THE PSYCHOPHYSICS OF ACTIVE KINESTHESIS AS MEASURED BY AMPLITUDE OF MOVEMENT

by

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ABSTRACT

The purpose of this study was to determine whether judgment of amplitude of active movement was subserved by a prothetic or metathetic process. To differentiate between these two processes several psychophysical methods were employed. Fifty volunteer subjects were randomly assigned to one of five groups of equal N. Each of the groups produced movements under one of five experimental conditions. These conditions were: Ratio Production, Magnitude Production, Bisection of Ascending Stimulus Series, Bisection of Descending Stimulus Series, and Category Production.

The results of Group I (R.P.) and Group II (M.P.) showed that judgments of amplitude of movement were constant over the movement continuum as used in this study. There was also a lack of an hysteresis effect shown in the comparison of bisections of ascending and descending stimulus series. The comparison of the subjective and physical variables of category production also showed constant sensitivity over the continuum range. Taken as a whole, the findings tended to support the conclusion that judgments of amplitude of movement are subserved by a metathetic process.

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"The teacher who walks in the shadow of the temple, among his followers, gives not of his wisdom but rather of his faith and his lovingness.

If he is indeed wise he does not bid you enter the house of wisdom, but rather leads you to the threshold of your own mind."

-- The Prophet.

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TABLE OF CONTENTS

CHAPTER PAGE

LIST OF TABLES

LIST OF FIGURES

CHAPTER I

STATEMENT OF THE PROBLEM

Introduction

Two psychophysical laws that have been shown to describe the characteristics of several different sensory modalities are laws by Stevens and Fechner. These laws describe the relationship between a physical stimulus within a sensory continuum and the subjective impression of the stimulus intensity.

Fechner's Law (91) proposes that equal stimulus ratios correspond to equal sensation differences, or in other words, the strength of the sensation (R) varies directly with the logarithm of the stimulus (S); stated in algebraeic form:

$$R = K\log S.$$

When the logarithm of the stimulus intensity is plotted against linear differences in sensation, Fechner's Law predicts a straight line. Fechner's Law is still used in psychophysical studies even though it has been labelled erroneous because of its use of equal just-noticeable differences (j.n.d.s) as a unit of scale (90, 20, 32).

This same reason has led Stevens to propose an alternate form of Fechner's Law.

Stevens' Power Function Law states that equal stimulus ratios produce equal subjective ratios. According to Stevens' Power Function Law, the subjective evaluation of a physical stimulus is related to the physical stimulus by a power function of the form:

$$R = KS^N;$$

where R is the subjective magnitude,

K is a constant whose value is determined by the units used, and

S is the physical stimulus, with

N being the exponent or the slope of the power function line on a log-log plot.

Stevens (82) has postulated that sensory modalities divided themselves into two classes depending upon certain operating characteristics.

Class I, or prothetic continua, are concerned with "how much", and discrimination is mediated by an additive or prothetic process at the physiological level. The receptors that subserve this class operate on a quantitative mechanism, adding excitation to excitation. On the other hand, class II or metathetic continua are concerned with "where" and "what kind", and discrimination is mediated by a metathetic or substitutive process at the physiological level. The receptors that subserve this class operate on a qualitative mechanism where excitation is substituted by excitation along the continuum.

There are four criteria that Stevens (82) has outlined that distinguish between the above two classes:

1. Subjective size of the just noticeable differences. On class I continua the subjects are not able to equalize intervals due to the variable size of the j.n.d. along the continuum. However, on class II continua, the subject has constant sensitivity along the continuum and is able to produce equal j.n.ds. The major difference between the two classes of continua is actually this constant and non-constant sensitivity along the sensory continuum.

Stevens (82) has reported that his power function holds on class I sensory continua, and that Fechner's Law holds on class II continua because of the equal j.n.d.s.

2. When a category rating scale is plotted against a ratio scale of subjective magnitude, the function obtained

is nonlinear for class I continua, and may be linear on class II sensory continua. A category rating scale is the function obtained when a subject judges a set of stimuli in terms of a set of categories.

3. Time order error is a third characteristic and refers to the fact that the second of two equal stimuli tends to be judged greater than the first. This is characteristic of class I continua, but not on judgments of class II.

4. Hysteresis, or "lagging behind" effect, describes what happens when the apparent sense differences between successive stimuli are judged in different order. Judgments of stimuli in an ascending series are usually judged higher in intensity than judgments of stimuli in a descending order. This effect is a characteristic of class I continua but is not found on class II sensory continua.

There has been strong psychophysical evidence in support of Stevens' Power Function Law. Stevens has shown that of sixteen sensory continua studied, twelve belonged to class I sensory continua and followed the Power Function Law (89), and four sensory continua (90) belonged to class II or metathetic continua. The Power Function Law and the distinction it makes between the two sensory continua has been shown to hold without exception (89, 20, 94).

These psychophysical findings can be related to kinesthesis, as kinesthesis is considered a sensory modality. Williams (97), along with Smith (80), has described the kinesthetic receptors in the joint capsule as functioning as a metathetic sensory continuum. They have stated that there are countless numbers of receptor cells in the joint which are sensitive to various portions of the movement arc of a given joint. Each cell is responsible for a specific section of the movement arc and this excitatory range was reported to be about fifteen to twenty degrees of arc. Therefore different joint angles would cause different receptors to discharge, describing a metathetic continuum.

Mountcastle and Powell (63) have also reported that the joint receptors subserving kinesthesis function metathetically, i.e. specific receptors depict specific joint angles. They also found that cells in the sensory cortex that correspond to the joint receptors are arranged in a topographic pattern, and that the pattern of neural activity depicted the joint angles and changes in those angles. As well as this qualitative or metathetic process, they also found a quantitative process at the cortical level. These cortical neurons discharged at a frequency that was specific to a given point position.

Mountcastle, Poggio and Werner (62) also supported the contention that the joint receptors function as a metathetic continua. They thought that the frequency of discharge of these receptors was not suitable for depicting position, as position must be depicted by which specific groups of receptors are being discharged. Yet in measuring the activity of the third order relay of joint receptors in the ventrobasal complex of the thalamus, they found the opposite: here, the frequency of discharge did depict the degree of movement and joint position. In other words, a metathetic process at the first order afferents had been transformed into a prothetic process in the thalamus.

In addition to these findings, Wood (98) in a behavioral study has shown that speed, one aspect of kinesthesis, operated as a prothetic continua. She found that the subjective impression of speed from a self-initiated shoulder movement was related to the actual speed of movement by a power function, and that other characteristics of prothetic sensory continua, such as hysteresis, were met.

In interpreting Wood's results and the neurophysiological evidence of Mountcastle, Poggio and Werner (62) it might be suggested that the subjective impression of some aspects of kinesthesis are formed as early as the third order afferent relay of the joint receptors in the thalamus, and that a prothetic mechanism is the final translation into subjective impression.

The knowledge of which receptors are responsible for kinesthesis and the operating characteristics of these receptors, is invaluable in studying the psychophysics of active kinesthesis, as it helps to explain the observed relationship between physical stimulus and subjective sensation.

The joint receptors, which include the spray or ruffini type endings and the pacinian corpuscles in the connective tissues of the joint capsule, along with the free (Golgi-type) endings in the ligaments, are considered by many to play the major role in kinesthetic discrimination (3, 9, 79, 75). These receptors have been shown to have direct connections to the sensory areas of the cortex that subserve perception, and therefore are directly responsible for subjective impression of kinesthesis (62, 79).

The other receptors that are considered to play a role in kinesthesis are the muscle spindle receptors found in muscle fibers. Such studies as Paillard and Brouchon (69) and Browne, Lee and Ring (10), have stated that the muscle spindles provide important information to the kinesthetic sense. Further support for this is given by Oscarsson and Rosen (68) and Albe-Fissard and Liebeskind (11), who discovered that the spindles have connections to the sensory cortex in cats and monkeys, which would mean that information from muscle spindles could be used in the subjective evaluation of joint movement and position.

Yet there has been put forth evidence that opposes this role of muscle spindles in kinesthesis. Studies by Holmqvist, Lundberg and Oscarsson (35), Laporte and Lundberg (41), and Oscarsson (66) have shown that the muscle spindle afferents do not project to the cortex, but to the cerebellum, which means that information from these receptors could not be used in subjective impression of joint action. Further to this, Merton (54), Rose and Mountcastle (75) and Mountcastle and Powell (63) have stated that because of spindle dependence on muscle stretch it could not possibly perform as a detector of joint position.

Other sources of information such as that arising from Golgi tendon organs, cutaneous receptors, and pattern of motor innervation, have also been suggested to contribute to the kinesthetic sense.

The Problem

As Stevens' Power Function Law (82), which distinguishes two classes of sensory continua and predicts a power function relationship between the physical stimulus and its subjective impression, has been generally accepted as the psychophysical law governing subjective impression on sensory modalities, this study endeavored to investigate the psychophysics of the amplitude of movement aspect of active kinesthesis.

In essence, the probelm investigated the question of whether the amplitude of a self-initiated arm movement, lateral flexion of the human shoulder, was a prothetic or metathetic continuum and whether the subjective impression of the movement was related to the actual physical movement by a power function of the form;

$R = KS^N$ or Fechner's Law: $R = C \log S$.

Definition of Terms

Continuum - refers to a closely graded series of stimuli, one step merging imperceptibly into the next; the information forms a straight line signifying changes in a single direction (32).

<u>Metathetic Continua</u> - refers to stimulus discriminations that are based on "what kind", "where" and quality; discrimination is mediated by a substitutive process at the physiological level (82).

<u>Prothetic Continua</u> - refers to stimulus discriminations that are based on quantity, "how much"; discrimination is mediated by an additive process at the physiological level (82).

<u>Kinesthesis</u> - discrimination of the positions and movements of the body parts based on information other than visual, auditory, tactual, or verbal. The discrimination is based on stimuli that arise from the tension, length, and distortion of body parts, in relation to each other and gravity. Active kinesthesis in this study was defined as the sensations (other than visual, auditory, tactual, and verbal) that arise from self-initiated lateral flexion of the preferred shoulder.

Sensory Modality - defined as a subjectively distinctive response within the central nervous system to the stimulation of a group of specific receptors (80).

Working Hypothesis

Based on the studies by Wood (98) and by Mountcastle, Poggio and Werner (62) it was hypothesized that the amplitude of movement aspect of kinesthesis will function as a prothetic sensory continuum. It was also hypothesized that the subjective impression of amplitude of movement was related to the physical degree of movement by a power function, as described by Stevens (82).

In essence, the hypothesis stated that amplitude of movement should show three characteristics of a prothetic continua:

1. the subjective impression of amplitude of movement should be related to the actual amount of movement by a power function of the form:

$$R = KS^N.$$

This power function should plot a straight line when the logarithm of subjective magnitude is plotted against the logarithm of the physical stimulus, i.e., degrees moved;

2. a hysteresis effect;

3. a nonlinear plot when the results of a category production method are plotted against the power function.

These expected characteristics are all due to one reason: the subject's inability to equalize intervals over continuum, or in other words, the nonconstant sensitivity along the continuum.

Limitations of the Study

1. The sample size of ten subjects for each of five experimental groups.

2. Directions to the subjects were given verbally by the experimenter.

3. The distinction by S.S. Stevens (82) between class I and class II sensory continua.

Deliminations of the Study

1. The type of movement used in the experimental task,

i.e., active lateral flexion of the human shoulder joint.

2. The investigation of amplitude of movement which is only one aspect of kinesthesis.

3. The analysis of data through Stevens' Power Function Law.

CHAPTER II

REVIEW OF THE LITERATURE

The literature has been reviewed under the following four major headings:

1) Psychophysics Pertinent to the Study of Kinesthesis;

2) Neurophysiology of Kinesthesis;

3) Behavioral Studies on the Psychophysics of Kinesthesis;

4) Kinesthetic Information.

This review contains some literature that is only peripherally related to the present problem since emphasis, for this section of the present study, was placed on an in-depth study of kinesthesis. However, because of the exhaustive nature of this review not all studies will be used in the discussion of the results of the present study.

Psychophysics Pertinent to the Study of Kinesthesis

To investigate the nature of any sensory system and its receptors, one must begin with psychophysics. Founded by Fechner, psychophysics is a science of the functional relations between body and mind. Psychophysics studies sensations, their relationship within a given sensory modality, and the stimuli that cause them. The main objective of this science is to investigate and observe quantitative relationships between physical stimuli and subjective magnitude.

To illustrate psychophysical functions, luminance and electric shock can be used. When the luminance of a spot of light is doubled in a dark field the apparent subjective brightness is little affected. To a typical observer the apparent increase in brightness is about twenty-five per cent. Yet doubling the current of a sixty cycle current passing through the fingers makes the sensation of shock seem about ten times as strong. It is apparent that the psychophysical function between these two examples is clearly different (90).

Weber's Law. Although there have been many psychophysical laws, the first one that showed any relevance was Weber's. It stated that in order for the second of two stimuli to be discriminated from the first, there must be a just noticeable difference (j.n.d.). The increment or j.n.d., between the two stimuli must be a constant fraction of the original stimulus (78).

To a good approximation Weber's Law holds in sensory continua, Stevens (86) has stated that the Weber fraction is constant on about 99 per cent of the useable range of stimulus intensity.

Guilford (32) has stated that Weber's Law cannot be regarded as a universal law of differential sensitivity, for it relates two physical measurements, stimulus increment with the stimulus, and does not relate, as it should to be a true psychophysical law, measurements on response to those of the stimulus. Therefore it should not be expected to apply constantly. All measurements are made on the stimulus scale, corresponding to certain landmarks on the response continuum. The landmarks are statistically derived at points of equal likelihood of two different judgments. In fact, the only thing psychophysical about Weber's Law is that the stimulus increment stands for a presumably constant psychological increment measured on the stimulus scale.

Fechner's Law. It was Fechner who first suggested investigating the relationship between a subjective intensity and the intensity of the physical stimulation evoking that subjective response. On the basis of Weber's Law and the assumption that j.n.d.s are equal, Fechner derived his logarithmic law (20). Its procedure was to measure j.n.d.s along the continuum and to use these measures as equal units on a scale of sensation (85). Because the increments in logarithms are constant, Fechner thought that their use in a scale of intensity would be more convenient, rather than the difference limen, for according to Weber's Law, the difference limen is a constant fraction of the standard stimulus and therefore must get bigger as we go up the scale.

Fechner's Law (91) proposed that equal stimulus ratios correspond to equal sensation differences, or in other words, the strength of the sensation (R) varies directly as the logarithm of the stimulus (S). The algebraic form of Fechner's Law is:

$$R = K \log S.$$

If Fechner's Law holds, it would produce a straight line function when equal sensory units are plotted against logarithmic physical units.

Stevens (90) has labelled Fechner's Law as being erroneous. Stevens' argument against acceptance of Fechner's Law was that it was built on the misconception that error itself provides a unit of measurement or the j.n.d. Under most circumstances the j.n.d., is a statistical concept, a measure of the dispersion or variability of a discriminatory response; in short, a measure of error. Fechner made dispersion among judgments, normally a nuisance to science, into a j.n.d., and used it as his unit of scale (89). In deriving his law, Fechner made the erroneous assumption that error (j.n.d.) is constant up and down the psychophysical scale. Does a stimulus forty j.n.d.s above threshold seem twice as great as a stimulus twenty j.n.d.s above threshold? Stevens (85) has stated that this does not hold true on the majority of sensory continua.

Stevens' Power Function . An alternate form, the power function, was suggested early as a substitute to Fechner's Law. Proposed by Plateau (89); it was briefly debated and then was forgotten until Stevens developed "the method of magnitude estimation" and discovered that it, not Fechner's Law, was consistent with his data.

Stevens explored the use of fractionation and multiplication in an effort to improve the psychophysical scaling procedures used by Fechner. The general procedure in Stevens' method was: a stimulus was presented and the subject was asked to adjust a variable stimulus to a value that was either half or twice as great. The important assumption of this method is the way in which the terms "one-half" and "twice" in the instructions are assumed to be used by the subject in arriving at his judgments. In Stevens' "method of magnitude estimation", the subject is instructed to assign a number to each stimulus presentation so that the numbers are proportioned to the subjective magnitude produced by the stimuli. Other methods used by Stevens that give essentially identical results, and that were variations of the magnitude estimation method, have been described by Stevens (83), Luce and Galanter (48), Guilford (32), Stevens (85), and Stevens and Galanter (94).

Stevens (82) has shown that there is a psychophysical law relating subjective magnitude to stimulus magnitude and the law simply stated, "equal stimulus ratios produce equal subjective ratios". According to Stevens, ratio scales of subjective magnitudes are related to the stimulus by a power function, and not Fechner's logarithmic function. Algebraically, Stevens' power function is expressed:

$$R = KS^{N}.$$

The subjective impression is "R", and "S" is the physical stimulus. The constant "K" is determined by the choice of units, and its value can be found where the power function line produced by ratio or magnitude production crosses the ordinate on a log.- log. plot. "K" can also be found algebraically by:

$$\log K = \log R - N^{\log} S.$$

Stevens (90) has shown that his power function can be converted into a linear equation:

$$\log R = \log K + N^{\log} S,$$

which has a certain practical use, for the function can be represented by a straight line on log.-log. coordinates. The slope of this straight line is equal to the value of the exponent (N) of the power function. Stevens (60) has given a formula for "N" which is:

$$N = \frac{\log S}{\log r} = \frac{\text{sensation ratio}}{\text{stimulus ratio}} = \frac{Y_2 - Y_1}{x_2 - x_1}.$$

Stevens (91) has also stated that the exponent "N" varies with each modality, with each modality having its own characteristic exponent.

In later publications Stevens (90 and 91) revised this power function to:

$$R = K\ (S - S_o)^N,$$

where S_o is an added constant value to correspond to the threshold. This additive constant was used to bring the zero of the physical scale into coincidence with the zero of the psychological scale. For ranges of stimuli well above the minimum detectable level, the value of S_o is usually negligible, but it assumes larger proportions when subjective scales are extended downward toward very low values.

Two Classes of Sensory Continua. Stevens (82) has reported that perceptual continua divide themselves into two general classes. Two continua which illustrate this fact are loudness and pitch. The j.n.d., for pitch remains constant whereas those of the loudness continuum are unequal. This fact suggests that there may be two basic mechanisms of discrimination underlying these two sensory continua. The uniform sensitivity on the pitch continuum and the non-uniformity on the loudness continuum also serve to explain several other functional differences between the two types of sensory continua.

The prothetic continua or class I (ex. loudness) are concerned with "how much", whereas metathetic continua or class II (ex. pitch) are concerned with "what kind", or "where". There are two basic physiological mechanisms that correspond to the two classes of continua. In class I continua discrimination is mediated by an additive or prothetic process at the physiological level. This class requires a quantitative receptor mechanism. Receptors mediating a prothetic continua respond in increasing numbers or frequency as the stimulus intensity is increased. On loudness, an example of class I, we progress along the continuum by adding excitation to excitation (82).

Discrimination on class II continua is mediated by a substitutive or metathetic process at the physiological level. This class requires a qualitative receptor mechanism. A stimulus change on this class would cause a different population of receptors to be activated with no increase in the number of receptors responding. An example is pitch, where we proceed along the continuum by substituting excitation for excitation, i.e., by changing the focus of excitation.

Stevens (82) has outlined four functional criteria that are relevant to the distinction between the two classes of sensory continua:

1. Subjective size of the just noticeable differences. On class I continua the j.n.d.s. are not equal in subjective size. In other words, a stimulus forty j.n.d.s above threshold will not be twice as great as a stimulus only twenty j.n.d.s. above threshold. On metathetic continua the stimulus forty j.n.d.s above threshold would seem twice as great, for on continua of class II the j.n.d.s turn out to be approximately equal in subjective size. Thus a crucial difference between these two classes of continua is that in metathetic continua the j.n.d.s are subjectively equal over the continuum, whereas in the prothetic continua, the j.n.d.s grow rapidly larger in subjective size as the upper end of

the continuum is reached.

Stevens (82) has stated that in class I or prothetic continua his power function is the form of the relationship between subjective magnitude and physical stimulus intensity, but not on metathetic continua. On metathetic continua Fechner's logarithmic function would be the form of the relationship, for Fechner's scale is based on equal j.n.d.s along the continuum, and the j.n.d.s on metathetic continua are equal.

2. Category rating scales. A category rating scale is the function obtained when a subject judges a set of stimuli in terms of a set of categories labelled either by numbers or adjectives. The form that these scales take when plotted against a ratio scale of subjective magnitude is different on the two classes of sensory continua. On class I the relationship between the two scales is nonlinear, whereas on class II the form may be linear, when so plotted (82).

On most prothetic continua investigated to date, the form of the non-linear relationship has been concave downward (82, 90, 95). Concave upward plots have also been found for prothetic continua (95).

The reason for the nonlinear curve in prothetic continua has been discussed as being the result of unequal j.n.d.s., or nonconstant sensitivity over the entire continuum (82). A given difference may seem large and obvious in the lower part of the continuum, but the same absolute difference is much less impressive in the upper part of the continuum. This asymmetry in the observer's sensitivity to differences results in a nonuniformity in the width of the categories. Near the lower end of the continuum the categories tend to be narrow and thus the slope of the function is steep. Near the upper end the categories broaden and the slope of the function declines, forming a concave downward plot. If the nonconstant sensitivity was reversed the plot formed would be concave upward (82).

On class II or metathetic continua, the j.n.d.s., are equal and the sensitivity or discrimination tends to be constant over the entire continuum. This results in a linear plot between category and ratio scales.

3. Time-order error. This refers to the fact that the second of two equal stimuli tends to be judged greater than the first. Stevens (82) stated that time-order error is characteristic of judgments on class I continua but not of

judgments on class II. The cause of the time-order error is, as it was for nonlinearity of category plots, the asymmetry of sensitivity over the sensory continuum.

4. Hysteresis, or "lagging behind" effect, describes what happens when successive stimuli are judged in different orders. This effect has been found most clearly in psychophysical bisection or equipartition experiments. If a certain range of a continuum is portioned in equal intervals by a subject, the position of the divisions obtained will depend on whether the stimuli are presented in an ascending or descending order (82). In an experiment on loudness by Stevens (82), the average subjective response of the bisecting level was set some five to eight dbs. higher in the ascending order than in the descending order. It appeared that the loudness the subject heard lagged behind what he should have heard as he went up or down the scale.

Hysteresis has been shown for subjective loudness, brightness and lifted weights (82), which are all prothetic continua, but has not been found in typical metathetic continua. Stevens (82) has stated that the evidence for hysteresis in class I continua and not in class II is suggestive, but not yet conclusive.

Eisler and Ottander's (19) research found that the hysteresis effect in prothetic continua is mostly, if not solely due to different "subjective zeros" or "S_o" in the psychophysical power functions:

$$R = K (S - S_o)^N$$

for ascending and descending series. According to Eisler and Ottander (19), precise knowledge of the zero point (S_o) would prevent hysteresis, and that seemed to be the case in certain metathetic continua such as position. Stevens (82) has stated in attempting to explain the hysteresis effect:

> ... in calling this phenomenon hysteresis I am trying to describe it, not explain it. I am not sure I know how to explain it.

As discussed earlier, Stevens (82) has stated that the power function applied to prothetic continua, but not to metathetic continua. The number of prothetic continua on which the power function has been shown to hold now exceeds two dozen (Stevens 89). Stevens (89) has stated that as yet no exception to the Power Function Law has been encountered. Ekman (20) has supported this idea of no exception to the Power Function Law along with Stevens and Galanter (94); Mountcastle, Poggio and Werner (62); Luce and Galanter (48); and Millar, Pederson and Sheldon (56).

Stevens' Power Function Law states that on metathetic continua the j.n.d.s are equal, and therefore Fechner's function would form the relationship between subjective magnitude and stimulus intensity, not the power function. This part of the Power Function Law was supported by Stevens (90) and Stevens and Galanter (94) who have shown the continua: pitch, apparent visual position (azemuth), proportion, and apparent inclination to belong to the metathetic continua class.

Individual Power Functions. All of the exponents of prothetic continua resulted from a procedure where the average of the judgments from a group of observers was calculated and used in developing the exponent. This procedure was justified because of the interest in the average exponent in forming a general law. Marks and Stevens (52) have shown that the psychophysical power function also holds for the individual perceiver. They showed that 150 psychophysical functions of separate observers held to the power function, and they concluded that the power function therefore cannot be an artifact of averaging. Stevens (90) has shown that on thirty-nine individual functions that related the magnitude of subjective effort to the force exerted on a precision hand dynamometer, good approximations to power functions were achieved. In addition, twenty-three separate loudness functions all obeyed the Power Function Law in a study on vowel loudness by Cross and Lane (17).

<u>Cross-Modality Studies</u>. Ekman and Sjoberg (21), as well as Luce and Galanter (48) have pointed out that despite the massive evidence in favor of the Power Function Law, questions arise, because initial developments of the power function rested mainly on methods that involved numerical estimations by the subjects.

Any questions about the power function due to the numerical estimation have been silenced by the results of a method in which the observer equates the apparent strengths of the sensations produced in two different sensory modalities. By means of such cross-modality matches made at various levels of stimulus intensity, an "equal-sensation function" can be mapped out, and its form can be compared with the form predicted by the magnitude scales for the two modalities involved.

Stevens (90) has shown that if, given an appropriate choice of units, two modalities are governed by the equations:

$$R_1 = KS^N$$

$$R_2 = KS^N$$

and if the subjective values R_1 and R_2 are equated by asking the observer to make the one sensation seem as strong as the other at various levels, then the resulting equal sensation function will be given by:

$$KS^{N_1} = KS^{N_2}$$

In terms of logarithms:

$$\log KS = N_2/N_1 \log KS$$

In log-log coordinates, therefore, the equal sensation function should be a straight line with a slope equal to the ratio of the two exponents.

This prediction was nicely borne out by a series of cross-modality matches between the subjective scales of loudness, of electric shock, and of vibration (84). Cross-modality matches have been made between loudness and ten other continua (93). The matching functions were all power functions. When the exponent values of the matching functions were divided by the exponent values previously determined for the various continua, the quotients predicted values for the loudness exponent. The matching functions between force of handgrip and nine other continua were all shown to approximate power functions - straight lines on log.-log. coordinates (90).

The ability to specify the power functions relative to other sensory continua, instead of numbers, seems to contradict the objections raised by Ekman and Sjoberg (21) and by Luce and Galanter (48) that the power function was based entirely on numerical estimations. Without resort to numerical estimation methods it has been shown that the over-all transfer function of several sensory modality were related to one another as a family of power functions (93). Stevens (92) has recommended that if one continuum was to be used as a validation it should be judgment of apparent length of lines with an "N" of 1.0.

Neurophysiology of Kinesthesis

The main goal of psychophysical research is to discover the quantitative relationship between stimulus input and subjective output, and also to discover the operating characteristics of the receptors and the entire sensory system of that particular sensory modality.

Stevens (84) has stated that the power function relationship of a given sensory continuum can relate some information as to the operating characteristics of the receptors and the entire neural chain between stimulus and subjective response.

A converse relationship could exist as well-- the known operating characteristics of the receptors and sensory system of a given sensory modality could supply important information about the psychophysical relationship between stimulus input and subjective output. One such sensory modality in which the neurophysiology of the receptors and of the neural chain could supply information on the psychophysical relationship, is kinesthesis.

Kinesthesis is the sensory modality that is concerned with the discrimination of position and movement of body parts, both actively and passively produced, and is based on information other than visual, auditory or tactile (36). The receptors giving rise to kinesthetic information are unique as to their anatomical location and their responsiveness to a particular form of energy. They are mechanoreceptors, excited by the deformation of their endings produced by the stretching or compression of the structures in which they are embedded. Kinesthetic discrimination is based on unique stimuli that arise from changes in length, tension, movement and the distortion of body parts in relation to each other and gravity. The receptors are involved in awareness of:

1) onset and duration of movement,

2) direction of movement,

3) velocity and acceleration of movement,

4) range of movement,

5) static positioning of joint segments prior to and after movement (36).

Which peripheral receptors are responsible for kinesthesis and their functional characteristics could tell us a great deal about the mechanisms which underlie the subjective formation of kinesthesis.

The receptors that have been thought to be involved in kinesthetic perception are: the muscle spindles found in ordinary muscle fibre; the golgi tendon organs which are found in muscle tendons; and the spray on Ruffini type endings and the pacimian corpuscles found in the connective tissue of articular joint capsules. The cutaneous receptors in the skin and the pattern of motor innervation have also been suggested as contributing to kinesthesis. These joint receptors and muscle spindles have been located and identified by Gardner (27), Boyd (81), Skoglund (79), Andrew (2) and by Howard and Templeton (36).

<u>Muscle Spindles</u>. Muscle spindles contain contractile elements

and two types of sensory elements which respond to changes in the length and tension in the spindle. The two types of sensory endings are commonly known as primary and secondary endings. When a muscle is stretched, the primary endings signal both the instantaneous length of the muscle and rate of stretching, while secondary endings signal mainly instantaneous length. When a muscle contracts, the tension on the spindle is released, and its sensory end organs cease firing until the slack in the spindle is taken up by the contraction of intrafusal muscle fibres inside the spindle. The discharge rate of the spindles is a very sensitive indicator of changes of muscle tension. The discharge of primary spindle endings is approximately proportional to the logarithm of the load or amount of stretch applied to the passive muscle, but adaptation is rapid, therefore the maximum discharge reached will depend as much on the rate at which the muscle is stretched as on the absolute tension (53).

In two experiments in which the amount of error was measured when one hand, passively or actively displaced, was located by the other hand, Paillard and Brouchon (69) showed that active movement was significantly better in precision than passive movement, and there was no significant difference between active and passive maintenance of the final position.

They also found that the dispersion of errors increased as a function of temporal interval. They concluded that there must have been more kinesthetic information available from active movement, and that there must have been an information deficit during passive movement. Since they felt that the amount of information from the joint receptors was the same under active and passive movement, they excluded the joint receptors as being responsible for their results. What they did conclude was that the information arising from the muscle spindle afferents provided important information that accounted for the superior accuracy of active movement.

Another experiment has reached similar results and conclusions. Browne, Lee and Ring (10) injected procaine into certain joints, thereby anaesthetizing the joint receptors. Although blindfolded, subjects were not able to perceive passive movement, yet they were able to move limbs voluntarily to specified positions. These authors (10) suggested that passive movement was mediated by joint receptors, while active movement was mediated by receptors within the muscles and tendons.

Yet Merton (54), and Rose and Mountcastle (75) have stated that the receptors within the muscles and tendons are not capable of providing kinesthetic information. According to these authors, muscle spindles respond to changes in muscle length, i.e., measure relative length, but with their contractile ends they would obviously be unsatisfactory instruments for making absolute length measurements. Mountcastle and Powell (63) have stated that since muscle spindles do not vary frequency of discharge in a linear, or any other sort of constant relation to muscle length, they could not perform as detectors of joint position. Both Goldscheider (29) and Angier (4) in their experiments on joint sensitivity concluded that the muscle spindles play an unimportant role in position sense.

Paillard and Brouchon (69) have stated that what Merton (54) and Rose and Mountcastle (75) have alleged about spindles not being able to supply kinesthetic information would be true for fixed positions of the limb. They (69) went on

> ... but if, as we are able to show, velocity detection with its characteristic decay in time may appear to provide potent calibrating information about the final position of the limb at the end of a movement, then the spindle becomes a not-to-be ignored candidate for such a function.

One argument advanced in support of the unimportant role played by muscle spindles in kinesthesis is that spindle afferents do not have a direct connection to the sensory areas of the cortex, but project instead to the cerebellum. (31, 35, 41, 42, 43, 46, 50, 66, 75). Much of this evidence was a result of work on cats.

Yet Oscarsson and Rosen (68) have stated that the muscle spindle afferents from the forelimb of the cat do, in fact, project to the somatosensory areas of the cortex unequivocally. This has also been confirmed in monkeys by Albe-Fissard and Liebeskind (1).

Matthews (53) has shown that the muscle spindles and tendon organs both respond directly to the amount of external stretch applied to the muscle and tendon. Fulton and Pi-Suner (25) indicated that since one of the factors which influence the external stretch of a muscle and tendon is movement and position of the bones to which they are attached, it follows that the muscle spindles can function, at least to some degree, as movement-position receptors. Skoglund (79) also supported a minor role in kinesthesis for the muscle spindle afferent information with this argument.

In an experiment by Cohen (15) in which he measured the contributions of tactile, musculo-tendinous and joint mechanisms to position sense in the human shoulder, the results showed that the muscle spindles and tendon receptors both made a small but significant contribution to kinesthesis.

Golgi Tendon Organs. Howard and Templeton (36) have described the tendon organs as having a higher treshold to external stretch than the muscle spindles; therefore at low tensions there will be a proportionately greater discharge from the spindles; as the tension increases, more and more tendon organs will discharge. Tendon organs respond to tension either actively or passively produced. Mountcastle and Powell (63) mentioned that the tension to which these receptors fire depends on muscle length, i.e., upon joint angle and upon the force exerted. They concluded that a number of golgi organs and their rates of discharge are not variables dependent solely upon the angle of the joint across which the muscle works; they cannot, therefore, inform joint position. Further to this, Paillard and Brouchon (69) have stated that the golgi tendon organs, with their high threshold to stretch, are not suited to give kinesthetic information in resting and passive movement conditions because of the low tensions. But on active movement they should give important kinesthetic information due to higher tension. Yet Weber and Dallenbach (95) have shown that loading of a moving limb, which should increase tension and therefore information from the golgi tendon organs, has no consistent effect on accuracy of position sense.

Browne, Lee and Ring (10), in their experiment on the sensitivity of anaesthetized joints, concluded that the muscle spindles and the tendon organs played an important role in kinesthesis. It has been demonstrated, however, that the receptors within the muscles and tendons are not capable of providing kinesthetic information (54,75). To detect position and movement, they would have to indicate the absolute length and tension of the muscle and tendon in which they are embedded, neither the golgi tendon organ nor the spindle can.

The most conclusive evidence refuting a role for golgi tendon organs in kinesthesis is that which indicates they do not have a direct connection to the classicial sensory areas of the cortex, but are connected to the cerebellum, and are therefore used in motor integration. This is supported by Merton (54), Rose and Mountcastle (75), Oscarsson (66) and Oscarsson (67).

Yet Cohen (15) concluded that the musculo-tendinous receptors made a small but significant contribution to position sense in the human shoulder.

<u>Cutaneous Receptors</u>. These receptors have been shown to

fire in response to deformation of the skin, so that they could serve to indicate changing skin tension resulting from changes in the position of the limb. Yet Sherrington (77), and Lee and Ring (44) reported that interference with the skin sensation around a joint does not affect position sense. This statement is also supported by Goldscheider (29) who anaesthetized the skin of the finger and found no loss in the sensitivity of kinesthesis. Cohen (15) concluded that the cutaneous receptors, along with the musclo-tendinous receptors, made a small but significant contribution to kinesthesis. Cohen stated that since the limb is rarely static, the tactile receptors must usually contribute useful information in regard to kinesthesis, but their basic stimulus must be movement rather than position.

Motor Innervation. In their discussion on kinesthesis,Howard and Templeton (36) stated that the pattern of motor innervation must be an available source of kinesthetic information.Yet Keele (37) departed from this by not including motor innervation as a part of kinesthesis. The reason he gave for this was that all the other sources of kinesthesis are afferent and of peripheral origin , whereas motor innervation is of central origin, and may have quite different consequences for movement control.

It has been shown in at least two experiments that active movement positioning was superior in accuracy to passive movement placing; Lloyd and Caldwell (45) showed this in the human leg and Paillard and Brouchon (69) showed this in the human arm. Many reasons have been given to account for the more accurate active movement including the pattern of motor innervation. Since passive movements don't have a pattern of motor innervation and active movements do, this could possibly account for some of the difference between the two.

Paillard and Brouchon (69) have inferred two possible ways that the pattern of motor innervation may explain the difference between active and passive movements:

First, they proposed an internal monitoring system, a system that serves kinesthesis by the "motor outflow". This concept covers the idea that some afferent control signal goes to the muscle, and also to some comparator or correlator structure in the nervous system. This system must have other information such as the starting position in order to be useful to kinesthetic judgments, for it can only signal movement of desired amplitude in a given direction. The system was proposed by Paillard and Brouchon to be capable of engraving certain movements to build up spatial standards as references. Once engrammed, such standards would be able to operate the programming of adjustment reactions which belong to the usual modes of reaction of the individual. Suprasystems of controls would emerge from this progressive organization that would be able to take charge of some reorganizations of their own.

Secondly, Paillard and Brouchon (69) proposed that the pattern of motor innervation could be altered by peripheral methods. They proposed that every motor command acting on the alpha motorneurons is preceded, accompanied, and followed by a pattern of innervation of gamma motorneurons which biases the spindle receptors of the muscle so as to initiate, sustain, and modulate the alpha discharge according to the aim of the desired action. They went on to state that this double motor system predisposes the primary endings in the spindles to act as speed detectors (gamma dynamic) and also to act as static position receptors (gamma static). Paillard and Brouchon (69), accredited the gamma dynamic system with its decay over time, as being responsible for their results of active movement being more accurate than passive movements.

Paillard and Brouchon terminated their discussion by warning that these two theories of motor innervation functioning were pure conjecture.

Joint Receptors. The joint receptors include not only the spray or Ruffini type endings and the pacinian corpuscles found in the connective tissue of the articulate joint capsule, but also the free (Golgi-type) endings found in the ligaments around joint capsules.

Generally, two experimental methods have been used to investigate the role played by these joint receptors in kinesthesis: one method includes anaesthetizing the joint capsule with procaine and then measuring position and movement sense; the other method consists of recording the potentials of joint neurons directly during actual limb movements and positions. The first method has generally shown that all sense of position and passive movement of the joint anaesthetized was lost. The second method usually showed that when tension was applied to the joint, slowly adapting discharges were recorded, and often an initial decline in response frequency during the first few seconds. These neurons discharged steadily for the whole period while steady tension was applied.

The overall conclusion drawn from experiments using either method was that the receptor organs of the joint capsule played a major role in position and movement sense or kinesthesis. This conclusion is supported by studies using the cat (2, 3, 9, 14, 26, 58, 63, 75, 79). The same conclusion was reached in studies with humans (15, 30, 54, 74).

Cohen (15) went on to state that there was no evidence present in his study on the human shoulder to indicate the relative role of each of the joint receptors in kinesthetics; yet Rose and Mountcastle (75) have stated that the majority of kinesthetic receptors in the joint capsule appear to be of a slow adapting variety.

Other evidence that supports the major role played by the joint receptors in kinesthesis is that the afferent projections of the joint receptors have direct connection to the somatosensory areas of the cortex, which means conscious perception of stimuli. Experiments have shown unequivocally that these joint receptor afferents project to the ventrobasal nuclear complex of the thalamus; to the contralateral sensory areas, SMI and SMII; and to the ipsilateral sensory area SMII of the cortex. This has been shown in monkeys by Mountcastle (60) and Mountcastle and Powell (63); and also in cats (28, 36, 58, 59, 61, 62, 73, 79).

Two Classes of Joint Receptors. The articulate joint receptors responsible for kinesthesis could be divided into two classes: fast or slow adapting (3, 9, 27, 63, 66, 80, 97).

The slow adapting receptors have been shown to be subserved by the spray or ruffini type endings in the joint capsule and the free (Golgi-type) endings in the ligaments. Smith (80) has outlined the operating characteristics of these slow adapting receptors.

1) Receptors fire at different frequencies for a specific joint angle regardless of the speed or direction of which the position was approached.

2) Receptors adapt slowly and often a single unit has a different adaptation rate for each joint angle.

3) More receptors are responsible to a limited range of the total joint action, i.e., there is a fractionation of the physiological range of motion.

Therefore, the slow-adapting receptors are dependent on joint angle, but independent of movement direction and speed.

On the other hand, Smith (80) has reported that fast adapting receptors are independent of joint angle but dependent upon velocity acceleration and direction of limb movement. She went on to outline the characteristics of these fast adapting receptors.

1) Receptors adapt rapidly to static positioning of the limbs.

2) Many receptors are unidirectional -- they respond to only one direction of movement.

3) The majority of receptors are sensitive to movement velocity; i.e., their overall discharge frequency increases as velocity increases.

4) Units have a rapid onset of firing and low velocity threshold; however, the velocity thresholds differ for groups of receptors.

The pacinian corpuscles found in the joint capsule are believed to function as the fast adapting receptors, and are believed to be less numerous than the slow adapting receptors (97).

Excitatory Angle. As well as the above receptor characteristics, Mountcastle and Powell (63) reported that the slow adapting receptors responded to movements in their excitatory angles with high frequency discharge, and that if this movement came to a halt within this excitatory range, the firing rate adapted to a lower steady rate in a few seconds. The important fact here was that the steady adapted rate of discharge is a variable influenced only by the joint angle -- they function as absolute detectors of angle. They also stated that this adapted rate for any angle was not affected by the speed or direction of movement before the steady position and does not vary over time.

Mountcastle and Powell (63) have also stated that the excitatory angle of joint receptors is about fifteen to twenty degrees of arc. These excitatory angles lie in a continuum along the arc of joint movement, and many showed maximal steady discharge rates at full flexion, others at full extension, and others at angles between flexion and extension (5, 9, 63, 80, 97). Movement of a joint would traverse the overlapping ranges of successive receptors. The profile of which receptors were active and the steady firing rate would picture the joint angles and movement. Direction and speed of movement would be depicted by which group of receptors increased or decreased in frequency of discharge and the extent of such changes (63, 80, 97).

Cortical Connections. Peripheral joint receptors have been shown to be connected to certain cortical cells in the sensory areas,therefore these cortical cells must be driven by connecting joint receptors.The relationship between joint receptor discharge and the connecting cortical cell potentials are of prime importance to the understanding of subjective perception of joint movement and position.

Mountcastle and Powell (63) have identified joint movement as the stimulus for activating certain cells in the postcentral gyrus. These cortical receptor cells appear to be grouped into receptive fields which, when fitted together, form a cortical projection pattern of the body. With such a topographic pattern the steady angles of the body joints and changes in those angles are depicted by the pattern of activity of the cortical cells. These authors (63) concluded that both the place of occurence of neural activity and temporal pattern of neural discharge are used to depict the place, intensity, and temporal cadence of sensory events; and that this mechanism provides a well-defined anatomical nucleus for fine kinesthetic differentiation between joint movements and positions.

Mountcastle and Powell (63) have also discussed the sensitivity relationships between connecting cortical and joint receptors. Most cortical cells respond to movement over a sixty to ninety degree range which is considerably wider than the joint receptor's range of fifteen to twenty degrees of arc. This situation suggests that a cortical neuron is "driven" by input from a number of peripheral receptors whose narrower excitatory ranges overlap one another in order to cover the ninety degrees of arc of the cortical neurons. Smith (80) stated that these reports tend to suggest that detailed kinesthetic information made available by the joint receptors does not reach the cortical centres that subserve perception; instead, only a summary of this information reaches these centres.

Mountcastle and Powell (63) along with Mountcastle, Covain and Harrison (61) have shown a reciprocal inhibition in adjacent cortical cells. These authors reported that some pairs of spatially related cortical cells are reciprocally related, one cell being active as the joint moves in one direction, and the other inhibiting its discharge rate and vice versa. These processes are believed to result in a sharpening of incoming neural kinesthetic information.

The response pattern of the cortical neurons have been shown to be similar and also opposite to the response patterns of the joint receptors. Mountcastle and Powell (63) have observed that the quick adapting cortical neurons are much less common than the slow adapting ones, and that the slow adapting cortical neurons show rapid onset, declining to a steady adapted rate during steady joint positioning --

two characteristics similar to those of the joint receptors. These authors have listed the characteristic response patterns of the cortical neurons to joint movement:

1) cortical cells begin to discharge at an absolute value of angular displacement.

2) the speed with which the joint is moved into the excitatory angle determines the frequency of the onset transient discharge of the neuron.

3) the final steady adapted rate of discharge depends on joint angle.

4) during maintained joint position the rate of neural discharge assumes a lower steady state. Some of these operating characteristics are similar to those of joint receptors to which they are connected.

Mountcastle, Poggio and Werner (62) have shown that the response pattern of the joint receptors differ from those of the cortical cells. Recording from the third order relay of joint receptor afferent projections in the ventrobasal neural complex of the thalamus, they found that the cortical cells signalled "intensively", by the increased rate of discharge in the relevant groups of cells, the degree of movement at the joint. Yet they concluded that at the level of the first order afferents at the joint receptors, rate of discharge could not signal position; position could only be signalled extensively, i.e., by determining which fibers of the total population were active. These points suggest that an important transformation has occurred in the neural chain that subserves kinesthesis as early as the third order afferent relay.

Their results also indicated that a power function of the form:

$$R = KS^N$$

adequately described the relationship between joint position and the response of the thalamic cells.

The subjective impression of joint movement and position is only formed after a large, delicate series of neural events in the central nervous system. The evidence presented above should assist in formulating a theory which reproduces this neural chain between the physical and subjective experiences.

<u>Psychophysical Conclusions Based on Neurophysiological Evidence</u>. The neurophysiological operating characteristics of the kinesthetic receptors presented above have depicted kinesthesis as functioning on both a metathetic and prothetic basis.

Mountcastle and Powell (63), Boyd and Roberts (9), Smith (80), and Williams (97) have all indicated that the joint receptors, which are mainly responsible for kinesthesis, function on a metathetic basis. These authors stated that different joint angles caused different groups of the total population of joint receptors to fire. Some fired at complete flexion, others at complete extension, and others between flexion and extension. Joint position would be determined by the discharge rate of a specific group of receptors, while joint movement would be determined by the overlapping of excitatory angles of a succession of joint receptors.

These authors have also indicated that a prothetic process may be involved in the subjective impression of joint position. They have stated that if a movement stops in the excitatory angle of a group of joint receptors, the rate of discharge of these receptors adapts to a lower, steadier state within a few seconds, and that this final lower, steady state is a variable influenced only by the joint angle. In other words, a specific joint angle would have a specific lower steady rate of discharge that was specific to that angle. Such a quantitative process indicates that a prothetic mechanism may assist in subserving joint position and movement along with a metathetic process. Mountcastle and Powell (63) concluded that the central nervous system utilizes both the place of occurrence (metathetic process) and the temporal pattern of neural activity (prothetic process) to depict position and movement of the body limbs.

Smith (80) and Williams (97) have suggested that the subjective impression of direction of movement was subserved by a metathetic mechanism. They stated that direction of joint movement was represented by a profile of which joint receptor cells showed transient increases in rate of discharge, and which decreased in activity. The same authors (80, 97) have also depicted that speed of joint movement must operate along a prothetic continuum, for they stated that speed of movement was indicated by the rate or extent of transient discharge of the joint receptors to movement. The faster the movement, the greater the discharge rate of the joint receptors; therefore speed of joint movement was coded quantitatively by frequency of joint receptor discharge.

In studying the neural activity of the cells in the postcentral gyrus, Mountcastle and Powell (63) have found that cells which were activated by joint receptors were arranged in topographic patterns and that the neural pattern of activity qualitatively depicted joint angles and changes in these angles. This suggests that joint position and movement might be subserved by a qualitative or metathetic process at the cortical level.

According to Mountcastle, Poggio and Werner (62), the joint receptors must signal joint position and movement metathetically, for they have stated that joint position and movement cannot be depicted by frequency of joint receptor discharge, or in other words, quantitatively. Position must be signalled qualitatively -- by a specific group of joint receptors discharging. Yet they (62) found that at the third order relay of joint receptor afferent projections in the ventrobasal neural complex of the thalamus, joint position and movement were signalled quantitatively or prothetically by the increased rate of discharge. They concluded that between the joint receptors, which signal joint movement and position metathetically, and the thalamic third order relay cells, which signal joint position and movement prothetically, a neural transformation must occur. These authors (62) also found that the relationship between joint position and discharge of thalamic cells followed a power function of the form:

$$R = KS^N,$$

which is a prothetic characteristic.

This neurophysiological evidence tends to indicate that the articular joint receptors, which are mainly responsible for kinesthesis, signal joint position and movement metathetically, and that this qualitative information process is transformed by the joint receptor third order afferents in the thalamus into a quantitative information, or prothetic process.

The presented neurophysiological evidence can only lead to suggestions about the psychophysics of kinesthesis. In order to discover the psychophysical relationship between stimulus input and subjective output on kinesthesis is to quantitatively measure these variables through behavioral studies.

Behavioural Studies on the Psychophysics of Kinesthesis

A very limited amount of behavioural research has been done in kinesthesis using psychophysical scaling methods or relating kinesthesis to Stevens' Power Function Law.

Goldscheilder (29) studied the sensitivity of nine body joints using passive movements and found that the sensitivity was directly related to the proximity of the limb to the trunk. In other words, these results of Goldscheilder indicated that when a body limb was in complete flexion, which is the position most approximate to the trunk, the sensitivity to passive movement should be maximal. Therefore it could be stated that sensitivity to passive movement is greater at the one limit of movement, in this case, complete flexion. Cleghorn and Darcus (13) have found, in their experiment on sensitivity to passive movements, that as the limb's degree of displacement from the body trunk increased, the sensitivity also increased. These results would suggest that at complete extension of a body limb there should be the greatest amount of sensitivity to passive movements. These two studies, Goldscheilder (29) and Cleghorn and Darcus (13), indicate that at the two extremes of joint movement the kinesthetic senstivity should be maximal. One suggestion that could account for the greater kinesthetic sensitivity at the limits of the joint movement is that the joint receptors must be discharging at a higher rate, or more receptors are discharging, which would supply greater amounts of kinesthetic information. This suggestion is given further support by Mountcastle, Poggio and Werner (62) who found that in active movement the joint receptors were maximally activated at the extremes of the range of joint movement. The important facts here are that the joint neurons fire maximally at the extreme range of movement, and that the sensitivity seems to be the greatest at these points. This kind of behaviour suggests that sense of movement may operate on a quantitative, or prothetic mechanism.

Wood (98) has shown that the subjective impression of the rate or speed of self-initiated arm movement was related to the actual speed by a power function. Other results obtained after putting fifty subjects through a speed production task, using active shoulder lateral flexion, showed hysteresis and a nonlinear plot for category production, which led her to conclude that kinesthesis was a prothetic continuum. Actually, she should have concluded that the sense of rate aspect of kinesthesis operated on a quantitative process, for as the above discussion shows, there may be many different aspects of kinesthesis: position sense, discrimination of amplitude of movement, direction of movement and acceleration sense, and that they may all function differently. In fact, the question of whether these aspects are indeed different parts of kinesthesis, or separate senses in themselves, has never been answered.

Force of handgrip and judgments of heaviness, two modalities that are similar to kinesthesis, and probably use kinesthetic information, have been found to operate along a prothetic continuum. Force of handgrip has been shown by Stevens and Mack (81) to hold to Stevens' Power Function Law (N = 1.7). Using a hand dynamometer the subject exerted forces that seemed to him proportional to numbers named in irregular order by the experimenter. Force of hand-grip has also been used in cross-modality studies with nine other continua, (68) and all the functions approximated power functions. Judgments of heaviness using lifted weights have also been shown to operate prothetically and to follow Stevens' Power Function Law (N = 1.45). (94).

It could be concluded that at the joint receptor first order afferents, position and movement sense operate by a metathetic process. Yet at the third order afferent relay of the thalamus, and behaviourally, some aspects of kinesthesis have been shown to operate prothetically. In order to answer the questions about the psychophysical properties of kinesthesis, each different aspect must be measured and studied independently.

To assist our understanding of how the subjective impression of joint movement or kinesthesis is formed, it would be useful to discuss the questions and problems that have arisen in regard to the use and usefulness of kinesthetic information from the joint receptors.

Kinesthetic Information

Does Kinesthetic Information Reach the Cortex? Evidence has shown that the afferent fibres of the joint receptors, and possibly those of the muscle spindles do, in fact, have direct connections to the sensory areas of the cortex (1, 28, 36, 58, 68). Yet it is another question whether information from the kinesthetic receptors reaches the cortex.

It is a well known fact that the central nervous system selectively permits sensory stimulation to enter centers subserving perception, thus it is possible that kinesthetic information, or a part of it, is inhibited from reaching the perceptual sensory areas. It has been shown (62, 63) that some of the kinesthetic information does reach the cortex. Yet Smith (80) has suggested that only a summary of the kinesthetic information produced by the kinesthetic receptors reaches the sensory areas of the cortex. The amount and quality of kinesthetic information reaching the cortical areas that subserve kinesthesis is an important area to the total understanding of kinesthesis and must be considered a primary item for further research.

Attention to Kinesthetic Information. Even if kinesthetic information does reach the cortical sensory areas, it must be attended to in order to be useful. Keele and Posner (38) have shown that attention to kinesthetic feedback was greatest at the beginning of a movement, decreased to a low value in the middle range of movement, and then showed a slight increase as the end of the movement approached. If we do attend more to incoming information at the beginning and end of a movement, should not our sensitivity be greater in these areas? Evidence presented above showed that joint and cortical neurons fired maximally at extreme joint range (5, 62, 63) and sensitivity was greater at these points (13, 29). Could this be a result of greater attention?

Smith's (80) suggestion of a summary of kinesthetic information reaching the cortex, could be a result of lack of attention to the incoming information. The attention to kinesthetic information reaching the cortex must also be investigated through further research.

Is Kinesthetic Information Used? If kinesthetic information reaching the cortex is attended to, is it useful information?

Notterman and Page (15) and Fleishman and Rich (24) have shown in their respective studies that kinesthetic information is used. Both studies showed that the subjects who were allowed to use kinesthetic feedback improved their performance over those subjects who were not allowed use of kinesthetic information.

Paillard and Brouchon (69) have suggested that we build up a known system of spatial relationships among the different mobile parts of the body, and a method of continuously evaluating their relative positions. This executive program would be built up in part by kinesthesis, and would provide a comparator mechanism to which incoming information could be referred; such a mechanism would provide us with useful kinesthetic information. These authors (69) stated that the useful information about joint position comes from the final dynamic phase of the movement, and not the final position.

The information as well as the methods by which it is coded and used will also be an important topic of further kinesthetic research.

CHAPTER III

METHODS AND PROCEDURES

Subjects

Fifty volunteer subjects, both male and female, right and left-handed, were used in the study. All the subjects were undergraduates between the ages of eighteen and twenty-five years at the University of British Columbia in the 1969-1970 academic year. The subjects were unacquainted with the apparatus used in the study and unfamiliar with the movement under study.

Apparatus

The apparatus used in the study consisted of a flat piece of white cardboard cut in an arc of one hundred degrees and affixed to a tabletop twenty-nine inches high. An arc of one hundred degrees was drawn on the piece of cardboard, and every half degree was marked (Figure 1). The length of the one hundred degree arc was one hundred centimeters or one centimeter per degree; the radius of the arc was 57.3 centimeters. The center point of this arc

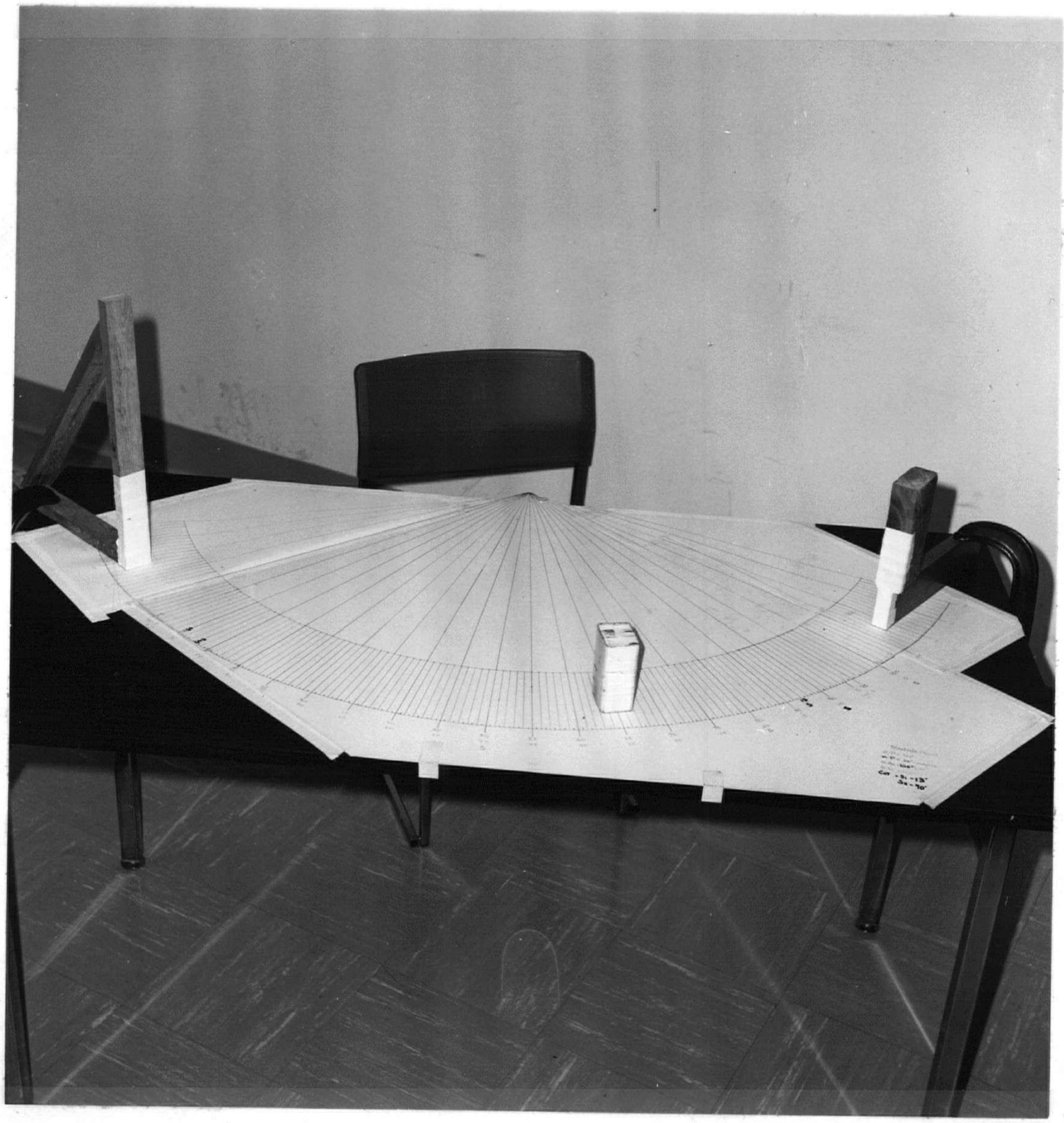

Figure 1

THE APPARATUS

protruded over the subject's side of the table approximately five centimeters. There were two adjustable wooden stopper bars, one at each end of the semicircle, that served as starting blocks; plus a portable wooden stopper block used by the experimenter in presenting standard movements and in measuring the subject's responses.

Procedure

The standard procedures for all subjects were as follows: as each subject entered the testing station the apparatus was completely covered. Each male subject was asked to remove his shirt and undershirt, and each female changed into a sleeveless jersey provided by the experimenter. This jersey was constructed in such a manner that it did not interfere with movement of the shoulder joint. Each subject was asked to remove any jewelry from his neck, preferred hand, or arm.

Each subject was asked to sit in a chair with both feet flat on the floor and to sit erect so that his back did not touch the back of the chair. The subject adjusted the chair position under directions from the experimenter so that he was facing one of the stoppers at either end of the apparatus with his frontal plane at an angle of approximately forty-five degrees to the table. Right-handed subjects faced the left stopper, and left-handed subjects sat facing the right stopper.

At this point in the procedure the subject was blindfolded and the apparatus uncovered. The subject was asked to extend his preferred arm over the apparatus, with the elbow straight; the fingers and thumb were pointed and together with the palm down. The non-preferred arm rested on the subject's lap. The subject was instructed to move, with the experimenter's guidance, his preferred shoulder over this extended center point of the arc. The subject was instructed to readjust the chair in order to move the shoulder joint over this point and not to lean from the body-erect position. In essence, this center point of the arc closely simulated the center of rotation of the shoulder joint, and thus the arm was analogous to the arc's radius. The subject was told that this position must be maintained at all times during the experimental session.

The subject's extended arm was guided by the experimenter's instructions to the corresponding stopper, and he was told that this was the starting position for each movement and to return to this position after every movement. The stopper was adjusted so that the medial side of the extended hand was at the zero degree mark (Figure 2).

When the subject had his extended arm and hand at the zero degree starting position, the shoulder angle was 180 degrees. At the end of the movement arc, when the extended

Figure 2

SUBJECT IN THE STARTING POSITION

arm and hand were at the one hundred degree mark, the shoulder angle was approximately eighty degrees.

The subject was asked to swing his extended arm in a horizontal plane, keeping his hand and arm about one inch above the apparatus at all times. The subject was asked to swing his extended arm in this manner at a velocity that corresponded to a velocity of approximately one second for every twenty degrees of movement and to keep his velocity constant for all movements of different lengths. Before the experimental trials began, the subject was allowed a few practice arm swings to acquaint himself with the required movement velocity. Throughout the experimental trials and standard movements the experimenter corrected any deviations from this velocity.

In each experimental group there were one or two standard movements which were given to the subject on each experimental trial. The standard movement was given to the subject by the experimenter in the following manner: the experimenter held a block of wood at the prescribed standard (measured in degrees) and the subject swung his extended arm and hand until the medial side of the index finger touched the wooden block (Figure 3). Each subject was allowed ten standard trials before the experimental trials began in order to become acquainted with the standard movement that was being

Figure 3

SUBJECT BEING GIVEN A STANDARD MOVEMENT

used.

Depending upon which group the subject was in, he was asked to produce certain fractions, magnitudes, and bisections of the standard movement. Each movement given as a response by the subject was measured in the following manner: the subject swung his extended hand and arm over the apparatus and held it over the apparatus for about two seconds at the amplitude which he felt corresponded to the requested movement. The experimenter moved a wooden block (right-angled) flush with the subject's medial side of the index finger of the extended hand without applying pressure; the bottom edge of the block marked the position of the subject's hand on the apparatus. The experimenter recorded this position to the nearest half degree of movement.

The subject was allowed to rest at any time during the experiment but was required to rest at the starting position and not for longer than one minute. The time between trials was approximately two seconds.

Experimental Design

The fifty subjects were randomly assigned to one of five experimental groups with the restrictions that two right-handed females, two left-handed males, and six right-handed males appear in each group to make a total of ten subjects per group. The five groups were labelled:

1. Ratio Production (R.P.);
2. Magnitude Production (M.P.);
3. Bisection of an Ascending Series (B.A.S.);
4. Bisection of a Descending Series (B.D.S.);
5. Category Production (C.P.).

Experimental Conditions

Group I - Ratio Production. Each of the ten subjects was given a standard movement of one hundred degrees and repeated it until he became acquainted with it. The subject was then asked to move to some fraction of the standard movement -- either 3/4, 1/2, 1/4, or 1/3. Each of the four fractions was presented four times each in random order so that each subject received sixteen experimental trials. Each experimental trial was preceded by the standard movement.

Group II - Magnitude Production. Each of the ten subjects was given a standard movement of fifty degrees, called one hundred, and repeated it until he was acquainted with it. The subject was then asked to produce movements that corresponded to fifty, seventy-five, one hundred and twenty-five, and one hundred and fifty in respect to the standard of one hundred. Each of the four magnitudes was repeated four times, with the standard between each trial for sixteen experimental trials per subject.

Group III - Bisection of Ascending Stimulus Values. Each of the ten subjects was given a standard movement of 6.25 degrees, and repeated it until he was acquainted with it. The subject was then asked to produce a movement that was "twice as great as the standard", then a movement that was "twice as great as that second movement", then a movement that was "twice as great as that third movement." In this manner the subject increased his movements by doubling the preceding movement. He produced movements that were 8/1, 4/1, and 2/1 of the standard 1. The standard, followed by the three movements was repeated six times for eighteen experimental trials per subject.

Group IV - Bisection of Descending Stimulus Values. Each of the ten subjects was given a standard movement of one hundred degrees and repeated it until he was acquainted with it. The subject was then asked to produce a movement that was "one-half of that movement", then another movement that was "one-half the second movement", then another movement that was "one-half the third movement". In this manner the subject reduced each movement by one-half of the preceding movement. He produced movements that were 1/2, 1/4, and 1/8 of the standard for they bisected three successive movements. The standard followed by the three movements was repeated six times for eighteen experimental trials per subject.

Group V - Category Production. Each of the ten subjects was given two standard movements. One was thirteen degrees and called Category 1; the other was a movement of ninety degrees and called Category 7. The standards were repeated until the subject was acquainted with them both. The subject was then told that there were seven categories, each one equidistant from one another. Then each subject was asked to produce movements that corresponded to the categories between 1 and 7 inclusive. Both standards were given in succession between experimental trials, and each of the seven categories was given five times each in random order for thirty-five experimental trials per subject.

Statistical Analysis

Group geometric and arithmetic means were calculated for all judgments of ratio, magnitude, bisections and category production groups. These values were transformed into common logarithm values. Since the differences between the geometric and arithmetic means were small, the arithmetic mean was used as the measure of the subjective impression because of its theoretical relation to other calculations.

The standard deviations of individual judgments about the group arithmetic mean were calculated for each of the five groups.

The statistical analysis included four graphic procedures:

1. The logarithmic values of the subjective magnitude were plotted against the logarithmic values of the physical stimulus for Group I (R.P.) and Group II (M.P.) in order to test for Stevens' power function.

2. The linear values of the subjective impression were plotted against the logarithmic values of the physical stimulus for Group I (R.P.) and Group II (M.P.) in order to test for Fechner's straight line function.

3. Using the results of the Bisection of Ascending and Descending groups, the two orders of presentation were plotted against each other over the physical stimuli in order to test for hysteresis.

4. Results of the Category Production group were plotted against the ratio scale of subjective magnitude of amplitude of movement (i.e., the power function) on both the ratio and magnitude production groups.

The lines of best fit were calculated for the functions on the log-log and linear-linear plots for Group I (R.P.) and Group II (M.P.). The quadratic curves of best fit were calculated and plotted for the functions of Bisection of Ascending and Bisection of Descending Stimulus Series. The quadratic curves were calculated and plotted for the Category Production (Group V) results against the ratio scale of subjective magnitude obtained from Group I (R.P.) and Group II (M.P.). The lines and quadratic curves of best fit were calculated by regression analysis using the method of least squares.

CHAPTER IV

RESULTS AND DISCUSSION

Results

Comparison of the Subjective Impression and the Physical Stimulus on Group I (R.P.). The arithmetic means, standard deviations and their logarithmic values, for each of the four judgment fractions of Group I (R.P.) are listed in Table I.

In order to test the relationship between the subjective and physical scores for Stevens' Power Function, the logarithmic mean of the subjective impression was plotted against the logarithm of the physical movement in degrees (Figure 4). The function obtained was a straight line of best fit, calculated by regression analysis using the method of least squares. The correlation between the two variables was $r = .846$ ($P < .05$, $df = 39$) (Table III).

To test for Fechner's function between the subjective and physical variables of Group I (R.P.), the logarithm of the physical stimulus was plotted against the arithmetic means of the four fractions (Figure 5). Using a regression

TABLE I

COMPARISON OF THE PHYSICAL DEGREES, SUBJECTIVE ARITHMETIC MEANS, AND STANDARD DEVIATIONS OF THE FOUR FRACTIONS OF GROUP I (RATIO PRODUCTION)

Fraction	Physical Degrees	Log. of Physical Degrees	Subjective Arithmetic	Log. of Subj. Arith. Means	Stand. Dev.	Log. of S. D.
1/4	25.00	1.398	40.10	1.592	9.73	.10
1/3	33.34	1.523	50.00	1.689	10.39	.09
1/2	50.00	1.698	67.73	1.828	8.33	.05
3/4	75.00	1.875	83.40	1.920	6.61	.03

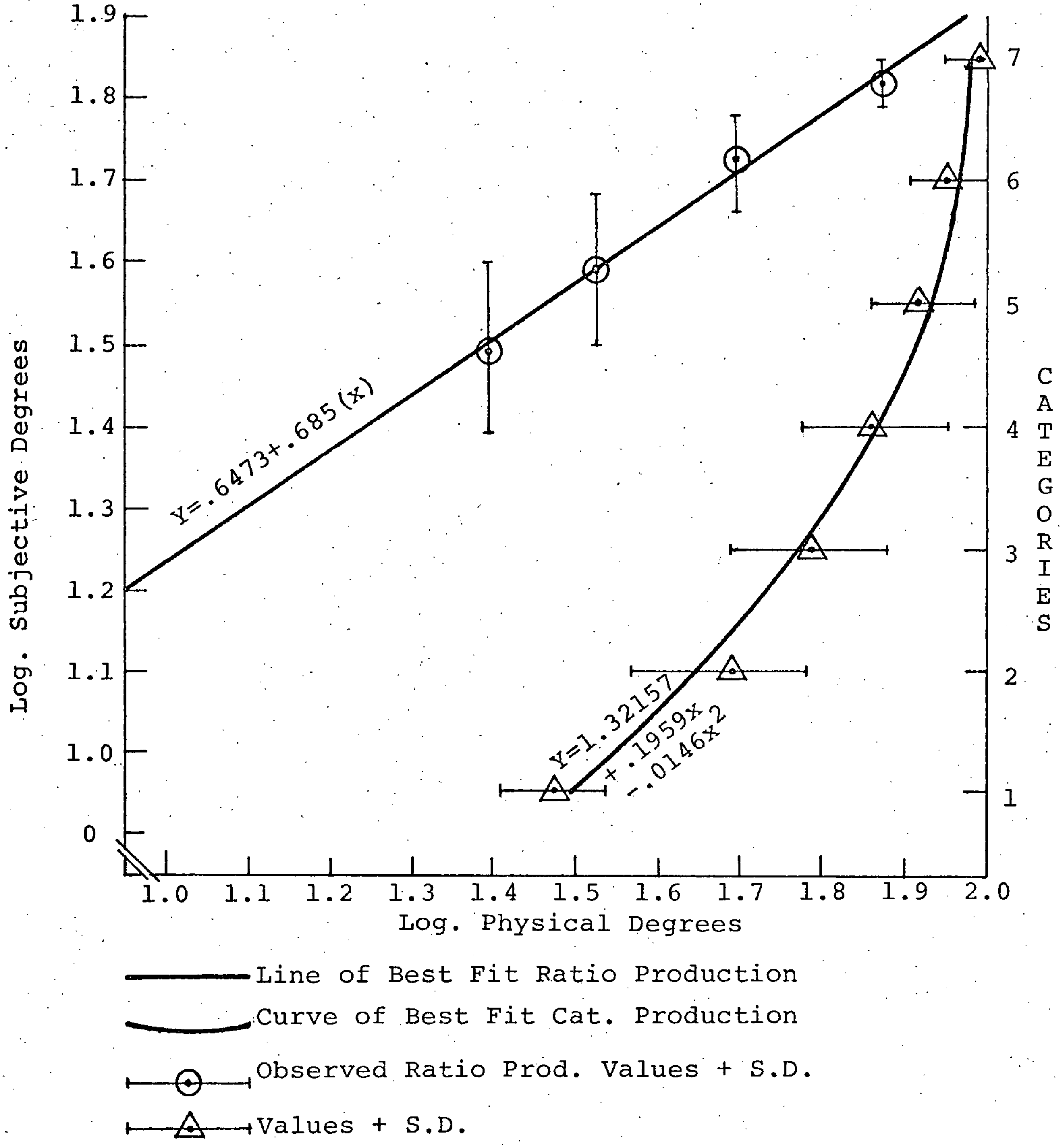

FIGURE 4
Ratio and Category Production Judgments of Amplitude of Movement in Log.-Log. Coordinates

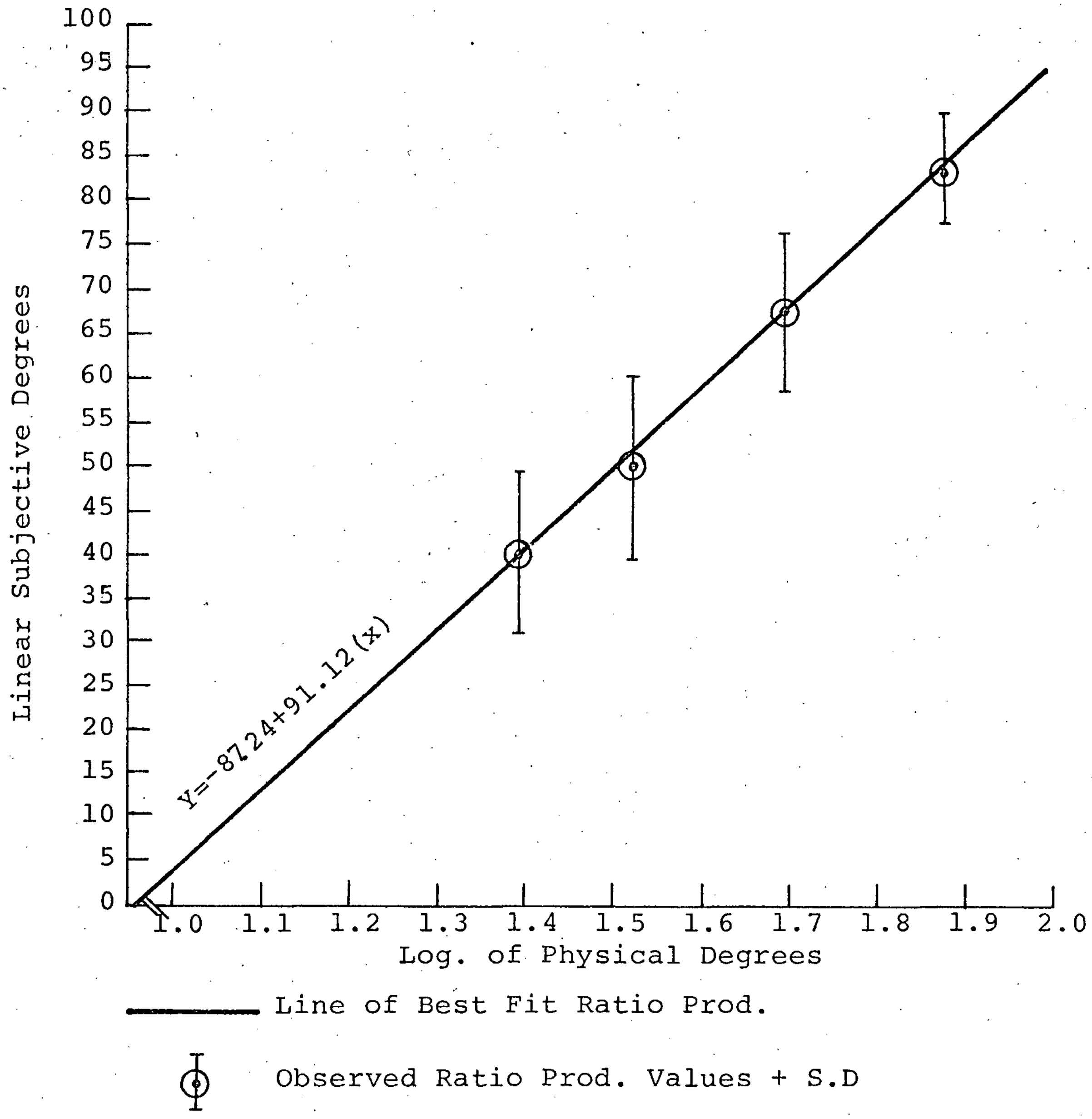

FIGURE 5

Ratio Production Judgments of
Amplitude of Movement in Linear-Log.
Coordinates

analysis as above, the function obtained was a best fit straight line. The correlation between the two variables was $r = .883$ ($P < .05$, $df = 39$) (Table III).

Since there was relatively little difference in the way Stevens' Power Function or Fechner's Law described these data, it was decided to further clarify the relationship between the subjective and physical variables for Group I (R.P.) by plotting them on linear-linear coordinates. Again using the same regression analysis the function obtained was a straight line (Figure 6). The correlation between the two variables was $r = .882$ ($P < .05$, $df = 39$) (Table III).

Comparison of the Subjective Impression and the Physical Stimulus on Group II (M.P.). The arithmetic means, standard deviations and the logarithmic values for each of the four judgment magnitudes of Group II (M.P.) are listed in Table II.

Analysis of these data was done in an identical manner to that completed on Group I (R.P.). The results were very similar, in that the best fit straight line that tested Stevens' Power Function (Figure 7) had a high correlation ($r = .956$, $P < .05$, $df = 39$). (Table III), while a test for Fechner's Law (Figure 8) also produced a best fit straight line with a correlation of $r = .945$ ($P < .05$, $df=39$) (Table III).

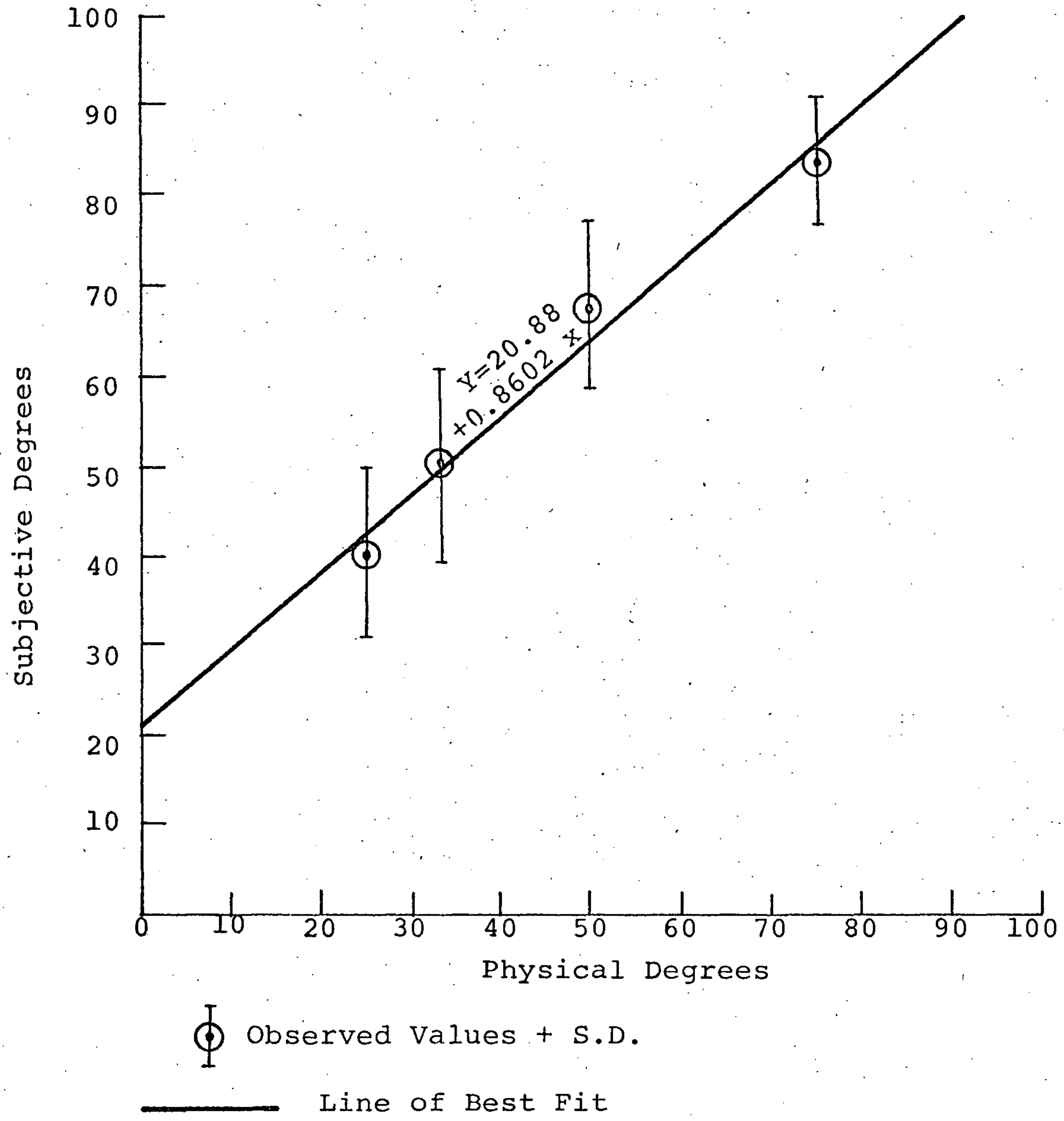

FIGURE 6

Ratio Production Judgments of Amplitude of Movement in Linear-Linear Coordinates

TABLE II

COMPARISON OF THE PHYSICAL DEGREES, SUBJECTIVE ARITHMETIC MEANS AND STANDARD DEVIATIONS OF THE FOUR MAGNITUDES OF GROUP II (MAGNITUDE PRODUCTION)

Magnitude	Physical Degrees	Log. Phy. Degrees	Subj. Arith. Means	Log. Arith. Means	Standard Deviation	Log. S.D.
50	25.00	1.398	30.99	1.486	5.29	.07
75	37.50	1.574	40.81	1.609	3.88	.04
125	62.50	1.796	72.20	1.857	6.27	.04
150	75.00	1.875	80.05	1.901	9.22	.05

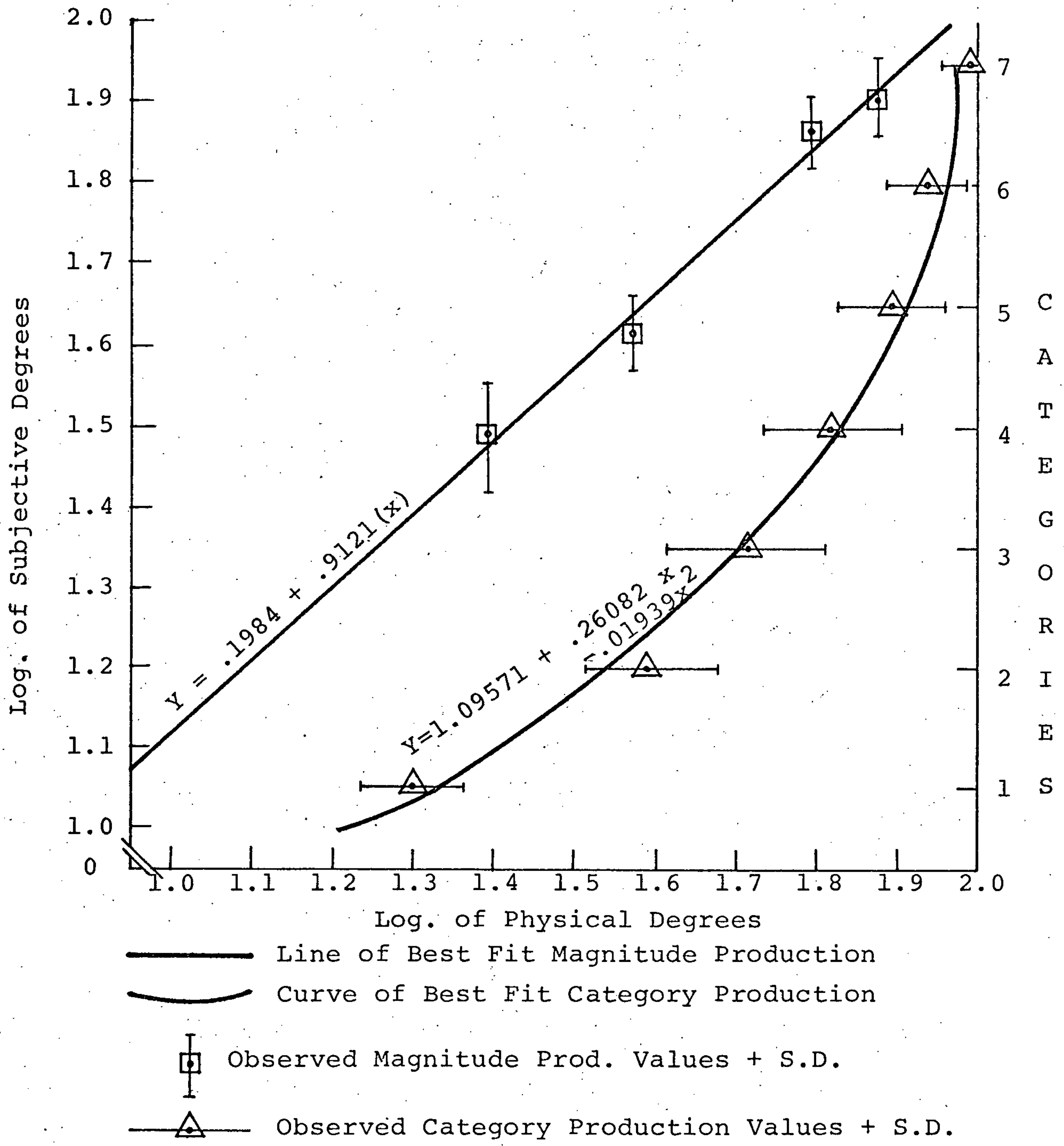

FIGURE 7

Magnitude and Category Production Judgments Amplitude of Movement in Log.-Log. Coordinates

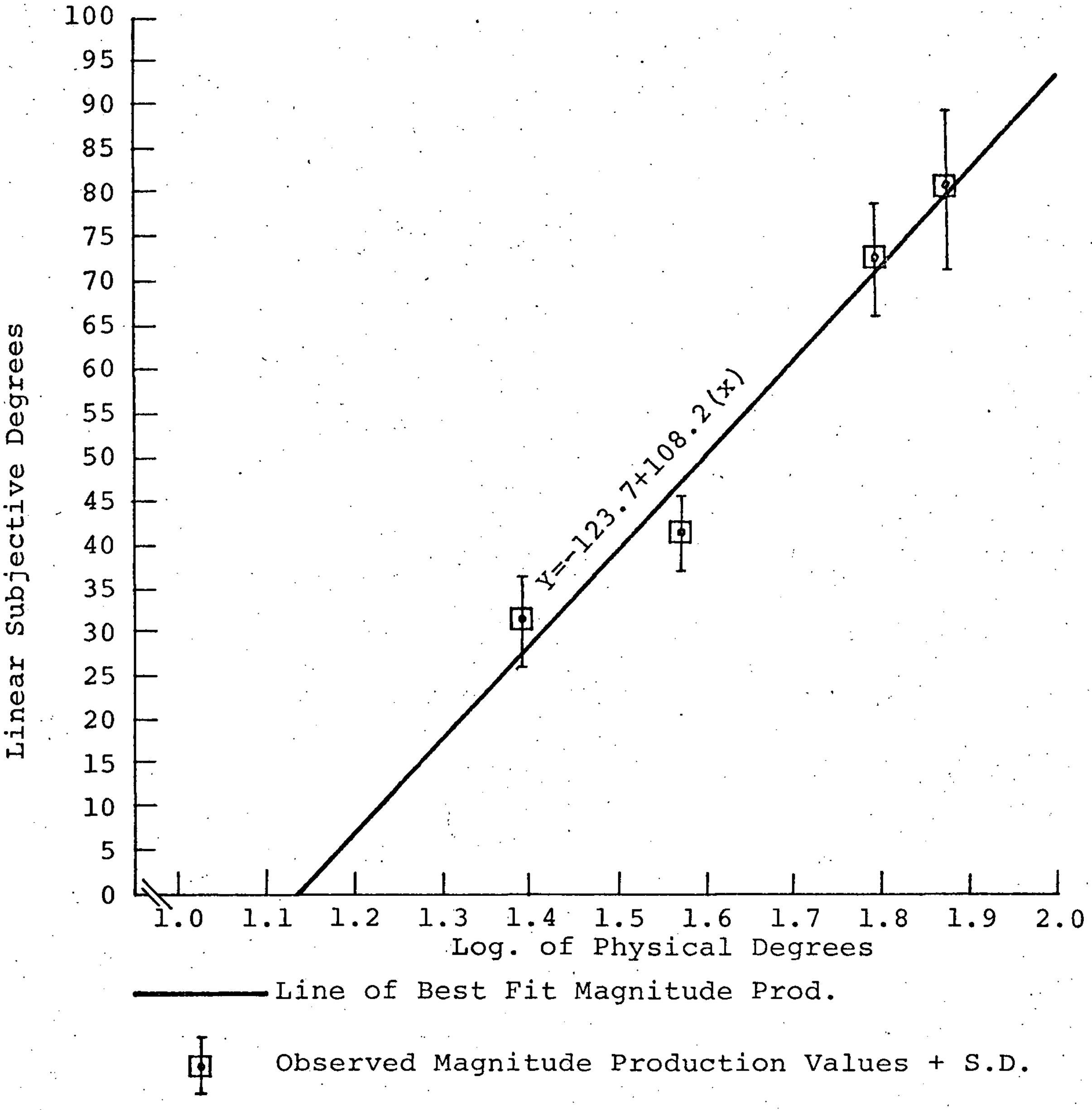

FIGURE 8

Magnitude Production Judgments of Amplitude
of Movement in Linear-Log. Coordinates

As in the analysis of Group I, these data were then plotted on linear-linear coordinates (Figure 9), and the resulting function was a best fit straight line with a correlation of $r = .953$ ($P < .05$, $df = 39$) (Table III).

Comparison of the Correlations for the Functions between the Subjective and Physical Variables for Groups I (R.P.) and II (M.P.) In order to determine if Stevens' Power Function, Fechner's Law, and the linear-linear functions fitted the data of Groups I (R.P.) and II (M.P.) equally well, a "Z" test (101) was computed to determine if the correlations were significantly different from each other. The correlation for each of the three functions of Groups I (R.P.) and II (M.P.) are listed in Table III.

In comparing the three correlations of Group I (R.P.), no significant differences were found (Table IV) using the .05 level of significance.

In comparing the three correlations of Group II (M.P.), no difference between any two correlations reached significance.

When taken collectively, the results indicate that these three straight line functions, that were fit to the data of

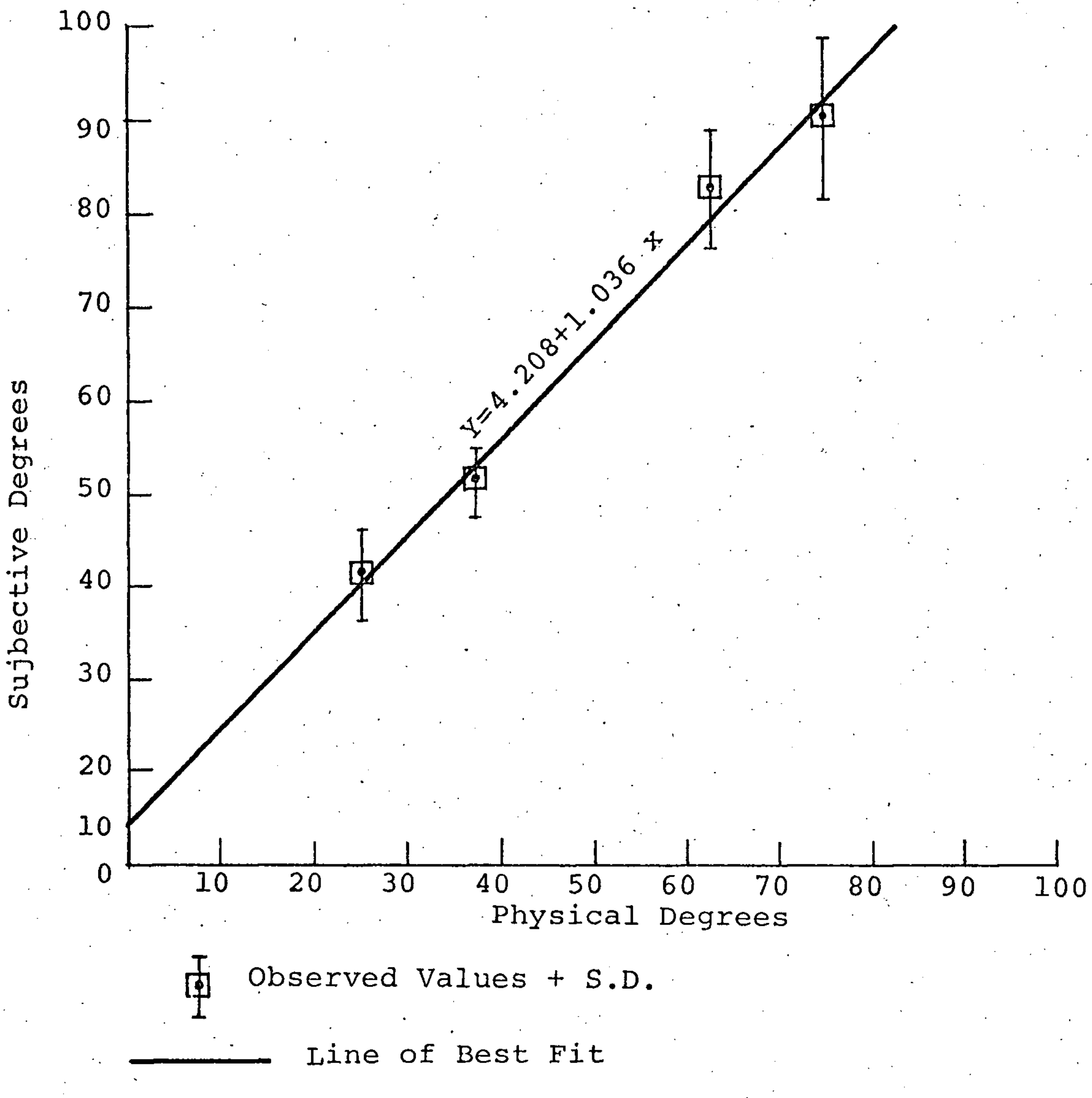

FIGURE 9

Magnitude Production Judgments of Amplitude of Movement in Linear-Linear Coordinates

TABLE III

CORRELATIONS FOR THE THREE FUNCTIONS OF GROUPS I (RATIO PRODUCTION) AND II (MAGNITUDE PRODUCTION) AND PERCENTAGE OF ACCOUNTED VARIANCE

No.	Function	Group I (R.P.) r	Group I (R.P.) % Acc. Var.	Group II (M.P.) r	Group II (M.P.) % Acc. Var.
1.	Stevens' Power Function (Log-Log)	.846	71.51	.956	91.46
2.	Fechner's Law (linear-log.)	.883	77.97	.945	89.23
3.	Linear-Linear	.882	77.78	.953	90.78

TABLE IV

"Z" TEST FOR DIFFERENCE BETWEEN THE THREE CORRELATIONS OF GROUPS I (RATIO PRODUCTION) AND II (MAGNITUDE PRODUCTION)*

	Group I (R.P.)			Group II (M.P.)		
	r_1-r_2	r_1-r_3	r_2-r_3	r_1-r_2	r_1-r_3	r_2-r_3
"Z"	.689	.593	.094	.443	.232	.210

*For two-tailed test, P=.05, "Z" required was 1.95

both Groups I (R.P.) and II (M.P.), fit the relationship between the subjective and physical variables of both groups equally well.

Comparison of the Subjective and Physical Scores of the Bisection of Ascending Series (Group III) with those of Bisection of Descending Series (Group IV). In order to test for an hysteresis effect, both the Bisection of Ascending and Descending stimulus series were plotted against degrees of movement (Figure 10) so that the same stimuli that appeared in both series could be compared. The physical stimulus, subjective arithmetic means, and standard deviations of the three bisections of Group III (Bi.As.) and Group IV (Bi.Des.) are listed in Table V.

The quadratic curves of best fit, as calculated by regression analysis using the method of least squares, did not show a hysteresis loop (Figure 10). The percentage of total variance accounted for by the curve of best fit for Group III (Bi.As.) was 99.98, and 99.90 for Group IV (Bi. Des.).

<u>Comparison of the Subjective Scores of Category Production (Group V) with the Ratio Scale of Subjective Magnitude Obtained from Ratio Production (R.P.)</u>. The physical stimulus, subjective arithmetic means, standard deviations, and their logarithmic values for the seven categories of Category Production (Group V), are listed in Table VI.

To test for the characteristic nonlinear function of a prothetic continuum when category production is employed, the subjective arithmetic means of each of the seven categories of Group V(C.P.) were plotted against the ratio scale of

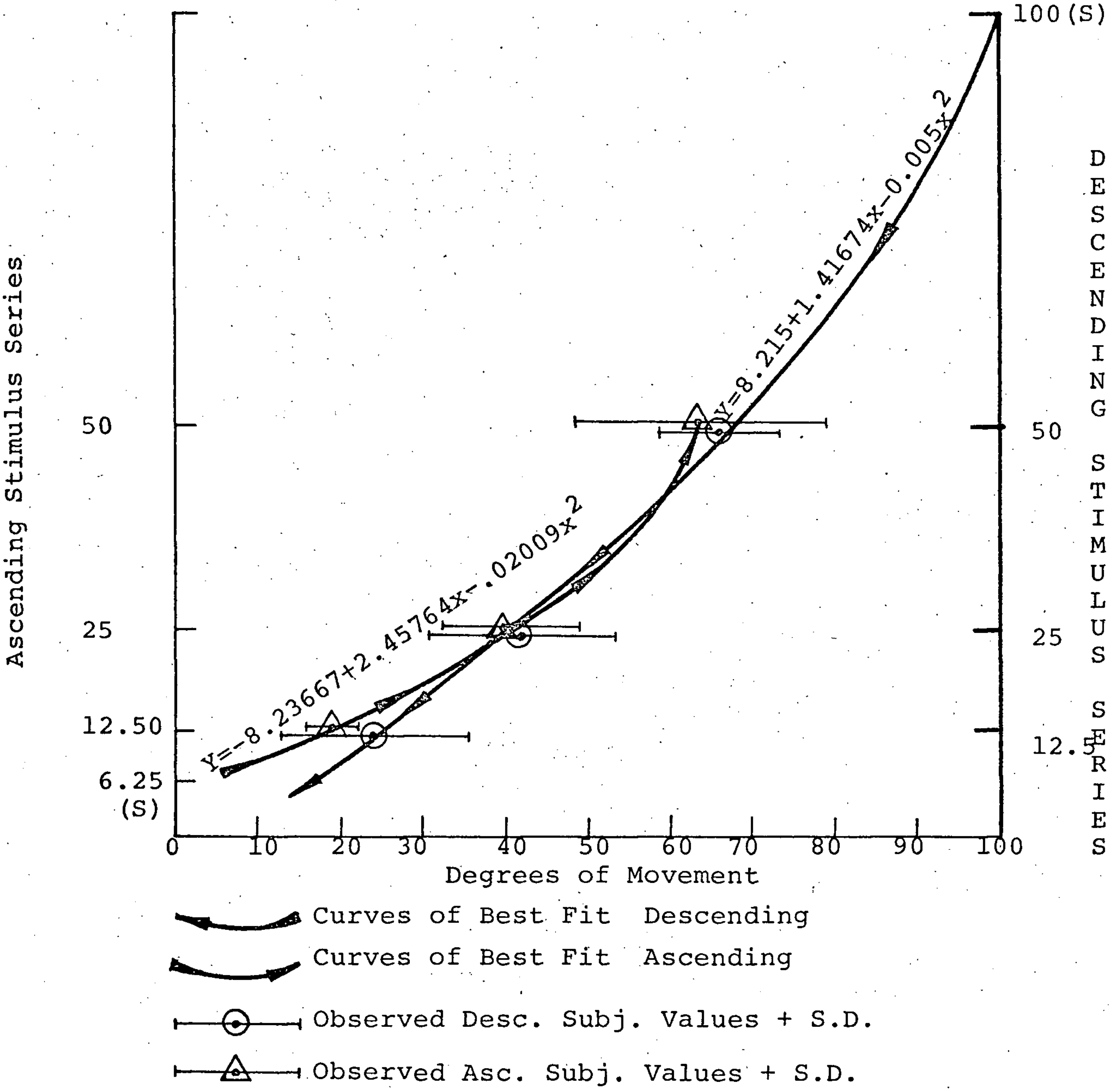

FIGURE 10

Comparison of the Functions of the Bisection of Ascending Series and Bisection of Descending Series

TABLE V

COMPARISON OF THE PHYSICAL DEGREES,SUBJECTIVE ARITHMETIC MEANS, AND STANDARD DEVIATIONS OF THE THREE BISECTIONS OF GROUP III (BISECTION OF A ASCENDING SERIES) AND GROUP IV (BISECTION OF A DESCENDING SERIES).

	Bisection	Phys. Deg.	Subj. Arith. Mean	Standard Deviation
Group III	twice as great	12.50	19.50	3.68
(Bi.As.)	twice as great	25.00	40.57	8.55
standard = 6.25°	twice as great	50.00	64.43	15.19
Group IV	1/2 less	50.00	65.87	7.40
(Bi.Des.)	1/2 less	25.00	41.88	11.26
standard = 100o	1/2 less	12.50	24.36	11.36

TABLE VI

COMPARISON OF THE PHYSICAL DEGREES, SUBJECTIVE ARITHMETIC MEANS, AND STANDARD DEVIATIONS OF THE SEVEN CATEGORIES OF GROUP V

Cat.	Phys. Deg.	Log. of Phy. Deg.	Arith. Mean	Log. of Arith. Mean	Standard Deviation	Log. of S.D.
1	13.0	1.114	16.18	1.209	4.12	0.615
2	26.0	1.415	34.09	1.532	6.77	0.830
3	39.0	1.591	46.04	1.663	8.96	0.952
4	52.0	1.716	60.38	1.780	7.87	0.896
5	65.0	1.813	72.91	1.862	4.84	0.684
6	78.0	1.892	81.26	1.909	2.92	0.465
7	90.0	1.954	93.79	1.972	3.09	0.489

subjective magnitude (i.e., the power function) obtained from Group I (R.P.). The function obtained was a quadratic curve, calculated by regression analysis using the method of least squares, which was concave upward (Figure 4).

<u>Comparison of the Subjective Scores of Category Production (Group V) with the Ratio Scale of Subjective Magnitude Obtained from Magnitude Production (M.P.)</u>. As in the immediately preceding analysis, the subjective arithmetic means of each of the seven categories of Group V (C.P.) (Table VI) were plotted against the ratio scale of subjective magnitude obtained from Group II (M.P.). Using the same regression analysis, the function obtained was a quadratic curve which was concave upward (Figure 7).

<u>Comparison of the Subjective Arithmetic Means and Physical Stimuli of the Seven Categories of Group V (C.P.)</u>. Since the data of Groups I (R.P.), and II (M.P.) were described equally well by three functions, (i.e., Stevens' Power Function, Fechner's Law, and a linear-linear plot) it seemed inappropriate to plot the data obtained from category production (Group V) against the so-called power function data. Therefore, to analyze the category production data to a greater extent, these data were plotted against the linear values of the physical stimuli. Using regression analysis by the method of least squares, the function obtained was a best fit straight line (Figure 11) with a correlation of $r = .970$ ($P < .05$, $df = 39$).

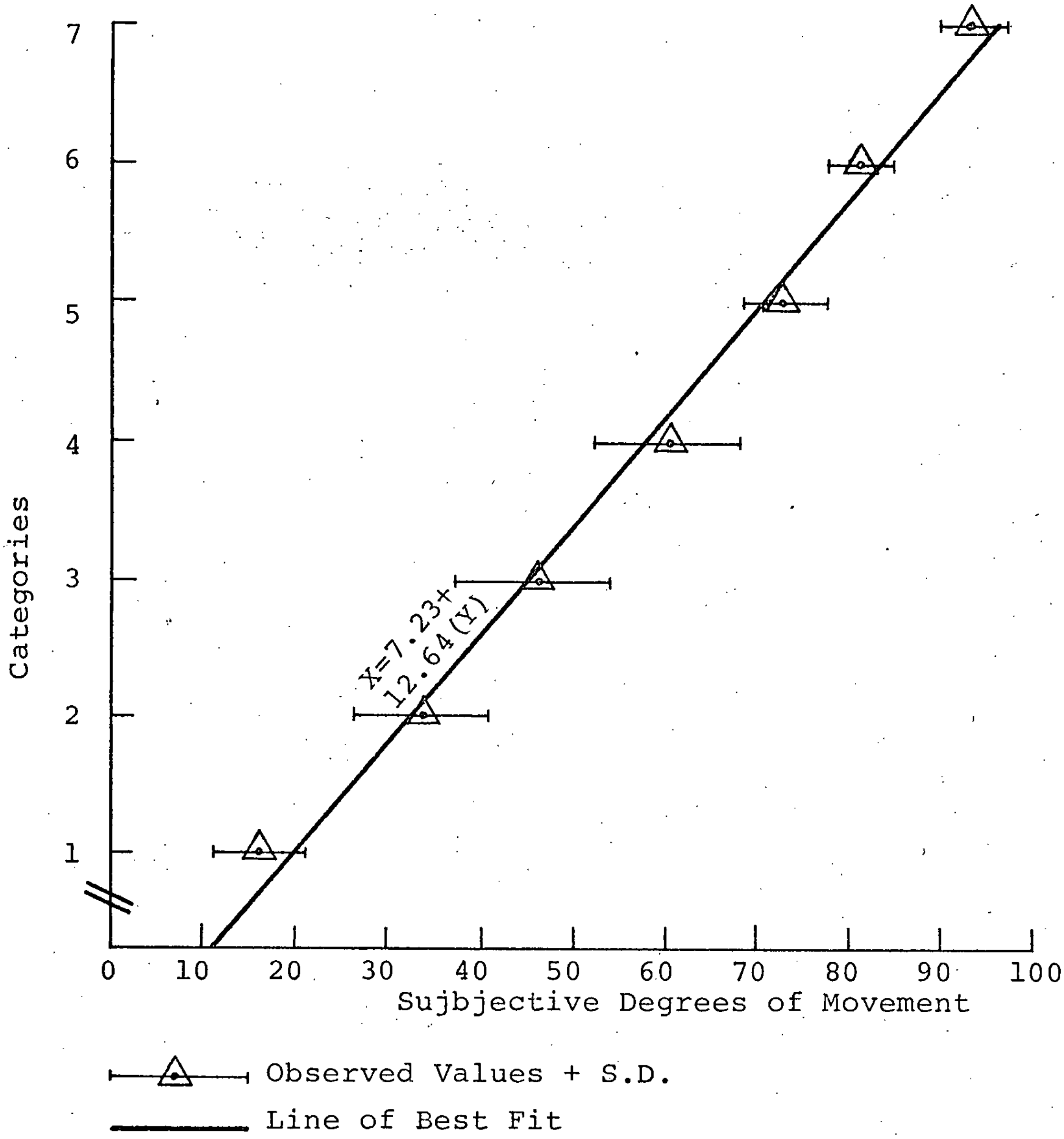

FIGURE 11

Category Production Judgments of Amplitude of Movement in Linear-Linear Coordinates

Discussion

Stevens' power function, a characteristic of prothetic continua, and Fechner's function, a characteristic of metathetic continua, both appeared to describe the relationship between the subjective and physical variables of Groups I (R.P.) and II (M.P.) equally well, as the correlations representing each function were not significantly different from each other (Table IV). One explanation that would account for this is the possibility that there is a power function relationship in which the exponent is equal to one. Such a function would fit Stevens' power function and also plot as a straight line on linear-linear coordinates. Since the data of Groups I (R.P.) and II (M.P.) both plotted as straight lines on linear-linear coordinates (Figures 6 and 9), the evidence from this particular analysis would suggest that the kinesthesis of amplitude of movement is subserved by a prothetic process. Nevertheless, these results by themselves are not unequivocal and further interpretation of the data from the total experiment must be made before any concrete conclusions can be reached.

In contradiction to the above results, support for the fact that the movement under study in this experiment was subserved by a metathetic process came from the lack of a hysteresis effect (Figure 10). In fact, the quadratic curve relating subjective magnitudes of the ascending bisections almost overlapped the quadratic curve relating subjective magnitudes of the descending bisections. This lack of hysteresis is a characteristic of constant sensitivity and metathetic processes. Thus a given stimulus would appear the same both in an ascending and descending order. Eisler and Ottander (19) have stated the "hysteresis loop" effect found on prothetic continua is mostly due to the "subjective zero" or the subjective impression of the zero point not being constant. These authors (19) have stated that in metathetic continua hysteresis was prevented by the precise knowledge of the subjective zero. This fact could possibly explain the lack of hysteresis in the present experiment since the subjective zero, or starting point, was constant and known to the subject.

Conflicting results, in terms of discriminating between a prothetic or metathetic process, were obtained for the category production data of Group V. Figures 4 and 7 show a concave upward function when the category data are plotted against the power functions derived from ratio and magnitude production. The fact that a concave function was obtained indicates non-constant sensitivity over the range of movement, and thus these results infer a prothetic process underlying amplitude of movement. However, some doubt about the meaning of these results is raised by the fact that Stevens (82, 90) reports that on the vast majority of prothetic continua, the function relating category production to the power function was concave downward. Further to this, as it has been previously established in the present discussion that the results to this point are at best ambiguous, it was decided to further analyze the category production data.

Since there was some doubt as to whether a power function was the best way to describe the relationship between amplitude of movement and the subjective judgment of amplitude, it was reasoned that the plot of category production data against the obtained power functions may have been meaningless. That is, it may be meaningless in that the category production data were plotted against a function (i.e., the power function) that did not accurately describe the data. In further analyzing the category production data, a linear function was found when the mean category responses were plotted against the actual category values (Figure 11). These results suggested that there is constant sensitivity over the range of movement which characterizes a sensory system subserved by a metathetic process. This result adds weight to the suggestion that the concave upward functions of Group V do not imply an underlying prothetic continuum. If amplitude of movement was subserved by a prothetic continuum, the function on the linear-

linear-coordinates should have been nonlinear, due to the nonconstant sensitivity along the continuum.

Thus when the experimental results are taken as a whole, the findings tended to support the conclusion that amplitude of movement is subserved by a metathetic process. This agrees with a great deal of the physiological evidence dealing with the role and function of the receptors, which are considered responsible for kinesthesis. According to Stevens (82), discrimination on a metathetic continuum is mediated by a substitutive process at the physiological level, and would require a qualitative receptor mechanism. A stimulus change would cause a different population of receptors to be activated with no increase in the numbers of receptors responding. This process of receptor substitution has been shown by many authors (3, 9, 14, 36, 54, 58, 63, 79, 80, 97) to be operating in the kinesthetic receptors of the joint capsule. These authors have indicated that different joint angles cause different receptors to fire. Some fire at complete flexion, others at complete extension, and others between flexion and extension. Thus joint position and degree of movement would be determined by the discharge rate of a specific group of receptors. Therefore the results of the present experiment, in conjunction with previous physiological evidence, would suggest that the joint receptors signal the joint's position and degree of movement by the discharge of a specific group of receptors, or in other words, signal amplitude of movement metathetically.

Whether cortical cells, which have been shown to be connected to the joint receptors responsible for kinesthesis (60, 28), also function metathetically, is not clearly supported by past physiological evidence. The results of the present experiment suggest that the subjective impression of the amplitude of movement is formed metathetically. Yet Mountcastle, Poggio and Werner (62) have found that the third order joint receptor afferents, which are located in the ventrobasal complex of the thalamus, fire quantitatively to changes in joint angles. These authors found that a power function of the type: $R = KS^N$, described the relationship between joint angle and thalamic cell activity. The authors proposed that metathetic information derived from joint receptors was transformed into prothetic information at the thalamus. As the results of the present experiment suggest that the final subjective impression is formed metathetically, a further transformation may occur after the third order afferents in the thalamus. In other words, prothetic information about joint position in the thalamus may undergo yet another or a series of other transformations before the final impression is formed. As the third-order relay of afferents in the thalamus is considered early in the entire neural chain between stimuli and response (62) it is quite probable that a series of changes occur in the neural impulse before the final impression is formed. It is also possible that the metathetic kinesthetic information passes through the thalamus without being altered, so that the information reaching the cortex is metathetically based.

Support for this latter position was given by Mountcastle and Powell (63) who found that cells in the sensory areas of the cortex, which are connected to the joint receptors, are arranged in a topographical pattern. These authors have stated that body angles, and changes in them, are depicted by the pattern of activity of these cortical cells. This would suggest that joint position and movement are signalled by a specific group of activated cortical cells, or in other words, metathetically. As the activity of these sensory area cortical cells would occur late in the neural chain, the suggestion is supported that judgments of amplitude of movement are formed by a metathetic process.

Wood (98), who used similar methods as those used in the present experiment, showed that the subjective impression of speed of a self-initiated arm movement was related to actual speed by a prothetic continuum. Wood's results and conclusions are supported by Smith (80) and Williams (97), as they have stated that speed of movement was indicated by the rate of transient discharges of the joint receptors to movement -- the faster the movement, the quicker the discharge rate of the activated group of joint receptors responsible for that angle. Therefore, speed of movement was coded quantitatively by frequency of changing receptor discharge.

Two other sensory continua which contain a kinesthetic component have also been shown to be subserved by a prothetic process. These include force of handgrip, using a hand dynamometer (81), and judgments of heaviness, using lifted weights. (94).

That speed of movement, judgments of heaviness, and force of handgrip are prothetic, does not contradict the results of the present experiment, which suggests that judgments of amplitude of movement are formed methathetically, as there are many different aspects of kinesthesis and each may function differently.

Kinesthetic Cues. This section of the discussion will deal with the subjective reports of the experimenter as well as reports from the subjects. An attempt will be made to relate these impressions to scientific findings, in an attempt to determine what factors are involved in discriminating amplitude of movement.

In the present experiment, attention to incoming kinesthetic information appeared to be lost during the middle range of the movement. An explanation for this phenomenon was found in a study by Keele and Posner (30) who reported that attention to kinesthetic feedback was greatest at the beginning, decreased to a low in the middle, and slightly increased at the end of the movement.

Because of this lack of attention, the subject may be using final position of the joint rather than amplitude of movement as a cue in kinesthetic judgments. This is supported by Paillard and Brouchon (69) who have suggested that kinesthetic information about joint movement comes from the final dynamic phase of the movement, not from the final static position or total movement.

Many of the subjects of the present experiment reported that much of the available kinesthetic information was of limited use, for they were not able to use it effectively in forming subjective magnitude. They stated that there was no comparison mechanism available to which the incoming kinesthetic information could be contrasted. Yet, in spite of this, it is surprising how accurate the kinesthetic reproductions of the present experiment and others (45) were.

Paillard and Brouchon (69) have suggested that there is a comparator mechanism, called the "spatial reference system", to which incoming kinesthetic information can be contrasted. This reference system would be of limited use in the present experiment, however, for the movements used were unfamiliar to the subject. Since there was no knowledge of results there should not be any information in this reference system. In that case, the incoming kinesthetic information can only be compared to the memory of the subjective impression of the given standard movement.

CHAPTER V

SUMMARY AND CONCLUSIONS

The purpose of this study was to investigate the psychophysics of active kinesthesis. In essence the study investigated whether the subjective impression of amplitude of movement of self-initiated, shoulder lateral flexion of the preferred arm was formed through a prothetic, or metathetic continuum as outlined by Stevens (82). Fifty volunteer subjects, both male and female, right and left handed, were randomly assigned to five groups of equal N. Each group was randomly assigned to one of five experimental conditions labelled: Ratio Production, Magnitude Production, Bisection of Ascending Series, Bisection of Descending Series and Category Production.

The Ratio Production group was given a standard movement of one hundred degrees and asked to produce movements that were 1/4, 1/2, 1/3, 3/4 of the standard movement. Each fractional movement was repeated randomly four times with the given standard preceding each movement. The Magnitude Production group was given a standard movement of fifty degrees that was arbitrarily called 100. The subject was then asked to produce movements that, when compared to the standard movement represented movements of 50, 75, 125 or 150. Each magnitude was produced four times at random with the standard given before each movement. The Bisection of Ascending Series group was given a standard of 6.25 degrees and then was asked to produce a movement twice that, then a movement twice that of the second movement, then a movement twice that of the third movement. The three increasing movements were produced in succession following the standard. Each set of three movements was repeated six times. The Bisection of Descending Series group was given a standard of one hundred degrees and then asked to produce a movement one-half that movement, then a movement one-half that of the second movement, then a movement one-half that of the third movement. The three decreasing movements were produced in successive order following the standard and each set of three movements was repeated six times. The Category Production group was given two standards. One was thirteen degrees and called Category 1 and the other was ninety degrees and called Category 7. The subject was told that there were seven categories, all equidistant from one another, and that he was to produce the category asked for. Each of the seven categories was given randomly five times, with both standards given between each category production.

The group arithmetic means were calculated for all judgments for all five groups. The subjective and physical variables were compared graphically and statistically for Ratio Production, Magnitude Production and Category Production. The subjective and physical values of Bisection of Ascending and Bisection of Descending were also graphically and statistically compared.

The results tended to support the conclusion that judgments of amplitude of movement of self-initiated, shoulder lateral flexion was subserved by a metathetic continuum.

Recommendations

1. If this study were repeated, Magnitude Estimation and Category Estimation methods should be used with about twenty stimuli per method.

2. This study should be verified by a retest and also a crossmodality study using length of lines and amplitude of movement. Stevens (82) has recommended the use of length of lines as a reference modality in crossmodality studies because of its exponent being one.

3. Another experiment similar to this one should be done in which the subject establishes his own standard, which may give the subject more useful information upon which to judge movements.

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APPENDIX A

Regression Line by Method of Least Squares

Group I (R.P.)

$Y = a + bx$ $\qquad$ $Y = .6473 + .6854\ (x)$ $\qquad$ Graph 1

(A) Log-log Plot - Graph # 1 (Stevens)

$$Y_1 = .6473 + .6854\ (1.9)$$

$$Y_1 = 1.94956$$

$$Y_2 = .6473 + .6854\ (1.2)$$

$$Y_2 = 1.46978$$

$K = .6473$ (log) of $R = KS^N$ antilog. 6473 = 4.44

71.51% prop. of total observed variance of Y which is accounted for by this regression line.

(B) Linear - Log Plot - Graph # 2 (Fechner)

$$Y = a + bx$$

$$Y = -87.24 + 91.12\ (x)$$

$$Y_1 = -87.24 + 91.12\ (2.0)$$

$$Y_1 = 95.0$$

$$Y_2 = -87.24 + 91.12\ (1.1)$$

$$Y_2 = 12.991$$

- no "K" in Fechner fraction
- 77.97% prop. of total observed variance of Y which is accounted for by this regression line.

Regression Line by Method of Least Squares

Group II (M.P.)

(a) Log.- Log Plot - Graph # 3 (Stevens)

$$Y = a + bx$$

$$Y = .1984 + .9121\ (x)$$

$$Y_1 = .1984 + .9121\ (1.9)$$

$$Y_1 = 1.93139$$

$$Y_2 = .1984 + .9121\ (1.2)$$

$$Y_2 = 1.29292$$

"K" = 1.984 (log) of $R = KS^N$ antilog .1984 = 1.58

91.46% prop. of total observed variance of Y which is accounted for by regression line.

(b) Linear-Log Plot - Graph # 4 (Fechner)

$$y = a + bx$$

$$y = -123.7 + 108.2\ (x)$$

$$y_1 = -123.7 + 108.2\ (2.0)$$

$$y_1 = 92.7$$

$$y_2 = -123.7 + 108.2\ (1.3)$$

$$y_2 = 16.96$$

no "K" in Fechner fraction

89.23% of total observed variance of Y which is accounted for by regression line.

Plot Points for Category Production

C	Log of Am $\bar{x}$	Points three Ratio Scale of Subj. Mag. (Power Function) R.P. (Graph 1)	M.P. (Graph 3)
1	1.209	1.475	1.30
2	1.532	1.696	1.595
3	1.663	1.785	1.712
4	1.780	1.865	1.820
5	1.862	1.922	1.896
6	1.909	1.954	1.940
7	1.972	1.996	1.995

Group I (R.P.)

Correlation Scores and '2' Best for Significance

Var 1 = 45.83 - average of 4 Phy. degrees

Var 2 = 1.619 - log of mean of four Physical Degrees

Var 3 = 1.757 - log of Var 4

Var 4 = 60.31 - arith. mean of four subjective arith. means

		r	Z	N
Z_1	(1) Var 2 vs Var 3 (Log-log) (Stevens)	.845.7	1.238	40
	(2) Var 2 vs Var 4 (Log-Linear) (Fechner)	.883.0	1.398	40

$$\sqrt{Z_1' - Z_2'} = \sqrt{\frac{1}{N_1 - 3} + \frac{1}{N_2 - 3}} = .232379$$

$$Z = \frac{(Z_1' - Z_2') \quad (\bar{Z}_1' - \bar{Z}_2')}{\sqrt{Z_1' - Z_2'}}$$

null hypothesis $\bar{Z}_1' = \bar{Z}_2'$

$$Z_1 = \frac{(1.238 - 1.398) - (0)}{.232379} = .689$$

- no significant difference between "r's" ∴ regression lines fits both Stevens' and Fechner's Laws

- "Z" must be 1.95 to be significant at .05 level of confidence for two-tailed test

Group I (R.P.)

Correlation Scores	Test for Significance	r	Z	N
Z_2	(3) Var. 1 vs. Var 4 (Linear-linear)	.8819	1.376	40
	(2) Var 2 vs . Var 4 (Log.-Linear)	.8830	1.398	40
Z_3	(3) Var 1 vs. Var 4 (Linear-linear)	.8819	.376	40
	(4) Var 2 vs. Var 3 (Log.-Log.)	.8457	1.238	40

$$\sqrt{Z_1' - Z_2'} = \sqrt{\frac{1}{N_1-3} + \frac{1}{N_2-3}} = .232379$$

$$Z_2 = \frac{(Z_1' - Z_2') - (\bar{Z}_1' - \bar{Z}_2')}{\sqrt{Z_1' - Z_2'}} \quad \text{null hypothesis } \bar{Z}_1' = \bar{Z}_2'$$

$$Z_2 = \frac{.60398 - 1.376 - 0}{.232379} = \frac{.022}{.232379} = \underline{\underline{.094}}^{*}$$

*Not sign at .05 head 2 tailed

$$Z_3 = \frac{(Z_1' - Z_2')(\bar{Z}_1' - \bar{Z}_2')}{\sqrt{Z_1' - Z_2'}} = \frac{1.376 - 1.238 - (0)}{.232379} = \frac{.138}{.232379} = .593^{*}$$

*Not sign at .05 level 2 tailed

Group II (M.P.)

Correlation Scores and "Z" test for Significance

Var 1 = 50.00 average of 4 Phy. degrees

Var 2 = 1.661 log of mean of four Physical degrees

Var 3 = 1.713 log of Var 4

Var 4 = 56.01 arith. mean of four subjective arith. means

		r	Z	N
Z_1	(1) Var 2 vs Var 3 = (log-log Stevens)	.9564	1.886	40
	(2) Var 2 vs Var 4 = (linear-log, Fechner)	.9446	1.783	40

$$\sqrt{Z_1' - Z_2'} = \sqrt{\frac{1}{N_1 - 3} + \frac{1}{N_2 - 3}} = .232379$$

$$Z = \frac{(Z_1' - Z_2') - (\overline{Z}_1' - \overline{Z}_2')}{\sqrt{Z_1' - Z_2'}}$$

null hypothesis: $\overline{Z}_1' = \overline{Z}_2'$

$$Z = \frac{(1.886 - 1.783) - (0)}{.232379} = .443$$

- no significant difference between "r"'s, ∴ regression line fits both Stevens' and Fechner's Laws
- "Z" must be 1.95 to be significant at .05 level of confidence for two-tailed test

Group II (M.P.)

Correlation Scores and "Z" Test for Sign

		r	Z	N
Z_2	Var 1 vs Var 4 (linear-linear)	.9528	1.832	40
	Var 2 vs Var 4 (linear-log)	.9446	1.783	40
Z_3	Var 1 vs Var 4 (linear-linear)	.9528	1.832	40
	Var 2 vs Var 3 (Log.-Log.)	.9564	1.886	40

$$\sqrt{Z_1' - Z_2'} = \sqrt{\frac{1}{N_1-3} + \frac{1}{N_2-3}} = .232379$$

$$Z_2 = \frac{(Z_1' - Z_2') - (\bar{Z}_1' - \bar{Z}_2')}{\sqrt{Z_1' - Z_2'}} \quad \text{null hypothesis } \bar{Z}_1' = \bar{Z}_2'$$

$$Z_2 = \frac{(1.832 - 1.783) - (0)}{.232379} = \frac{.049}{.232379} = .210^{*}$$

$$Z_3 = \frac{(1.832 - 1.886) - (0)}{.232379} = \frac{.054}{.232379} = .232^{*}$$

*not sign at .05 level 2 tailed

Curves of Best Fit by Polynomial Regression

graph 5 Gp3 $Y = 8.23667 + 2.45764\ x - 0.02009\ x^2$

explained variance by this line is .9998 of the total variance due to subj. means

graph 5 Gp4 $Y = 8.215 + 1.41674\ x - 0.005\ x^2$

explained variance by this line is .999 of the total variance due to subj. means

graph 1 Gp5 $Y = 1.32157 + 0.19590\ x - 0.01460\ x^2$

against power function of Gp I (R.P.) Graph #1, explained variance by this line is .982 of the total variance due to subj. means

graph 3 Gp5 $Y = 1.09571 + .26082\ x - 0.01939\ x^2$

against power function of Gp II (M.R.) Graph #3, explained variance by this line is .9828 of the total variance due to subj. means

Line of Best Fit - Group V - Linear-Linear Graph # 8

r = .9723

variance accounted - 94.54%

X = 7.230 + 12.64 x

X = 7.230 + 12.64 (1)

X = 19.87

Y = 7.230 + 12.64 (6)

Y = 83.07

Line of Best Fit - Group II - Linear-Linear Graph # 6

r = .9528

variance accounted = 90.78%

Y = 4.208 + 1.036 x

Y = 4.208 + 1.036 (10) = 14.568

Y = 4.208 + 1.036 (80) = 87.09

Line of Best Fit - Group I - Linear-Linear Graph # 3

r = .8819

variance accounted 77.78%

Y = 20.88 + 0.8602 (x)

y = 20.88 + 0.8602 (10) = 29.48

y = 20.88 + 0.8602 (80) = 89.69

APPENDIX B

DATA RECORD SHEET

Group# 1 Ratio Production 10 Subjects

Subject No.____ Name:________________ Hand:________________

Standard Movement: 100°

No	Stimulus	Required in degrees	Subject's Response
	S	100	
1	3/4	75	
	S	100	
2	1/4	25	
	S	100	
3	1/3	33.34	
4	1/3	33.34	
5	1/4	25	
6	1/4	25	
7	1/2	50	
8	3/4	75	
9	3/4	75	
10	1/3	33.34	
11	1/4	25	
12	1/2	50	
13	1/2	50	
14	3/4	75	
15	1/2	50	
16	1/3	33.34	

Data Record Sheet

Group # 2 Magnitude Production 10 subjects

Subject ________ Name: ______________________________ Hand: __________

Standard Movement: 50 degrees, called 100

No	Stimulus	Required Response	Subject's Responce
	S (100)	50	
1	75	37.5	
	S (100)	50	
2	75	37.5	
	S	50	
3	150	75	
	S		
4	50	25	
	S		
5	50	25	
	S		
6	150	75	
	S		
7	75	37.5	
	S		
8	150	75	
	S		
9	50	25	
	S		
10	50	25	
	S		
11	125	62.5	
	S		
12	75	37.5	
	S		
13	125	62.5	
	S		
14	150	75	
	S		
15	125	62.5	
	S		

DATA Record Sheet

Group 3 Bisection of Ascending Stimulus Series 10 subjects

Subject No. ____ Names ________________ Hand: ________

No	Stimulus	Required in degrees	Subject's Response
S		6.25	
1	Twice as much	12.50	
2	"	25.00	
3	"	50.00	
S		6.25	
1	Twice as much	12.50	
2	"	25.00	
3	"	50.00	
S		6.25	
1	"	12.50	
2	"	25.00	
3	"	50.00	
S		6.25	
1	"	12.50	
2	"	25.00	
3	"	50.00	
S		6.25	
1	"	12.50	
2	"	25.00	
3	"	50.00	
S		6.25	
1	"	12.50	
2	"	25.00	
3	"	50.00	

Data Record Sheet

Group #4 Bisection of Descending Stimulus Series
10 subjects

Subject No____ Name: ______________________ Hand: ______________

No	Stimulus	Required	Response
	S	100	
1.	1/2 Less	50	
2.	"	25	
3.	"	12.5	
	S	100	
1.	1/2 Less	50	
2.	"	25	
3.	"	12.5	
	S	100	
1.	1/2 Less	50	
2.	"	25	
3.	"	12.5	
	S	100	
1.	1/2 Less	50	
2.	"	25	
3.	"	12.5	
	S	100	
1.	1/2 Less	50	
2.	"	25	
3.	"	12.5	
	S	100	
1.	1/2 Less	50	
2.	"	25	
3.	"	12.5	

DATA Record Sheet

Group # 5 Category Production 10 subjects

Subject No.___ Name ____________ Hand __________

No. 1 STANDARD 13 degrees
No. 2 STANDARD 90 degrees

No	Stimulus	Required	Response
	S1	13	
	S2	90	
1	C1	13	
	S1	13	
	S2	90	
2	C3	39	
3	C5	65	
4	C1	13	
5	C4	52	
6	C2	26	
7	C7	90	
8	C2	26	
9	C1	13	
10	C3	39	
11	C3	39	
12	C7	90	
13	C7	90	
14	C6	75	
15	C7	90	
16	C2	26	
17	C1	13	
18	C4	[illegible]	

	Stimulus	Required	Response
19	C5	65	
20	C6	78	
21	C4	52	
22	C5	65	
23	C7	90	
24	C6	78	
25	C3	39	
26	C4	52	
27	C4	52	
28	C2	26	
29	C5	65	
30	C1	13	
31	C2	26	
32	C6	78	
33	C3	39	
34	C5	65	
35	C6	78	

C1 – 13 degrees
C2 – 26 "
C3 – 39 "
C4 – 52 "
C5 – 65 "
C6 – 78 "
C7 – 90 "
C1 – 13 " [illegible]

APPENDIX C

TABLE I

RESULTS

Group I	F	degrees	Log	G.M.	Log G.M.	Md	A.M.	Log AM	AMSD	Log S.D.
R.P.										
S=100°	1/4	25.00	1.398	38.55	1.586	1.552	40.10	1.592	9.730	.10
	1/3	33.34	1.523	48.42	1.685	1.583	50.00	1.689	10.39	.09
	1/2	50.00	1.698	67.14	1.827	.587	67.73	1.828	8.33	.05
	3/4	75.00	1.875	82.99	1.919	.415	83.40	1.920	6.61	.03
					md.:	1.043				
Group II	50	25.00	1.398	30.41	1.483	.581	30.99	1.486	5.29	.07
M.P.	75	37.50	1.574	40.46	1.607	.352	40.81	1.609	3.88	.04
S=50°	125	62.50	1.796	71.95	1.857	.255	72.20	1.857	6.27	.04
(100)	150	75.00	1.875	79.43	1.900	.617	80.05	1.901	9.22	.05
					md:	.451				
Group III	twice	12.5					19.5		3.68	
S=	as	25.00					40.57		8.55	
6.250	great	50.00					64.43		15.19	
BiAsc										
Group IV	1/2	50.00		65.163	1.814	.707	65.87		7.404	
S=100°	1/2	25.00		40.272	1.605	1.608	41.88		11.26	
BiDes	1/2	12.50		21.979	1.342	2.381	24.36		11.36	
					md:	1.565				
Group V	C1	13.0	1.114	15.417	1.188	.763	16.18	1.209	4.124	0.615
S1=C1=	C2	26.0	1.415	32.885	1.517	1.205	34.09	1.532	6.765	0.830
13°	C3	39.0	1.591	44.771	1.541	2.269	46.04	1.663	8.960	0.952
S2=C7=	C4	52.0	1.716	59.566	1.775	.814	60.38	1.780	7.867	0.896
90°	C5	65.0	1.813	72.444	1.860	.466	72.91	1.862	4.836	0.684
	C6	78.0	1.892	81.096	1.909	.164	81.26	1.909	2.919	0.465
	C7	90.0	1.954	93.756	1.972	.034	93.79	1.972	3.086	0.489
					md:	.673				
					Gmd:	.974				

RAW DATA

Subject

	F	1	2	3	4	5	6	7	8	9	10
	1/4	45.5	55	30.5	40.5	40.5	35	63	41.5	47	39.5
	1/4	38.5	44.5	32.5	33.0	33.5	22	53.5	36.5	52	26.5
	1/4	48.5	45	20	27	35.5	32.5	60.5	39	44.5	35
	1/4	35.5	49	22	45	34	28.5	64	34.5	34.5	39
Group I	1/3	60	6-	33	40.5	40	35	60	46	60	54
Ratio	1/3	52	54.5	42.5	70	47	43	76.5	54	63	53
Prod-	1/3	53	55.5	16.5	60.5	44	39.5	61	51	47	44
uction	1/3	52	65	29	55	40.5	35	62	51	51.5	43
	1/2	77	72	62	80	60	53.5	77.5	64.5	72.5	62
	1/2	70	70.5	59	79.5	56.5	55.5	80	64.5	74	67.5
	1/2	71	66	58.5	82.5	56	52	80	61.5	64.5	66
	1/2	68.5	68	58	80	62	66	80.5	71.5	75	63
	3/4	90	82	74	94	79	80.5	86	79	77	77
	3/4	90.5	84	87	92.5	75	75	95.5	86.5	84	76
	3/4	86	82	70.5	95	75	68.5	95	82	87	76.5
	3/4	90.5	89.5	77	95.5	70.5	86.5	90	84.5	86.5	83.5
	50	29	40	31	21	20.5	23	36.5	25.5	24.5	35
	50	39	38	34.5	26	25	24.5	33	31	28	28
	50	35.5	47	32	30	27	25.5	34	27	32	30
Group II	50	37	41	34	37	22.5	29.5	36	26.5	30	33
Magni-	75	37	45	43.5	33	30	45.5	35.5	33	41.5	42.5
tude	75	37.5	47	42	40	35.5	46	32	34	40	37.5
Prod-	75	42.5	52.5	51	39.5	43	40	41	41.5	37.5	38
uction	75	43	48.5	46	46.5	37 -	43.5	44.5	38	42	39
	125	70	70.5	77.5	78	71	80	63.5	64.5	70.5	76
	125	70	60	76	72.5	76	72	66	58	66	80.5
	125	70	68	82.5	94	73.5	78	65.5	65.5	67	76
	125	72	75	75.5	69	72.5	83	59	68	69	78.5
	150	65.5	67.5	96.5	74	84	87	71	73.5	77	87
	150	78	50	93	81.5	77.5	95.5	75.5	76	77	80
	150	74	75	94	93	82	90	74	72	69.5	87
	150	80	72.5	98	90	82.5	89	75.5	67	80	82

RAW DATA

Subject

Group III	1	2	3	4	5	6	7	8	9	10
twice as much	17	16	13.5	16	16.5	21.5	16	14.5	19	22
"	40	31	31.5	31	34.0	60	26	32.5	51	39.5
"	75	50	48	48.5	55.0	100.0	46.5	57.0	95	57
" X	15	16.5	14.5	17	18.0	19	12.5	26	15	24
"	31	50.5	35	34	42	41.5	25	52	50.5	46.5
"	70	66.0	51.5	47	58	60	44.5	92.5	96.5	58
"	15	16.0	20	14	24	21.5	13.5	21	14	24.5
"	27	30.5	37	30.5	44.5	41.5	26	46	47	35.5
"	38	56.5	53.5	52.0	61	71	44	77.5	92	52.5
"	20	14.5	23	16.5	24	20	15.5	21.5	25	25.5
Twice much	35	33.5	45.5	29	47	44.5	27.5	48	73	45.5
"	49	52.5	61	46	61.5	74.5	51.5	78	94	74
"	17	20	26.5	20	25	18.5	13.0	31	14	37
"	25.5	39.5	54	33.5	44	46	29.5	54.5	51	63.5
"	42.0	59.5	69	43	65.5	77	43.0	82.5	92	89
"	20	20.5	28	13.5	23	18	13.5	24.5	22.5	26
"	25	46	47	30.5	34.5	46.5	30.5	51.5	46	47.5
"	38	80	72	46	58	68	50.5	84.5	95.5	95
Group IV - Bisection Descending										
1/2 Less	76	56.5	85.5	69	58	63	61.5	71.5	65	67
"	60	26	57	48.5	37.5	30.5	31	46	37	35
"	45.5	12	26	33	19	19.5	10.5	32	13	13.5
"	78.5	52	82.5	78	63	61	60	69.5	62	69.5
"	58	27	50	58	47	33.5	31	48	37	36
"	40	16	32	36.5	23	20	11.5	30	15	23.5
"	78	55.5	85	70	60.5	60	78	64	63.5	77
"	61	31	59	58	40	32	36.5	36	35	52.5
"	47	22	30	27	23	16	18.5	23	14.5	19
1/2 Less	75.5	58	80	75.5	63	54	52	66	55	66
"	65	34.5	45	49	36	30.5	19	44	27.5	38
"	50	20	30.5	37	19	19	6.5	27	11.5	17
"	73	64	36	74	64	55.5	55	68.5	52	16
"	62-	36	50.5	51.5	36	33.	26	49	32	59.5
"	55.5	21.5	35	29.5	19	18	11.5	32	16	20.5
"	79	58	84	73.5	66.5	52.5	55	68.5	61	60.5
"	68	36.5	50	49	42	27.5	24	52	29	36
"	63	21.5	26.5	31	24	18	8	26.5	15.6	19

RAW DATA

Subject

Group V Category Production

	1	2	3	4	5	6	7	8	9	10
C1	18	13	10.5	14.5	22	18.5	22.	16.5	21	21
C1	10	13.5	12	14	9.5	16.5	16.5	15	27	15
C1	16	16	14	7	17	15.5	10	21	28	14.5
C1	15	18	16	9	14	30	12.5	20	29.5	12.5
C1	16	12	14	11	11	17.5	13	15	24.5	13.5
C2	49.5	32	30	29	41	31	34	36	44	25
C2	47	37	34.5	18.5	20.5	35	26	42	40	29
C2	37.5	39.5	41	24.5	35	44	26	37	42	27
C2	32	39	30	16.5	26	52.5	37	26	37	29
C2	30.5	31	32	14	36	54	35	38	45.5	29
C3	65	35	46	29.5	42	46	62	38.5	63	46
C3	64.5	50	55	33.5	29	55	34	46	57.5	45
C3	45	47	54	32	33	52	36	49	50.5	44
C3	58	41	61.5	26	27	64	47	45	52.5	44
C3	53	44.5	54	31	35	52	56.5	40	42	43
C4	67	56	62	53	37.5	64.5	45	47	66.5	50
C4	66	60	61	47	54	63	45	64	71	64
C4	72.5	53	66	33	52	74	68	67.5	70	69
C4	63	57	61.5	44	56.5	62	78	50	69	59
C4	67	60.5	67.5	36	56.5	75	65.5	57.5	69	60
C5	76	73	76	72	67	82.5	84	72.5	74	71
C5	75	82	76.5	56	63.5	72	56	75	92	71
C5	72	70	80	57	76.5	73.5	85.5	84	87	73.5
C5	68,5	68	72	59	66	80	75	70	74	79
C5	73	72	80.5	67	70.5	66	69.5	61.5	75	73
C6	70	84	77	82	76	80	71	82	89	82
C6	80	80	75.5	73	76	83	74	84	98	85
C6	80	82	81	85	94	81.5	84	81	87	83
C6	80	78	84	82	82	85	94	83	89.5	80.5
C6	75	83.5	88	81.5	76	72	86	64	78	81
C7	89	91	92	90	92	96	100	88	100	97
C7	91	100	100	85	98.5	97.5	94	91	99.5	93
C7	94	95.5	92	88	95	98	86	86	100	93
C7	90	96	94	89.5	92	98	94	96	100	92.5
C7	90	90	91	92.5	91	98.5	95	95.5	98	94