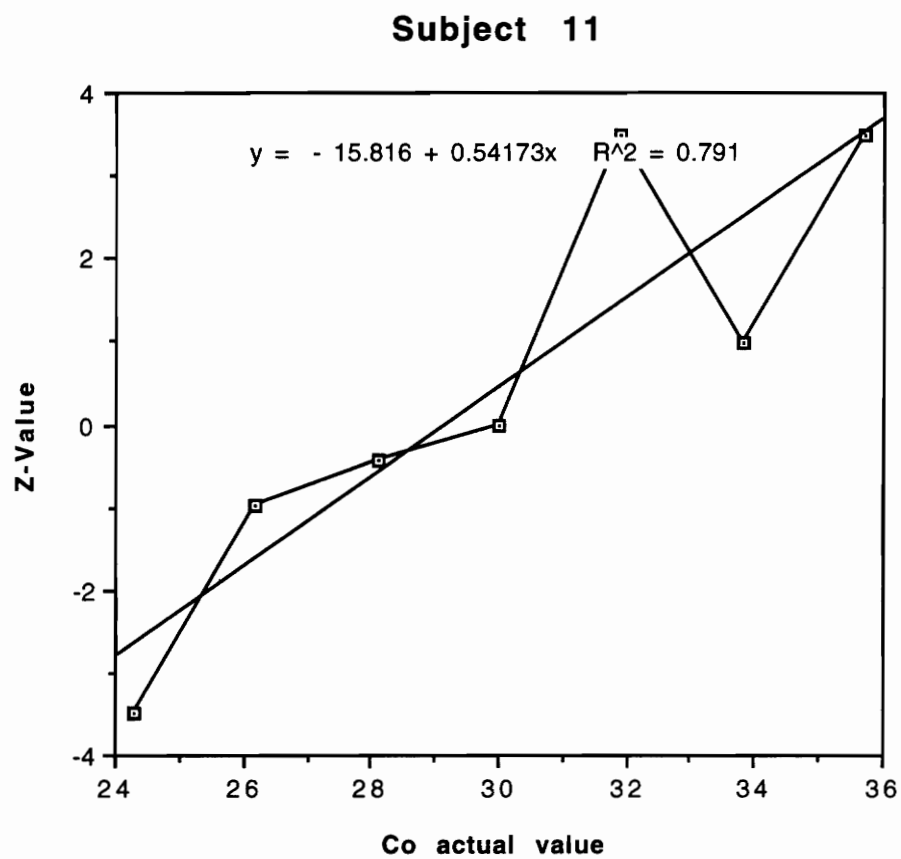


Figure C.11 Co Value vs. Z-Value Graph, Subject 11

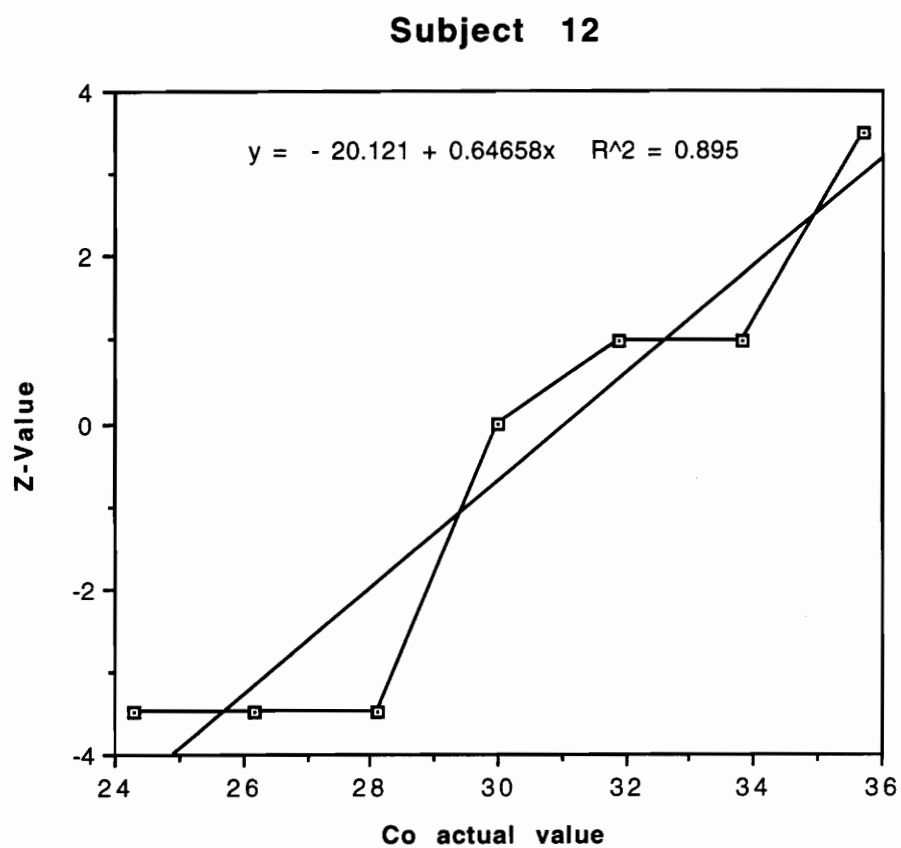


Figure C.12 Co Value vs. Z-Value Graph, Subject 12

Table C1 Weber Fraction Calculations

| Subject | equation: $Co(z)=$  | Co(.75) | Co(.50) | Co(.25) | DLu   | DLI   | DL                    | Weber fraction |
|---------|---------------------|---------|---------|---------|-------|-------|-----------------------|----------------|
|         |                     |         |         |         |       |       | $\frac{(DLu-DLI)}{2}$ | DL/PSE         |
| 1       | $(z+18.049)/.58902$ | 31.78   | 30.642  | 29.505  | 1.137 | 1.137 | 1.137                 | 0.037          |
| 2       | $(z+17.897)/.58906$ | 31.52   | 30.382  | 29.245  | 1.137 | 1.137 | 1.137                 | 0.037          |
| 3       | $(z+18.399)/.5991$  | 31.829  | 30.711  | 29.593  | 1.118 | 1.118 | 1.118                 | 0.036          |
| 4       | $(z+13.36)/.44109$  | 31.808  | 30.289  | 28.77   | 1.519 | 1.519 | 1.519                 | 0.050          |
| 5       | $(z+21.837)/.74199$ | 30.333  | 29.43   | 28.527  | 0.903 | 0.903 | 0.903                 | 0.031          |
| 6       | $(z+11.958)/.39898$ | 31.651  | 29.971  | 28.292  | 1.679 | 1.679 | 1.679                 | 0.056          |
| 7       | $(z+14.901)/.49406$ | 31.516  | 30.16   | 28.804  | 1.356 | 1.356 | 1.356                 | 0.045          |
| 8       | $(z+11.489)/.38083$ | 31.928  | 30.168  | 28.409  | 1.759 | 1.759 | 1.759                 | 0.058          |
| 9       | $(z+16.447)/.53147$ | 32.207  | 30.946  | 29.686  | 1.261 | 1.261 | 1.260                 | 0.041          |
| 10      | $(z+20.455)/.68432$ | 30.87   | 29.891  | 28.912  | 0.979 | 0.979 | 0.979                 | 0.033          |
| 11      | $(z+15.816)/.54173$ | 30.432  | 29.195  | 27.959  | 1.237 | 1.237 | 1.237                 | 0.042          |
| 12      | $(z+20.121)/.64658$ | 32.155  | 31.119  | 30.083  | 1.036 | 1.036 | 1.036                 | 0.033          |

$$DLu = Co(.75) - Co(.50)$$

$$DLI = Co(.50) - Co(.25)$$

**APPENDIX D PAIRED COMPARISON TABLES**

Table D1 Paired Comparisons of Weight Levels: Absolute Error  
 Post-Hoc Test: Newman-Keuls Test

|       | Vs.   | Diff. | Significant? |
|-------|-------|-------|--------------|
| 25 kg | 45 kg | .052  | no           |
|       | 90 kg | .349  | yes          |
| 45 kg | 90 kg | .296  | yes          |

Table D2 Paired Comparisons of Weight x Distance Levels: Absolute Error  
 Post-Hoc Test: Newman-Keuls Test

|            | Vs.        | Diff.  | Significant? |
|------------|------------|--------|--------------|
| 25 kg, 2 m | 25 kg, 6 m | 1.681  | yes          |
|            | 45 kg, 2 m | .140   | no           |
|            | 45 kg, 6 m | 1.646  | yes          |
|            | 90 kg, 2 m | .483   | yes          |
|            | 90 kg, 6 m | 1.896  | yes          |
| 25 kg, 6 m | 45 kg, 2 m | -1.541 | yes          |
|            | 45 kg, 6 m | -.035  | no           |
|            | 90 kg, 2 m | -1.199 | yes          |
|            | 90 kg, 6 m | .215   | yes          |
| 45 kg, 2 m | 45 kg, 6 m | 1.506  | yes          |
|            | 90 kg, 2 m | .343   | yes          |
|            | 90 kg, 6 m | 1.756  | yes          |
| 45 kg, 6 m | 90 kg, 2 m | -1.163 | yes          |
|            | 90 kg, 6 m | .250   | yes          |
| 90 kg, 2 m | 90 kg, 6 m | 1.414  | yes          |

Table D3 Paired Comparisons of Weight x Distance Levels  
Relative Error Least Squares Means

|          | Vs.      | Diff. | Std. Error | t-Test | P-Value |
|----------|----------|-------|------------|--------|---------|
| kg25, m2 | kg25, m6 | -.055 | .070       | -.791  | .4373   |
|          | kg45, m2 | -.002 | .070       | -.032  | .9751   |
|          | kg45, m6 | -.072 | .070       | -1.042 | .3087   |
|          | kg90, m2 | .029  | .070       | .418   | .6803   |
|          | kg90, m6 | -.178 | .070       | -2.558 | .0179   |
| kg25, m6 | kg45, m2 | .053  | .070       | .760   | .4555   |
|          | kg45, m6 | -.017 | .070       | -.251  | .8043   |
|          | kg90, m2 | .084  | .070       | 1.209  | .2396   |
|          | kg90, m6 | -.123 | .070       | -1.767 | .0911   |
| kg45, m2 | kg45, m6 | -.070 | .070       | -1.010 | .3233   |
|          | kg90, m2 | .031  | .070       | .449   | .6577   |
|          | kg90, m6 | -.176 | .070       | -2.527 | .0192   |
| kg45, m6 | kg90, m2 | .102  | .070       | 1.460  | .1585   |
|          | kg90, m6 | -.105 | .070       | -1.516 | .1437   |
| kg90, m2 | kg90, m6 | -.207 | .070       | -2.976 | .0070   |

**APPENDIX E PUSH/AIM DATA**

Table E1 Experimental Push/Aim Data

| Subject | Weight | Distance | Apparent<br>Size | Absolute<br>Error |
|---------|--------|----------|------------------|-------------------|
| sub1    | 25 kg  | 2 m      | small            | 0.77              |
| sub1    | 25 kg  | 2 m      | small            | -0.1              |
| sub1    | 25 kg  | 2 m      | small            | 0.49              |
| sub1    | 25 kg  | 2 m      | small            | 0.23              |
| sub1    | 25 kg  | 2 m      | large            | 0.11              |
| sub1    | 25 kg  | 2 m      | large            | 0.62              |
| sub1    | 25 kg  | 2 m      | large            | 0.07              |
| sub1    | 25 kg  | 2 m      | large            | 0.12              |
| sub1    | 25 kg  | 6 m      | small            | -0.77             |
| sub1    | 25 kg  | 6 m      | small            | -1.55             |
| sub1    | 25 kg  | 6 m      | small            | -1.03             |
| sub1    | 25 kg  | 6 m      | small            | -1.85             |
| sub1    | 25 kg  | 6 m      | large            | -1.54             |
| sub1    | 25 kg  | 6 m      | large            | -1.41             |
| sub1    | 25 kg  | 6 m      | large            | -1.22             |
| sub1    | 25 kg  | 6 m      | large            | -2.45             |
| sub1    | 45 kg  | 2 m      | small            | 0.26              |
| sub1    | 45 kg  | 2 m      | small            | 0.28              |
| sub1    | 45 kg  | 2 m      | small            | -0.09             |
| sub1    | 45 kg  | 2 m      | small            | 0.21              |
| sub1    | 45 kg  | 2 m      | large            | 0.5               |
| sub1    | 45 kg  | 2 m      | large            | 0.84              |
| sub1    | 45 kg  | 2 m      | large            | 0.17              |
| sub1    | 45 kg  | 2 m      | large            | 0.23              |
| sub1    | 45 kg  | 6 m      | small            | -1.64             |
| sub1    | 45 kg  | 6 m      | small            | -1.6              |
| sub1    | 45 kg  | 6 m      | small            | -2                |
| sub1    | 45 kg  | 6 m      | small            | -1.4              |
| sub1    | 45 kg  | 6 m      | large            | -1.18             |
| sub1    | 45 kg  | 6 m      | large            | -1.22             |
| sub1    | 45 kg  | 6 m      | large            | -1.67             |
| sub1    | 45 kg  | 6 m      | large            | -1.37             |
| sub1    | 90 kg  | 2 m      | small            | 0.36              |
| sub1    | 90 kg  | 2 m      | small            | 0.01              |
| sub1    | 90 kg  | 2 m      | small            | 0.02              |
| sub1    | 90 kg  | 2 m      | small            | 0.55              |
| sub1    | 90 kg  | 2 m      | large            | -0.13             |
| sub1    | 90 kg  | 2 m      | large            | 0.12              |
| sub1    | 90 kg  | 2 m      | large            | -0.15             |
| sub1    | 90 kg  | 2 m      | large            | -0.46             |
| sub1    | 90 kg  | 6 m      | small            | -1.88             |
| sub1    | 90 kg  | 6 m      | small            | -1.3              |
| sub1    | 90 kg  | 6 m      | small            | -2.18             |
| sub1    | 90 kg  | 6 m      | small            | -2.1              |
| sub1    | 90 kg  | 6 m      | large            | -0.6              |
| sub1    | 90 kg  | 6 m      | large            | -2.45             |

|      |       |     |       |       |
|------|-------|-----|-------|-------|
| sub1 | 90 kg | 6 m | large | -2.03 |
| sub1 | 90 kg | 6 m | large | -2.5  |
| sub2 | 25 kg | 2 m | small | -0.03 |
| sub2 | 25 kg | 2 m | small | -0.37 |
| sub2 | 25 kg | 2 m | small | -0.08 |
| sub2 | 25 kg | 2 m | small | 0.13  |
| sub2 | 25 kg | 2 m | large | -0.11 |
| sub2 | 25 kg | 2 m | large | 0.02  |
| sub2 | 25 kg | 2 m | large | 0.47  |
| sub2 | 25 kg | 2 m | large | -0.13 |
| sub2 | 25 kg | 6 m | small | -2.06 |
| sub2 | 25 kg | 6 m | small | -1.65 |
| sub2 | 25 kg | 6 m | small | -1.78 |
| sub2 | 25 kg | 6 m | small | -1.28 |
| sub2 | 25 kg | 6 m | large | -1.19 |
| sub2 | 25 kg | 6 m | large | -1.63 |
| sub2 | 25 kg | 6 m | large | -1.81 |
| sub2 | 25 kg | 6 m | large | -1.88 |
| sub2 | 45 kg | 2 m | small | -0.23 |
| sub2 | 45 kg | 2 m | small | -0.12 |
| sub2 | 45 kg | 2 m | small | 0.27  |
| sub2 | 45 kg | 2 m | small | -0.07 |
| sub2 | 45 kg | 2 m | large | 0.18  |
| sub2 | 45 kg | 2 m | large | -0.01 |
| sub2 | 45 kg | 2 m | large | 0.82  |
| sub2 | 45 kg | 2 m | large | -0.19 |
| sub2 | 45 kg | 6 m | small | -0.34 |
| sub2 | 45 kg | 6 m | small | -1.16 |
| sub2 | 45 kg | 6 m | small | -2.4  |
| sub2 | 45 kg | 6 m | small | -1.94 |
| sub2 | 45 kg | 6 m | large | -1.46 |
| sub2 | 45 kg | 6 m | large | -0.32 |
| sub2 | 45 kg | 6 m | large | -0.56 |
| sub2 | 45 kg | 6 m | large | -1.36 |
| sub2 | 90 kg | 2 m | small | 0.06  |
| sub2 | 90 kg | 2 m | small | -0.31 |
| sub2 | 90 kg | 2 m | small | -0.21 |
| sub2 | 90 kg | 2 m | small | -0.9  |
| sub2 | 90 kg | 2 m | large | -0.01 |
| sub2 | 90 kg | 2 m | large | -0.64 |
| sub2 | 90 kg | 2 m | large | -0.13 |
| sub2 | 90 kg | 2 m | large | -0.35 |
| sub2 | 90 kg | 6 m | small | -1.35 |
| sub2 | 90 kg | 6 m | small | -0.98 |
| sub2 | 90 kg | 6 m | small | -1.04 |
| sub2 | 90 kg | 6 m | small | -1.05 |
| sub2 | 90 kg | 6 m | large | -0.66 |
| sub2 | 90 kg | 6 m | large | -1.14 |
| sub2 | 90 kg | 6 m | large | -2.2  |
| sub2 | 90 kg | 6 m | large | -1.02 |
| sub3 | 25 kg | 2 m | small | -0.05 |

|      |       |     |       |       |
|------|-------|-----|-------|-------|
| sub3 | 25 kg | 2 m | small | 0.43  |
| sub3 | 25 kg | 2 m | small | 0.32  |
| sub3 | 25 kg | 2 m | small | 0.45  |
| sub3 | 25 kg | 2 m | large | -0.38 |
| sub3 | 25 kg | 2 m | large | 0.15  |
| sub3 | 25 kg | 2 m | large | 0.02  |
| sub3 | 25 kg | 2 m | large | 0.03  |
| sub3 | 25 kg | 6 m | small | -2.2  |
| sub3 | 25 kg | 6 m | small | -1.58 |
| sub3 | 25 kg | 6 m | small | -1.85 |
| sub3 | 25 kg | 6 m | small | -1.4  |
| sub3 | 25 kg | 6 m | large | -1.58 |
| sub3 | 25 kg | 6 m | large | -1.58 |
| sub3 | 25 kg | 6 m | large | -1.02 |
| sub3 | 25 kg | 6 m | large | -2.13 |
| sub3 | 45 kg | 2 m | small | 0.01  |
| sub3 | 45 kg | 2 m | small | -0.09 |
| sub3 | 45 kg | 2 m | small | -0.01 |
| sub3 | 45 kg | 2 m | small | 0     |
| sub3 | 45 kg | 2 m | large | -0.03 |
| sub3 | 45 kg | 2 m | large | 0.1   |
| sub3 | 45 kg | 2 m | large | -0.39 |
| sub3 | 45 kg | 2 m | large | 0.14  |
| sub3 | 45 kg | 6 m | small | -1.82 |
| sub3 | 45 kg | 6 m | small | -1.37 |
| sub3 | 45 kg | 6 m | small | -1.77 |
| sub3 | 45 kg | 6 m | small | -1.71 |
| sub3 | 45 kg | 6 m | large | -1.67 |
| sub3 | 45 kg | 6 m | large | -2.11 |
| sub3 | 45 kg | 6 m | large | -1.79 |
| sub3 | 45 kg | 6 m | large | -1.86 |
| sub3 | 90 kg | 2 m | small | -0.89 |
| sub3 | 90 kg | 2 m | small | -0.72 |
| sub3 | 90 kg | 2 m | small | -0.09 |
| sub3 | 90 kg | 2 m | small | -0.32 |
| sub3 | 90 kg | 2 m | large | -0.54 |
| sub3 | 90 kg | 2 m | large | -0.12 |
| sub3 | 90 kg | 2 m | large | -0.49 |
| sub3 | 90 kg | 2 m | large | -0.59 |
| sub3 | 90 kg | 6 m | small | -2.4  |
| sub3 | 90 kg | 6 m | small | -1.87 |
| sub3 | 90 kg | 6 m | small | -2.75 |
| sub3 | 90 kg | 6 m | small | -2.6  |
| sub3 | 90 kg | 6 m | large | -1.5  |
| sub3 | 90 kg | 6 m | large | -2.7  |
| sub3 | 90 kg | 6 m | large | -1.9  |
| sub3 | 90 kg | 6 m | large | -2.08 |
| sub4 | 25 kg | 2 m | small | 0.52  |
| sub4 | 25 kg | 2 m | small | -0.31 |
| sub4 | 25 kg | 2 m | small | -0.01 |
| sub4 | 25 kg | 2 m | small | 0.32  |

|      |       |     |       |       |
|------|-------|-----|-------|-------|
| sub4 | 25 kg | 2 m | large | 0.31  |
| sub4 | 25 kg | 2 m | large | 0.54  |
| sub4 | 25 kg | 2 m | large | 0.21  |
| sub4 | 25 kg | 2 m | large | -0.02 |
| sub4 | 25 kg | 6 m | small | -0.59 |
| sub4 | 25 kg | 6 m | small | -0.4  |
| sub4 | 25 kg | 6 m | small | -1.41 |
| sub4 | 25 kg | 6 m | small | -0.92 |
| sub4 | 25 kg | 6 m | large | -1.26 |
| sub4 | 25 kg | 6 m | large | -1.07 |
| sub4 | 25 kg | 6 m | large | -1.15 |
| sub4 | 25 kg | 6 m | large | -0.54 |
| sub4 | 45 kg | 2 m | small | 0.63  |
| sub4 | 45 kg | 2 m | small | 0.21  |
| sub4 | 45 kg | 2 m | small | 0     |
| sub4 | 45 kg | 2 m | small | 0.27  |
| sub4 | 45 kg | 2 m | large | -0.22 |
| sub4 | 45 kg | 2 m | large | 0.08  |
| sub4 | 45 kg | 2 m | large | 0.21  |
| sub4 | 45 kg | 2 m | large | 0.54  |
| sub4 | 45 kg | 6 m | small | -0.82 |
| sub4 | 45 kg | 6 m | small | -1.73 |
| sub4 | 45 kg | 6 m | small | -1.1  |
| sub4 | 45 kg | 6 m | small | -1.04 |
| sub4 | 45 kg | 6 m | large | -0.06 |
| sub4 | 45 kg | 6 m | large | -0.87 |
| sub4 | 45 kg | 6 m | large | -0.84 |
| sub4 | 45 kg | 6 m | large | -1.3  |
| sub4 | 90 kg | 2 m | small | -0.51 |
| sub4 | 90 kg | 2 m | small | -0.29 |
| sub4 | 90 kg | 2 m | small | 0.21  |
| sub4 | 90 kg | 2 m | small | 0.09  |
| sub4 | 90 kg | 2 m | large | -0.71 |
| sub4 | 90 kg | 2 m | large | -0.26 |
| sub4 | 90 kg | 2 m | large | 0.08  |
| sub4 | 90 kg | 2 m | large | -0.15 |
| sub4 | 90 kg | 6 m | small | -1.1  |
| sub4 | 90 kg | 6 m | small | -1.09 |
| sub4 | 90 kg | 6 m | small | -0.79 |
| sub4 | 90 kg | 6 m | small | -0.81 |
| sub4 | 90 kg | 6 m | large | -0.85 |
| sub4 | 90 kg | 6 m | large | -0.55 |
| sub4 | 90 kg | 6 m | large | -1.14 |
| sub4 | 90 kg | 6 m | large | -0.81 |
| sub5 | 25 kg | 2 m | small | -0.51 |
| sub5 | 25 kg | 2 m | small | 0.64  |
| sub5 | 25 kg | 2 m | small | 0.31  |
| sub5 | 25 kg | 2 m | small | -0.19 |
| sub5 | 25 kg | 2 m | large | 0.04  |
| sub5 | 25 kg | 2 m | large | -0.17 |
| sub5 | 25 kg | 2 m | large | -0.41 |

|      |       |     |       |       |
|------|-------|-----|-------|-------|
| sub5 | 25 kg | 2 m | large | 0.09  |
| sub5 | 25 kg | 6 m | small | -0.31 |
| sub5 | 25 kg | 6 m | small | -1.58 |
| sub5 | 25 kg | 6 m | small | -1.62 |
| sub5 | 25 kg | 6 m | small | -1.55 |
| sub5 | 25 kg | 6 m | large | -1.12 |
| sub5 | 25 kg | 6 m | large | -1.76 |
| sub5 | 25 kg | 6 m | large | -1.95 |
| sub5 | 25 kg | 6 m | large | -1.21 |
| sub5 | 45 kg | 2 m | small | 0.02  |
| sub5 | 45 kg | 2 m | small | -0.08 |
| sub5 | 45 kg | 2 m | small | -0.47 |
| sub5 | 45 kg | 2 m | small | -0.31 |
| sub5 | 45 kg | 2 m | large | 0.23  |
| sub5 | 45 kg | 2 m | large | -0.17 |
| sub5 | 45 kg | 2 m | large | -0.06 |
| sub5 | 45 kg | 2 m | large | -0.1  |
| sub5 | 45 kg | 6 m | small | -1.68 |
| sub5 | 45 kg | 6 m | small | -1.89 |
| sub5 | 45 kg | 6 m | small | -1.62 |
| sub5 | 45 kg | 6 m | small | -1.83 |
| sub5 | 45 kg | 6 m | large | -1.51 |
| sub5 | 45 kg | 6 m | large | -1.43 |
| sub5 | 45 kg | 6 m | large | -1.43 |
| sub5 | 45 kg | 6 m | large | -1.78 |
| sub5 | 90 kg | 2 m | small | -0.03 |
| sub5 | 90 kg | 2 m | small | -0.59 |
| sub5 | 90 kg | 2 m | small | -0.48 |
| sub5 | 90 kg | 2 m | small | -0.8  |
| sub5 | 90 kg | 2 m | large | -0.73 |
| sub5 | 90 kg | 2 m | large | -0.89 |
| sub5 | 90 kg | 2 m | large | -0.6  |
| sub5 | 90 kg | 2 m | large | -1    |
| sub5 | 90 kg | 6 m | small | -2.12 |
| sub5 | 90 kg | 6 m | small | -2.2  |
| sub5 | 90 kg | 6 m | small | -1.75 |
| sub5 | 90 kg | 6 m | small | -2.1  |
| sub5 | 90 kg | 6 m | large | -1.89 |
| sub5 | 90 kg | 6 m | large | -0.85 |
| sub5 | 90 kg | 6 m | large | -1.75 |
| sub5 | 90 kg | 6 m | large | -1.59 |
| sub6 | 25 kg | 2 m | small | 0.27  |
| sub6 | 25 kg | 2 m | small | -0.62 |
| sub6 | 25 kg | 2 m | small | 0.16  |
| sub6 | 25 kg | 2 m | small | -0.7  |
| sub6 | 25 kg | 2 m | large | -0.45 |
| sub6 | 25 kg | 2 m | large | 0.18  |
| sub6 | 25 kg | 2 m | large | 0.03  |
| sub6 | 25 kg | 2 m | large | -0.55 |
| sub6 | 25 kg | 6 m | small | -2.05 |
| sub6 | 25 kg | 6 m | small | -2.13 |

|      |       |     |       |       |
|------|-------|-----|-------|-------|
| sub6 | 25 kg | 6 m | small | -2.15 |
| sub6 | 25 kg | 6 m | small | -2.3  |
| sub6 | 25 kg | 6 m | large | -2.57 |
| sub6 | 25 kg | 6 m | large | -2.35 |
| sub6 | 25 kg | 6 m | large | -2.4  |
| sub6 | 25 kg | 6 m | large | -2.55 |
| sub6 | 45 kg | 2 m | small | 1.11  |
| sub6 | 45 kg | 2 m | small | -0.3  |
| sub6 | 45 kg | 2 m | small | 0.24  |
| sub6 | 45 kg | 2 m | small | -0.53 |
| sub6 | 45 kg | 2 m | large | -0.14 |
| sub6 | 45 kg | 2 m | large | -0.15 |
| sub6 | 45 kg | 2 m | large | -0.05 |
| sub6 | 45 kg | 2 m | large | -0.08 |
| sub6 | 45 kg | 6 m | small | 0.37  |
| sub6 | 45 kg | 6 m | small | -1.86 |
| sub6 | 45 kg | 6 m | small | -1.66 |
| sub6 | 45 kg | 6 m | small | -2.4  |
| sub6 | 45 kg | 6 m | large | -1.99 |
| sub6 | 45 kg | 6 m | large | -1.76 |
| sub6 | 45 kg | 6 m | large | -2.12 |
| sub6 | 45 kg | 6 m | large | -2.05 |
| sub6 | 90 kg | 2 m | small | -0.02 |
| sub6 | 90 kg | 2 m | small | -0.5  |
| sub6 | 90 kg | 2 m | small | -0.18 |
| sub6 | 90 kg | 2 m | small | -0.5  |
| sub6 | 90 kg | 2 m | large | -0.77 |
| sub6 | 90 kg | 2 m | large | -0.84 |
| sub6 | 90 kg | 2 m | large | -0.31 |
| sub6 | 90 kg | 2 m | large | -0.19 |
| sub6 | 90 kg | 6 m | small | -1.05 |
| sub6 | 90 kg | 6 m | small | -0.71 |
| sub6 | 90 kg | 6 m | small | -2.14 |
| sub6 | 90 kg | 6 m | small | -2.65 |
| sub6 | 90 kg | 6 m | large | -2.13 |
| sub6 | 90 kg | 6 m | large | -1.92 |
| sub6 | 90 kg | 6 m | large | -2.9  |
| sub6 | 90 kg | 6 m | large | -1.14 |
| sub7 | 25 kg | 2 m | small | -0.7  |
| sub7 | 25 kg | 2 m | small | -1.9  |
| sub7 | 25 kg | 2 m | small | -0.07 |
| sub7 | 25 kg | 2 m | small | -0.14 |
| sub7 | 25 kg | 2 m | large | -0.41 |
| sub7 | 25 kg | 2 m | large | -0.05 |
| sub7 | 25 kg | 2 m | large | -0.55 |
| sub7 | 25 kg | 2 m | large | -0.29 |
| sub7 | 25 kg | 6 m | small | -2.5  |
| sub7 | 25 kg | 6 m | small | -1.75 |
| sub7 | 25 kg | 6 m | small | -2.26 |
| sub7 | 25 kg | 6 m | small | -1.81 |
| sub7 | 25 kg | 6 m | large | -1.9  |

|      |       |     |       |       |
|------|-------|-----|-------|-------|
| sub7 | 25 kg | 6 m | large | -2.1  |
| sub7 | 25 kg | 6 m | large | -1.68 |
| sub7 | 25 kg | 6 m | large | -1.81 |
| sub7 | 45 kg | 2 m | small | -0.64 |
| sub7 | 45 kg | 2 m | small | -0.64 |
| sub7 | 45 kg | 2 m | small | -1.2  |
| sub7 | 45 kg | 2 m | small | -0.02 |
| sub7 | 45 kg | 2 m | large | -0.61 |
| sub7 | 45 kg | 2 m | large | -0.03 |
| sub7 | 45 kg | 2 m | large | 0     |
| sub7 | 45 kg | 2 m | large | -0.82 |
| sub7 | 45 kg | 6 m | small | -1.52 |
| sub7 | 45 kg | 6 m | small | -1.82 |
| sub7 | 45 kg | 6 m | small | -1.67 |
| sub7 | 45 kg | 6 m | small | -2.28 |
| sub7 | 45 kg | 6 m | large | -2.09 |
| sub7 | 45 kg | 6 m | large | -1.39 |
| sub7 | 45 kg | 6 m | large | -1.33 |
| sub7 | 45 kg | 6 m | large | -1.73 |
| sub7 | 90 kg | 2 m | small | -0.62 |
| sub7 | 90 kg | 2 m | small | -0.71 |
| sub7 | 90 kg | 2 m | small | -0.51 |
| sub7 | 90 kg | 2 m | small | -0.56 |
| sub7 | 90 kg | 2 m | large | -0.97 |
| sub7 | 90 kg | 2 m | large | -0.11 |
| sub7 | 90 kg | 2 m | large | -0.59 |
| sub7 | 90 kg | 2 m | large | -0.21 |
| sub7 | 90 kg | 6 m | small | -1.35 |
| sub7 | 90 kg | 6 m | small | -1.95 |
| sub7 | 90 kg | 6 m | small | -1.46 |
| sub7 | 90 kg | 6 m | small | -2.62 |
| sub7 | 90 kg | 6 m | large | -1.39 |
| sub7 | 90 kg | 6 m | large | -2.7  |
| sub7 | 90 kg | 6 m | large | -2.72 |
| sub7 | 90 kg | 6 m | large | -1.65 |
| sub8 | 25 kg | 2 m | small | -0.24 |
| sub8 | 25 kg | 2 m | small | 0.14  |
| sub8 | 25 kg | 2 m | small | -0.39 |
| sub8 | 25 kg | 2 m | small | -0.19 |
| sub8 | 25 kg | 2 m | large | 0.21  |
| sub8 | 25 kg | 2 m | large | -0.07 |
| sub8 | 25 kg | 2 m | large | -0.29 |
| sub8 | 25 kg | 2 m | large | 0.84  |
| sub8 | 25 kg | 6 m | small | -2.5  |
| sub8 | 25 kg | 6 m | small | -2.05 |
| sub8 | 25 kg | 6 m | small | -1.98 |
| sub8 | 25 kg | 6 m | small | -1.28 |
| sub8 | 25 kg | 6 m | large | -1.91 |
| sub8 | 25 kg | 6 m | large | -2.53 |
| sub8 | 25 kg | 6 m | large | -1.31 |
| sub8 | 25 kg | 6 m | large | -1.59 |

|      |       |     |       |       |
|------|-------|-----|-------|-------|
| sub8 | 45 kg | 2 m | small | 0.77  |
| sub8 | 45 kg | 2 m | small | -0.15 |
| sub8 | 45 kg | 2 m | small | -0.09 |
| sub8 | 45 kg | 2 m | small | 0.02  |
| sub8 | 45 kg | 2 m | large | -0.45 |
| sub8 | 45 kg | 2 m | large | -0.48 |
| sub8 | 45 kg | 2 m | large | -0.01 |
| sub8 | 45 kg | 2 m | large | -0.6  |
| sub8 | 45 kg | 6 m | small | -2.46 |
| sub8 | 45 kg | 6 m | small | -2    |
| sub8 | 45 kg | 6 m | small | -1.34 |
| sub8 | 45 kg | 6 m | small | -1.43 |
| sub8 | 45 kg | 6 m | large | -1.85 |
| sub8 | 45 kg | 6 m | large | -2.13 |
| sub8 | 45 kg | 6 m | large | -1.78 |
| sub8 | 45 kg | 6 m | large | -1.81 |
| sub8 | 90 kg | 2 m | small | -1    |
| sub8 | 90 kg | 2 m | small | -0.54 |
| sub8 | 90 kg | 2 m | small | -0.42 |
| sub8 | 90 kg | 2 m | small | -0.46 |
| sub8 | 90 kg | 2 m | large | -0.61 |
| sub8 | 90 kg | 2 m | large | -0.53 |
| sub8 | 90 kg | 2 m | large | -0.66 |
| sub8 | 90 kg | 2 m | large | -0.65 |
| sub8 | 90 kg | 6 m | small | -2.35 |
| sub8 | 90 kg | 6 m | small | -2.95 |
| sub8 | 90 kg | 6 m | small | -2.41 |
| sub8 | 90 kg | 6 m | small | -1.63 |
| sub8 | 90 kg | 6 m | large | -1.35 |
| sub8 | 90 kg | 6 m | large | -1.68 |
| sub8 | 90 kg | 6 m | large | -2.42 |
| sub8 | 90 kg | 6 m | large | -2.6  |
| sub9 | 25 kg | 2 m | small | 0.52  |
| sub9 | 25 kg | 2 m | small | 0.44  |
| sub9 | 25 kg | 2 m | small | 0.36  |
| sub9 | 25 kg | 2 m | small | 0.51  |
| sub9 | 25 kg | 2 m | large | 0.35  |
| sub9 | 25 kg | 2 m | large | -0.05 |
| sub9 | 25 kg | 2 m | large | 0.02  |
| sub9 | 25 kg | 2 m | large | 0.23  |
| sub9 | 25 kg | 6 m | small | -1.26 |
| sub9 | 25 kg | 6 m | small | -1.62 |
| sub9 | 25 kg | 6 m | small | -1.56 |
| sub9 | 25 kg | 6 m | small | -1.82 |
| sub9 | 25 kg | 6 m | large | -2.02 |
| sub9 | 25 kg | 6 m | large | -1.98 |
| sub9 | 25 kg | 6 m | large | -1.16 |
| sub9 | 25 kg | 6 m | large | -1.12 |
| sub9 | 45 kg | 2 m | small | 0.38  |
| sub9 | 45 kg | 2 m | small | -0.05 |
| sub9 | 45 kg | 2 m | small | -0.16 |

|       |       |     |       |       |
|-------|-------|-----|-------|-------|
| sub9  | 45 kg | 2 m | small | 0.13  |
| sub9  | 45 kg | 2 m | large | 0.9   |
| sub9  | 45 kg | 2 m | large | 0.24  |
| sub9  | 45 kg | 2 m | large | -0.13 |
| sub9  | 45 kg | 2 m | large | 0.13  |
| sub9  | 45 kg | 6 m | small | -0.96 |
| sub9  | 45 kg | 6 m | small | -2.6  |
| sub9  | 45 kg | 6 m | small | -1.74 |
| sub9  | 45 kg | 6 m | small | -1.96 |
| sub9  | 45 kg | 6 m | large | -2.37 |
| sub9  | 45 kg | 6 m | large | -2    |
| sub9  | 45 kg | 6 m | large | -1.81 |
| sub9  | 45 kg | 6 m | large | -2.02 |
| sub9  | 90 kg | 2 m | small | 0.45  |
| sub9  | 90 kg | 2 m | small | -0.13 |
| sub9  | 90 kg | 2 m | small | 0.09  |
| sub9  | 90 kg | 2 m | small | 0.07  |
| sub9  | 90 kg | 2 m | large | -0.24 |
| sub9  | 90 kg | 2 m | large | -0.57 |
| sub9  | 90 kg | 2 m | large | -0.5  |
| sub9  | 90 kg | 2 m | large | -0.06 |
| sub9  | 90 kg | 6 m | small | -0.68 |
| sub9  | 90 kg | 6 m | small | -2.16 |
| sub9  | 90 kg | 6 m | small | -2.53 |
| sub9  | 90 kg | 6 m | small | -2.48 |
| sub9  | 90 kg | 6 m | large | -1.27 |
| sub9  | 90 kg | 6 m | large | -2.37 |
| sub9  | 90 kg | 6 m | large | -2.7  |
| sub9  | 90 kg | 6 m | large | -2.25 |
| sub10 | 25 kg | 2 m | small | -0.11 |
| sub10 | 25 kg | 2 m | small | -0.46 |
| sub10 | 25 kg | 2 m | small | -0.26 |
| sub10 | 25 kg | 2 m | small | 0.08  |
| sub10 | 25 kg | 2 m | large | 0.09  |
| sub10 | 25 kg | 2 m | large | 0.1   |
| sub10 | 25 kg | 2 m | large | 0.16  |
| sub10 | 25 kg | 2 m | large | 0.42  |
| sub10 | 25 kg | 6 m | small | -1.63 |
| sub10 | 25 kg | 6 m | small | -1.33 |
| sub10 | 25 kg | 6 m | small | -1.94 |
| sub10 | 25 kg | 6 m | small | -1.55 |
| sub10 | 25 kg | 6 m | large | -1.67 |
| sub10 | 25 kg | 6 m | large | -0.96 |
| sub10 | 25 kg | 6 m | large | -1.4  |
| sub10 | 25 kg | 6 m | large | -1.07 |
| sub10 | 45 kg | 2 m | small | -0.22 |
| sub10 | 45 kg | 2 m | small | -0.16 |
| sub10 | 45 kg | 2 m | small | -0.08 |
| sub10 | 45 kg | 2 m | small | -0.12 |
| sub10 | 45 kg | 2 m | large | 0.11  |
| sub10 | 45 kg | 2 m | large | 0     |

|       |       |     |       |       |
|-------|-------|-----|-------|-------|
| sub10 | 45 kg | 2 m | large | -1.83 |
| sub10 | 45 kg | 2 m | large | -0.12 |
| sub10 | 45 kg | 6 m | small | -0.77 |
| sub10 | 45 kg | 6 m | small | -1.41 |
| sub10 | 45 kg | 6 m | small | -1.72 |
| sub10 | 45 kg | 6 m | small | -1.58 |
| sub10 | 45 kg | 6 m | large | -1.67 |
| sub10 | 45 kg | 6 m | large | -2.08 |
| sub10 | 45 kg | 6 m | large | -1.43 |
| sub10 | 45 kg | 6 m | large | -1.81 |
| sub10 | 90 kg | 2 m | small | -0.4  |
| sub10 | 90 kg | 2 m | small | -0.24 |
| sub10 | 90 kg | 2 m | small | -0.46 |
| sub10 | 90 kg | 2 m | small | -0.46 |
| sub10 | 90 kg | 2 m | large | -0.17 |
| sub10 | 90 kg | 2 m | large | -0.25 |
| sub10 | 90 kg | 2 m | large | -1.22 |
| sub10 | 90 kg | 2 m | large | -0.53 |
| sub10 | 90 kg | 6 m | small | -0.41 |
| sub10 | 90 kg | 6 m | small | -2.04 |
| sub10 | 90 kg | 6 m | small | -2.09 |
| sub10 | 90 kg | 6 m | small | -2.05 |
| sub10 | 90 kg | 6 m | large | -2.1  |
| sub10 | 90 kg | 6 m | large | -1.62 |
| sub10 | 90 kg | 6 m | large | -1.9  |
| sub10 | 90 kg | 6 m | large | -1.97 |
| sub11 | 25 kg | 2 m | small | 2.6   |
| sub11 | 25 kg | 2 m | small | 0.54  |
| sub11 | 25 kg | 2 m | small | 0.17  |
| sub11 | 25 kg | 2 m | small | 0.52  |
| sub11 | 25 kg | 2 m | large | 0.22  |
| sub11 | 25 kg | 2 m | large | 0.36  |
| sub11 | 25 kg | 2 m | large | 0.87  |
| sub11 | 25 kg | 2 m | large | 0.36  |
| sub11 | 25 kg | 6 m | small | -1.26 |
| sub11 | 25 kg | 6 m | small | -2.46 |
| sub11 | 25 kg | 6 m | small | -0.87 |
| sub11 | 25 kg | 6 m | small | -0.96 |
| sub11 | 25 kg | 6 m | large | -1.55 |
| sub11 | 25 kg | 6 m | large | -1.76 |
| sub11 | 25 kg | 6 m | large | -1.44 |
| sub11 | 25 kg | 6 m | large | -1.37 |
| sub11 | 45 kg | 2 m | small | -0.51 |
| sub11 | 45 kg | 2 m | small | -1.06 |
| sub11 | 45 kg | 2 m | small | 0.12  |
| sub11 | 45 kg | 2 m | small | 0.1   |
| sub11 | 45 kg | 2 m | large | -0.37 |
| sub11 | 45 kg | 2 m | large | -0.17 |
| sub11 | 45 kg | 2 m | large | 0.16  |
| sub11 | 45 kg | 2 m | large | 0.21  |
| sub11 | 45 kg | 6 m | small | -1.94 |

|       |       |     |       |       |
|-------|-------|-----|-------|-------|
| sub11 | 45 kg | 6 m | small | -1.13 |
| sub11 | 45 kg | 6 m | small | -1.14 |
| sub11 | 45 kg | 6 m | small | -2.2  |
| sub11 | 45 kg | 6 m | large | -1.54 |
| sub11 | 45 kg | 6 m | large | -2.55 |
| sub11 | 45 kg | 6 m | large | -1.54 |
| sub11 | 45 kg | 6 m | large | -1.38 |
| sub11 | 90 kg | 2 m | small | 0.32  |
| sub11 | 90 kg | 2 m | small | -0.31 |
| sub11 | 90 kg | 2 m | small | -0.27 |
| sub11 | 90 kg | 2 m | small | -0.26 |
| sub11 | 90 kg | 2 m | large | -0.11 |
| sub11 | 90 kg | 2 m | large | -0.13 |
| sub11 | 90 kg | 2 m | large | -0.4  |
| sub11 | 90 kg | 2 m | large | 0.09  |
| sub11 | 90 kg | 6 m | small | -2.83 |
| sub11 | 90 kg | 6 m | small | -2.74 |
| sub11 | 90 kg | 6 m | small | -1.98 |
| sub11 | 90 kg | 6 m | small | -2.7  |
| sub11 | 90 kg | 6 m | large | -1.88 |
| sub11 | 90 kg | 6 m | large | -2.53 |
| sub11 | 90 kg | 6 m | large | -2.13 |
| sub11 | 90 kg | 6 m | large | -3.1  |
| sub12 | 25 kg | 2 m | small | 0.3   |
| sub12 | 25 kg | 2 m | small | 0.02  |
| sub12 | 25 kg | 2 m | small | 0.37  |
| sub12 | 25 kg | 2 m | small | 0.36  |
| sub12 | 25 kg | 2 m | large | 0.11  |
| sub12 | 25 kg | 2 m | large | 0.58  |
| sub12 | 25 kg | 2 m | large | 0.49  |
| sub12 | 25 kg | 2 m | large | 0.38  |
| sub12 | 25 kg | 6 m | small | -1.69 |
| sub12 | 25 kg | 6 m | small | -1.19 |
| sub12 | 25 kg | 6 m | small | -1.12 |
| sub12 | 25 kg | 6 m | small | -0.73 |
| sub12 | 25 kg | 6 m | large | -2.03 |
| sub12 | 25 kg | 6 m | large | -1.1  |
| sub12 | 25 kg | 6 m | large | -1.49 |
| sub12 | 25 kg | 6 m | large | -0.55 |
| sub12 | 45 kg | 2 m | small | -0.66 |
| sub12 | 45 kg | 2 m | small | 0.05  |
| sub12 | 45 kg | 2 m | small | 0.15  |
| sub12 | 45 kg | 2 m | small | 0.19  |
| sub12 | 45 kg | 2 m | large | -0.52 |
| sub12 | 45 kg | 2 m | large | 0.08  |
| sub12 | 45 kg | 2 m | large | 0.13  |
| sub12 | 45 kg | 2 m | large | 0.35  |
| sub12 | 45 kg | 6 m | small | -1.18 |
| sub12 | 45 kg | 6 m | small | -0.76 |
| sub12 | 45 kg | 6 m | small | -1.2  |
| sub12 | 45 kg | 6 m | small | -1.57 |

|       |       |     |       |       |
|-------|-------|-----|-------|-------|
| sub12 | 45 kg | 6 m | large | -0.55 |
| sub12 | 45 kg | 6 m | large | -0.89 |
| sub12 | 45 kg | 6 m | large | -1.53 |
| sub12 | 45 kg | 6 m | large | -0.82 |
| sub12 | 90 kg | 2 m | small | -0.58 |
| sub12 | 90 kg | 2 m | small | -0.43 |
| sub12 | 90 kg | 2 m | small | -1.6  |
| sub12 | 90 kg | 2 m | small | -0.64 |
| sub12 | 90 kg | 2 m | large | -0.42 |
| sub12 | 90 kg | 2 m | large | -2.03 |
| sub12 | 90 kg | 2 m | large | -0.15 |
| sub12 | 90 kg | 2 m | large | -0.33 |
| sub12 | 90 kg | 6 m | small | -1.3  |
| sub12 | 90 kg | 6 m | small | -2.3  |
| sub12 | 90 kg | 6 m | small | -1.08 |
| sub12 | 90 kg | 6 m | small | -1.17 |
| sub12 | 90 kg | 6 m | large | -1.17 |
| sub12 | 90 kg | 6 m | large | -1.03 |
| sub12 | 90 kg | 6 m | large | -1.3  |
| sub12 | 90 kg | 6 m | large | -1.22 |

## VITA

Ralindo M. Pagulayan ("Rally") was born on May 17, 1969 in Los Angeles, California. He spent most of his life growing up in Westminster, Maryland. He received his B.S. in Industrial and Systems Engineering from Virginia Tech in May of 1991 and went on to pursue his Master's degree in the Human Factors Engineering Laboratory at Virginia Tech. He is an active member of the Human Factors Society. He will be working for Computing Devices Canada in Calgary, Alberta, Canada as a human factors engineer.



Ralindo M. Pagulayan