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## Reaction time, magnitude estimates, and the psychophysical law.

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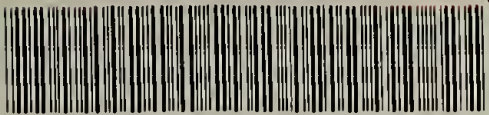
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REACTION TIME, MAGNITUDE ESTIMATES, AND THE  
PSYCHOPHYSICAL LAW

A Thesis Presented

By

ARMAND VINCENT CARDELLO

Submitted to the Graduate School of the  
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REACTION TIME, MAGNITUDE ESTIMATES, AND THE  
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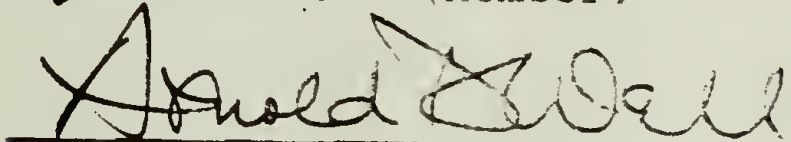
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February 1974

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### Abstract

A psychophysical experiment was run to scale brightness. Two types of responses were employed — simple reaction times and magnitude estimates. In one condition reaction times and magnitude estimates were recorded simultaneously for each stimulus presentation. In the other condition, reaction times and magnitude estimates were recorded separately in successive series of stimulus presentations.

Reaction times in the simultaneous condition were adversely affected by what appeared to be competing sets for performing the two tasks, while magnitude estimates were found to be a power function of stimulus intensity.

In the successive condition reaction times were found to be a negative logarithmic function of stimulus intensity. However, unlike the reaction times, magnitude estimates were found to be a power function of stimulus intensity.

The results were interpreted as lending support to a two-stage model of psychophysical processing similar to that proposed by Ekman (1964) and Treisman (1964a, b). Methodological considerations for psychophysical scaling were discussed, and it was proposed that the Fechner-Stevens controversy is really a pseudo-controversy.

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# REACTION TIME, MAGNITUDE ESTIMATES, AND THE PSYCHOPHYSICAL LAW

ARMAND VINCENT CARDELLO

Psychophysics, as conceived by its founder, Gustav Theodore Fechner, is "the exact science of the functionally dependent relations of body and soul or, more generally of the material and the mental, of the physical and the psychological worlds" (Fechner, 1860, p.7). As such, one primary task of psychophysics is the determination of the mathematical relationship between the magnitude of sensations and the intensity of the physical stimuli which arouse them. This relationship can be stated in the form

$$\psi = f(\phi) \quad (1)$$

where  $\psi$  is the sensation magnitude aroused by the stimulus, and  $\phi$  is the physical intensity of the stimulus.

Over the past century, two forms of this psychophysical function have been proposed. The first was proposed by Fechner in 1850 and maintains that sensation magnitude increases as a logarithmic function of stimulus intensity:

$\psi = k \log \phi$ . The second was proposed by Plateau in 1872 and was recently revived by Stevens (1957). It maintains that sensation magnitude increases as a power function of stimulus intensity:  $\psi = k \phi^n$ , where  $n$  is a constant that depends on the sensory modality investigated. The major controversy in psychophysical scaling for the past 15 years has been concerned with which of these two is

the "correct" form of the psychophysical law.

### Fechner's Law

According to Boring (1957, pp. 275-277), Gustav Fechner was trained early in medicine and physics, but later became possessed by the 19th century "philosophy of nature." This philosophy attempted to demonstrate the spiritual meaning prevalent within nature, and led Fechner to the belief that mind and matter were two aspects of the same reality. This panpsychism, coupled with his training in the physical and biological sciences, was the impetus for him to begin the task of applying quantitative scientific methods to the study of mind. Fechner was convinced that if he could describe a mathematical relationship between mind and matter, this would serve to vindicate his metaphysical contentions.

Having worked with Weber at the University of Leipzig, Fechner was well aware of the relationship which Weber had discovered between the size of the difference threshold and the absolute intensity at which it is determined. This relationship, which Fechner later termed "Weber's Law," states that the increase in the intensity of a stimulus necessary to establish a just noticeable difference (j.n.d.) in sensation is a constant fraction of the absolute intensity of the stimulus, or

$$\frac{\Delta\phi}{\phi} = k \quad (2)$$

where  $\phi$  is the absolute intensity of the stimulus,  $\Delta\phi$  is the change in intensity necessary for a j.n.d., and  $k$  is a constant, between zero and one.



Fechner believed that Weber's Law was essentially correct and that it could serve as a starting point for the establishment of a psychophysical law relating sensation magnitude (mind) to stimulus magnitude (matter). However, in its original form, Weber's Law relates only physical variables, as  $\phi$  and  $\Delta\phi$  are objective measures of the stimulus. In order to establish a function in the form of Equation (1), a psychological variable must be introduced. Fechner pondered this problem and the solution presented itself to him "as he lay abed on October 22, 1850" (Stevens, 1961a, p. 80). His solution required the assumption that all j.n.d.'s are equal, regardless of the absolute value of the stimulus level at which they are determined. This assumption, which was later termed "Fechner's conjecture" by his critics, has been the target of most of the criticism aimed at his derivation of the psychophysical law. However, the important aspect of the assumption is that it allows for the necessary psychological variable to be introduced into the equation. For it follows that, if all j.n.d.'s are equal, and if a j.n.d. is described by Weber's Law, then

$$\Delta\psi = c \frac{\Delta\phi}{\phi} \quad (3)$$

where  $\phi$  is the intensity of the stimulus,  $\Delta\phi$  is the increase in the intensity of the stimulus necessary for a j.n.d.,  $\Delta\psi$  is a j.n.d., and  $c$  is a constant of proportionality. Fechner termed Equation (3) the "fundamental formula," and working with it, carried out a strictly

mathematical derivation to arrive at his psychophysical law. The first step was to assume that differentials could be substituted for the differences in the equation. The second step involved the integration of this modified fundamental formula between stimulus threshold ( $\phi_0$ ) and any possible physical intensity ( $\phi$ ). This is expressed mathematically as

$$\int_{\psi_0}^{\psi} d\psi = \int_{\phi_0}^{\phi} c \frac{d\phi}{\phi}$$

or after integration,

$$\psi = c \log \phi + C \quad (4)$$

where  $\psi$  is the sensation magnitude,  $\phi$  is the intensity of the stimulus,  $C$  is a constant of integration, and  $c$  is a constant of proportionality. Fechner termed Equation (4) the "measurement formula" and it is in the form required by Equation (1). However, Fechner wanted to eliminate the unknown constant of integration. He accomplished this by assuming that the sensation magnitude experienced at stimulus threshold is zero, therefore

$$c \log \phi_0 + C = 0$$

or

$$C = -c \log \phi_0. \quad (5)$$

When the value for  $C$  from Equation (5) is substituted into Equation (4), the result is

$$\psi = c \log \phi - c \log \phi_0,$$

which reduces to

$$\psi = c \log \frac{\phi}{\phi_0}. \quad (6)$$

If the stimulus intensity at threshold is taken as the unit of stimulus measure, Equation (6) further reduces to

$$\psi = c \log \phi \quad (7)$$

which is the form of the equation that is most commonly known as "Fechner's Law."

Fechner's derivation of the law has been criticized for various reasons, some more valid than others. First is the fact that Fechner assumed Weber's Law to be true. Although it has been well confirmed that Weber's Law holds for the mid-range of stimulus intensities, the relationship breaks down at both very high and very low intensities (Woodworth and Schlosberg, 1956). At these extremes the difference threshold becomes larger than would be predicted by Weber's Law as determined in the mid-range. These systematic departures from the law led some investigators to propose alternative formulations. Thus, Fullerton and Cattell (1892) proposed that difference thresholds increase in proportion to the square root of the stimulus, i.e.  $\Delta\phi = c\sqrt{\phi}$ , while Guilford (1932) proposed that difference thresholds increase in proportion to a power of the stimulus, i.e.  $\Delta\phi = c\phi^n$ . These new formulations proved to be either no more accurate than Weber's Law itself, or were so general as to be trivial. It seems that Weber's Law as originally stated in Equation (2) is a good description of the relationship for the greater part of the stimulus range



(Woodworth & Schlosberg, 1956; Savage, 1970).

The second and most important criticism of Fechner's derivation is that it is based on the assumption that j.n.d.'s are equal. This criticism is well deserved, for it is, indeed, only an assumption. There is no a priori reason for its acceptance, and the only empirical evidence which could be brought to bear on the truth of the assumption would necessarily require some already existing measure of sensation. There is no obvious reason why Fechner did not merely assume that Weber's Law held for both physical and psychological magnitudes. This assumption would have led to a new "fundamental formula,"  $\frac{\Delta\phi}{\phi} = \frac{\Delta\psi}{\psi}$ ; the mathematical development of which entails a psychophysical power law.

A third criticism of Fechner lies in the validity of his integration of the fundamental formula. In order to apply the calculus to Equation (3),  $\Delta\phi$  and  $\Delta\psi$  must become infinitesimal (approach  $d\phi$  and  $d\psi$ ). This poses no problem as it relates to  $d\phi$ , because one can conceive of an infinitesimal change in a physical intensity. However, it is very unclear as to what  $d\psi$ , an infinitesimal change in sensation, can represent. By definition,  $\Delta\psi$  is the sensation difference which is just large enough to be noticeable. Any difference less than  $\Delta\psi$  would mean it is not noticeable, and therefore, not a sensation difference at all. Although this criticism bears truth, it is not crucial to the derivation of the logarithmic law.

The Fechnerian relationship can also be established by using discrete steps of sensation, as will be seen below.

Given Fechner's Law, the question arises as to the empirical evidence which supports it. Fechner's own method for empirical verification was that of "summing j.n.d.'s." In this method the stimulus threshold is first determined by one of the classical psychophysical methods, and this stimulus intensity is assigned a sensation value of zero (0.0). Then the intensity which is just noticeably greater than threshold intensity is determined and assigned a sensation value of one (1.0). Likewise, the next just noticeably greater intensity is determined and assigned a sensation value of two (2.0). As each j.n.d. is determined one sensation unit is added to the total. Thus each j.n.d. represents an equal sensation unit, and the sum total of j.n.d.'s which comprise any particular stimulus intensity is taken as the sensation value for that stimulus. When the sensation value determined in this manner is plotted against the intensity of the stimulus, the resultant function is a logarithmic one. This method, although confirming Fechner's Law, also demonstrates its greatest weakness. The method of summing j.n.d.'s directly measures only physical variables, i.e. the  $\phi$ 's and  $\Delta \phi$ 's of Weber's Law. At no time are sensations directly measured. The sensation values are assigned by the experimenter on the assumption that each j.n.d. is equivalent to one sensation unit.

The claim that Fechner's methodology is indirect, and therefore without validity, has been championed by S.S. Stevens in his "repeal" of Fechner's Law (Stevens, 1961a).

### Stevens' Law

One practical outcome of Fechner's Law was the development of a logarithmic scale of auditory intensities -- the decibel scale. This scale was employed for the convenience of having a scale of intensity which is proportional to the scale of loudness. If Fechner's Law were correct, a tone of 100dB would sound twice as loud as a tone of 50 dB. In point of fact, a tone of 100 dB sounds forty times as loud as one of 50 dB (Stevens, 1970a). This discrepancy indicated that there was something wrong with the logarithmic law.

Aware of this discrepancy and employed to determine an alternative scale of loudness, S.S. Stevens began a career-long inquiry into psychophysical scaling. Trained in the philosophy of measurement, he established a hierarchy of scales defined by the mathematical transformations that leave the scale form invariant (Stevens, 1951). This hierarchy proceeds from the simplest scale, nominal, to those of ordinal, interval and ratio. The ratio scale affords the greatest amount of information regarding the relationships among the measured entities, as it mathematically subsumes each of the other scales. For this reason, Stevens proposed that ratio scales be used in the measurement



of sensation. The decision to use ratio scaling, coupled with the objection that Fechner's method of summing j.n.d.'s was indirect, led Stevens to the use of bisection and fractionation methods of scaling loudness. These methods require the subject to directly estimate the stimulus intensity which appears one-half (one-third, twice, three times, etc.) as loud as another stimulus. (It should be pointed out that a form of ratio scaling had been used much earlier by Merkel (1888), but little came of the method.) The results of these ratio scaling procedures led to the development of the "sone" scale of loudness (Stevens, 1936). This scale proved to be non-linearly related to the decibel scale and suggested a power function between subjective loudness and sound intensity. Convinced that his methodology was correct, Stevens began a search for other direct ratio methods. In 1953, as a result of a rather trite comment made during a coffee-break at the Harvard Psycho-acoustics Laboratory, Stevens struck upon his solution. Richard Held, a colleague, commented that Stevens treated his subjects as though they had a built-in loudness scale from which they could read off values, as though from an instrument. This conception led Stevens to allow subjects to assign their own internal numbers to represent the magnitude of their sensations, and he termed the method "magnitude estimations" (Stevens, 1970b).

The results from magnitude estimation and subsequent direct ratio scaling methods (magnitude production, ratio

production, ratio estimation) led Stevens to the rediscovery of Plateau's power law. Stevens maintained that on scores of psychological continua, direct ratio methods indicated that sensation grows as a power function of stimulus intensity (Stevens, 1957). This relationship is expressed mathematically as

$$\psi = c \phi^n \quad (8)$$

where  $\psi$  is the sensation magnitude,  $\phi$  is the intensity of the stimulus,  $n$  is the exponent of the power function, and  $c$  is a constant of proportionality. Furthermore, the exponent of the power function is an invariant characteristic of the sensory continuum being measured, and is directly related to the transduction of energy which takes place at the end-organ (Stevens, 1961b, 1970a).

Stevens (1961b) has stated his formulation more generally as

$$\psi = c (\phi - \phi_0)^n \quad (9)$$

to include a correction factor. This correction factor,  $\phi_0$ , is the intensity at stimulus threshold. It is subtracted from the stimulus intensity being measured so as to correct for differences in stimulus thresholds among sensory continua. The assumption underlying this correction factor is that the effective stimulus is only that portion of the intensity which is above threshold. For most sensory continua and ranges of stimuli, this correction factor has negligible effect. It is only at very low intensities or when the sensory system is adapted to supra-

threshold levels that the threshold parameter becomes an important factor. Thus, Equation (9) is the general form of the power law, and it has often been termed "Stevens' Law."

Having formulated his psychophysical law, Stevens returned to the question that Fechner had raised, as to whether j.n.d.'s were equal. His conclusion was that Fechner's assumption was certainly wrong and that equal stimulus ratios do not produce equal sensation differences as is indicated in Equation (3). Rather, equal stimulus ratios produce equal sensation ratios,  $\frac{\Delta S}{S} = \frac{\Delta \Psi}{\Psi}$ , because when this equation is integrated, it results in the psychophysical power law.

It is important to note that Fechner's critics object to his derivation of the psychophysical law on the grounds that it is based on an assumption that may or may not be true; however, the same critics often fail to point out that Stevens' derivation also relies on an assumption. The assumption that Stevens makes is not directly stated, but can be inferred from the method by which his law was derived. This assumption is that direct ratio procedures actually measure sensation magnitudes. This basic assumption is as important to an analysis of the power law as the assumption of equal j.n.d.'s is to an analysis of the logarithmic law; yet the only "empirical" evidence which Stevens has presented to support the face



validity of his procedures are subjects' verbal reports that "they feel certain that they are gauging the strength or intensity of their sensations" (Stevens, 1964, p. 383).

The question of the validity of Stevens' direct ratio methods has been brought to the forefront by Garner (1953, 1954), Attneave (1962), Ekman (1964) and Treisman (1960, 1964a, b). These investigators argue that Stevens' methods are not nearly as direct as he claims, but that the power law is an artifact of the use of numbers as a response mode. Instead, they propose a two-stage model of psychophysical processing to explain the results of magnitude estimation methods and related ratio procedures. The first or input stage involves a transduction of the stimulus intensity ( $\phi$ ) into a sensation magnitude ( $\psi$ ). However, the second or output stage transduces this sensation magnitude into a numerical value which is then given as the response ( $R$ ). One can see from this schema that if Stevens contends that the power law transformation enters into the system at the end-organ, then he must assume linearity both in the central nervous system and in the effector system. What Garner, Attneave, Ekman, and Treisman have argued is that the output stage need not be linear. If it is not, then the fact that  $R$  is a power function of  $\phi$  tells us nothing about the relationship between  $\psi$  and  $\phi$ . They propose that Stevens' power function really relates  $R$  to  $\phi$  and is, therefore, a result of compounding the input and output functions. Garner and Attneave contend

that these two functions are power functions. Mathematically stated, their contention is if  $\Psi = \phi^m$  and  $R = \Psi^n$  then  $R = \phi^{mn}$ , where  $\phi$  is the stimulus intensity,  $\Psi$  is the sensation magnitude,  $R$  is the response magnitude and  $m$  and  $n$  are the exponents of the power functions. It is clear that this model entails that the exponents of Stevens' power functions are really composed of two multiplicative factors, one for the input stage and one for the output stage, and that the exponent of interest for relating sensation magnitude ( $\Psi$ ) to stimulus intensity ( $\phi$ ) is only that of the input stage. Ekman and Treisman have argued along similar lines, but contend that Stevens' power function results from a logarithmic input function and an exponential output function. Mathematically stated, their contention is if  $\Psi = m \log \phi$  and  $R = e^{\Psi}$  then  $R = \phi^n$ , where  $\phi$  is the stimulus intensity,  $\Psi$  is the sensation magnitude,  $R$  is the response magnitude,  $e$  is the base of natural logarithms,  $m$  is a constant of proportionality, and  $n$  is the exponent of the power function. Thus, their model assumes the accuracy of Fechner's Law as a description of the relationship between  $\Psi$  and  $\phi$ .

Stevens (1964) has countered the above arguments with the statement that the critics are dealing with intervening variables that cannot be measured. He asserts that the only observables in the situation are the stimulus input and the numerical response output, and that these are related by a power function. Stevens might, indeed, be

correct in his rebuttal of the two-stage models on these grounds; however, the criticism concerning the peculiarity of the numerical response mode has not been met. Recent evidence (Rule, 1969, 1971, 1972; Rule & Curtis, 1973) indicates that subjects' subjective numbers are a negatively accelerated function of objective number. In a further effort to repudiate this adverse criticism, Stevens (1964, 1966, 1969) has cited the results of cross-modality matching studies. In this procedure the subject matches an intensity on one stimulus continuum to an intensity on another stimulus continuum. Here numbers are not used at all, yet prediction of the results can be made from knowledge of the exponents of the power functions governing the two matched continua. If the function governing the growth of sensation on one continuum is known from magnitude estimation to be  $\psi_a = \phi_a^\alpha$  and that for the other continuum is known to be  $\psi_b = \phi_b^\beta$ , then when the psychological magnitudes are matched, we should get

$$\phi_a^\alpha = \phi_b^\beta \quad (10)$$

This equation can be rewritten

$$\log \phi_a = \frac{\beta}{\alpha} \log \phi_b \quad (11)$$

which states that the exponent of the equal sensation function is given by the ratio  $\frac{\beta}{\alpha}$  of the exponents of the two matched continua. The fact that this relationship has been confirmed empirically by cross-modality matching experiments led Stevens to accept this method as evidence for the veracity of his power law. In fact, Stevens'



enthusiasm for this method has motivated him to declare that "the procedure of magnitude estimation is actually a form of cross-modality matching in which numbers are matched to stimuli" (Stevens, 1971, p. 428). However, by subjugating magnitude estimation to a form of cross-modality matching, Stevens has reduced the empirically determined absolute values of the exponents to merely relative values. This is a result of the closing of a methodological circle by which each sensory continuum is used to measure each other sensory continuum. The resultant exponents are then only relative to the particular continuum used to derive them. Furthermore, both Treisman (1964b) and Savage (1970) point out that Equation (11) can also be deduced if the growth of sensation for both continua follows a logarithmic law, even though the exponent in this case is an arbitrary constant.

A still more general criticism of Stevensonian psychophysics has been raised by Warren (1958) and Warren and Warren (1958). They claim that the psychophysical power law does not describe the input-output operating characteristics of the sensory system, but that it describes learned relationships among stimuli. This "learning hypothesis" contends that as a child, the subject has learned the rules for assigning numbers to stimuli by observing the relationships between physical stimuli and some other physical attribute associated with the stimuli - such as distance.

For example, a child will learn to call an object of a certain brightness one-half as bright when it is moved twice the distance away from a point source. However, by the inverse square law, the actual luminance is  $\frac{1}{4}$  of its original value. This mismatch results in the child learning that brightness increases by the function  $\psi = \phi^{0.5}$ . Likewise, in cross-modality matching, it is contended that the subjects are matching two continua as they would appear if moved equal distances from their sources. If this analysis is correct, both magnitude estimation and cross-modality matching describe the learned relationship among stimulus intensities, and not the operating characteristics of the sensory system. However, the relative sparsity of point sources in the normal environment, along with the roundabout nature of the purported learning, casts doubt on the cogency of this theory.

To summarize the review up to this point, we have seen that both Fechner's Law and Stevens' Law are based on assumptions. In the former case it is the assumption that j.n.d.'s are equal, while in the latter case it is the assumption that the ratio methods directly measure sensations. Furthermore we have seen that each "law" has the support of empirical data behind it. For Fechner's Law it is the data resulting from the method of summing j.n.d.'s, while for Stevens' Law it is the data resulting from the methods of direct ratio scaling. In this regard,

it has been pointed out by Phillips (1964) that it is logically consistent that two different psychophysical functions have been generated by two so greatly different methodologies. For this reason, the controversy over the correct psychophysical function can be seen to parallel those between the specificity and the neural interpretation theories of sensory coding and the telephone and place theories of hearing (Dzendolet, 1969). Lastly, it has been shown that both methodologies can be criticized on very important grounds. Therefore, the question arises as to what other empirical evidence can be brought to bear on the problem of discriminating between the two psychophysical laws.

#### Evidence from Partition Scaling

The first line of evidence to be considered is the result of partition scaling methods. Partition scales are those that require the subject to divide a segment of the continuum into a finite number of equally spaced categories. Partition scales were first employed by Plateau, when he asked various artists to paint a shade of gray which would divide the sensation distance between a patch of white and a patch of black into two equal parts.

The most common method for constructing a partition scale is the procedure of category scaling. In category scaling the subject is presented with a series of stimuli, varying in intensity, which he must place into n equally spaced



and numbered sensation categories (usually seven). He is instructed to place the weakest stimulus into category 1 and the strongest stimulus into category 7, with intermediate stimuli distributed in such a way that the intervals between categories are subjectively equal. When the mean category placement is determined for each stimulus and plotted against stimulus intensity the results support a logarithmic function at times, and a power function at other times, depending upon the stimulus continuum being scaled. This ambiguity has led Stevens and Galanter (1957) to distinguish between two types of sensory continua — prothetic and metathetic. Prothetic continua are defined as those "for which discrimination appears to be based on additive mechanism by which excitation is added to excitation at the physiological level," while metathetic continua are defined as those "for which discrimination behaves as though based on a substitutive mechanism at the physiological level" (Stevens and Galanter, 1957, p. 377).

Prothetic continua (such as brightness and loudness) produce category scales which are concave downward relative to ratio scales, whereas metathetic continua (such as pitch and position) produce category scales that are linearly related to ratio scales. Stevens (1957) argues that the chief factor resulting in the non-linearity of the scales on the prothetic continua is a discrimination bias on the part of the subject, caused by the subject's variation in sensitivity to differences. Since the subject discriminates

better at the lower end of the continuum than at the higher end, his ability to tell one magnitude from another varies over the scale and affects the width of his categories. Since this bias is not present on metathetic continua, the category scale is linearly related to the ratio scale. This explanation has been criticized by Treisman (1964a) on the ground that there is no reason why this bias should not affect the direct ratio methods in the same way as the partition methods. In any case, the results of partition scaling support Fechner's Law on prothetic continua and Stevens' Law on metathetic continua. As such partition scales do not provide good empirical evidence for discriminating between the two laws.

#### Evidence from Electrophysiology

The second line of evidence to be considered is the result of electrophysiological studies of stimulus coding. When Adrian (1926) demonstrated that stimulus intensity was coded in the nervous system by the frequency of nerve impulses, there arose an opportunity to obtain evidence bearing on the psychophysical law. The first such evidence came directly from Adrian's laboratory (Adrian and Matthews, 1927). Here it was found that the impulse frequency coming from the optic nerve of the eel was a logarithmic function of stimulus intensity. These results were taken as empirical support for the veracity of Fechner's Law. A few years later Matthews (1931) recorded the impulse frequency from a muscle spindle in the middle toe of a frog. When



the impulse frequency was plotted against the logarithm of the load, a straight line was produced, indicating a logarithmic relationship. Hartline and Graham (1932) performed a similar experiment, but this time recorded from the nerve fiber emanating from the eccentric cell of the horseshoe crab (*Limulus polyphemus*). Their results also confirmed that spike frequency was a logarithmic function of stimulus intensity.

These original reports have been followed by a great number of similar studies which seem to confirm Fechner's logarithmic law. Galambos and Davis (1943) and Tasaki (1954) have reported that the impulse frequency in single auditory fibers in the guinea pig increases as a logarithmic function of sound pressure. Katz (1950) has shown that spike frequency in proprioceptive fibers of muscle spindles in frogs is a linear function of the receptor potential, and furthermore, that both of these physiological measures are logarithmic functions of stimulus intensity. Granit (1955) has reported that spike frequency in the lateral line organ of the eel is a logarithmic function of the rate of flow of semicircular fluid, while Rushton (1959) has plotted Fourtes (1959) data from the *Limulus* eye and concluded it too, confirms a logarithmic law. Similar results have been found by Pfaffman, Erickson, Frommer, and Halpern (1961) for the integrated potentials from chorda tympani and medulla of rats; by Desmedt (1962) for the massed response of the cochlear nerve of



cats, by DeValois, Jacobs, and Jones (1962) for frequency of firing of single cells in the lateral geniculate of monkeys, by Nomoto, Suga and Katsuki (1964) for spike frequency in the auditory neurons of monkeys, and by Yamada (1965) for the integrated potentials from the glassopharyngeal nerve in rats and rabbits.

Recently, however, numerous studies have reported that certain physiological measures of intensity seem to be a power function of stimulus intensity. Teas, Eldredge, and Davis (1962) have reported that the amplitude of the action potential of the auditory nerve in guinea pigs grows roughly as a power function of sound pressure. Mountcastle, Poggio and Werner (1963) and Poggio and Mountcastle (1963) have demonstrated that impulse frequency in single neurons in the ventrobasal thalamic nuclei of monkeys is a power function of stimulus intensity (angle of rotation), while Werner and Mountcastle (1965) have shown the same relationship for the impulse frequency in Iggo touch corpuscle axons in monkeys. Similar findings have been reported by Boudreau (1965) for the amplitude of the action potential in the superior olivary complex of cats, by Vatter (1966) for the amplitude of visual-evoked potentials in squirrels, by Easter (1968) for impulse frequency in the ganglion cells of goldfish, and by Dodge, Knight, and Toyoda (1970) for the amplitude of the generator potential in the eye of *Limulus*.

As is evidenced by this review, until the beginning of the 1960's, most physiological evidence tended to support Fechner's Law, whereas, after this period the evidence began to shift in favor of Stevens' Law. This led Stevens (1970b) to the conclusion that early studies did not find power functions because the investigators were not looking for them: "So there again, we find Fechner's logarithmic law guiding the expectations of the physiologists. Remembering 20 years of my own misdirected attention, I understand how hard it is to see power functions when you expect a different form" Stevens, 1970a, p. 1046). Stevens "supported" this claim by replotting the data of Adrian and Matthews (1927) and Hartline and Graham (1932) and stating that their data could be fit "equally well" by power functions. However, Stevens, did not state what criterion for "equally well" he had employed, i.e., whether it was simple visual inspection of the data or some statistical measure of goodness-of-fit. If it was simple visual inspection of the data, then Stevens is left open to exactly the same criticism that he raised against the early physiologists, for it is entirely possible that Stevens, and contemporary physiologists also, are looking for power functions and not logarithmic ones. (As an example, in a matter of only three years, DeValois, Jacobs, and Jones (1965) reversed the decision that their earlier data (DeValois, et al., 1962) had shown a logarithmic function and claimed that it now supported a power function.)

If, however, Stevens did calculate a measure of goodness-of-fit for these data, then he most certainly should have published these statistics for the fits of both the logarithmic and power function. In this way, it would be operationally clear what "equally well fit" means. The lack of such statistical data relegates Stevens' claim to a mere statement of opinion.

Thus, whatever reasons one might try to postulate for the peculiar historical development of findings in physiology, we are left with the conclusion that the data, taken as a whole, appear to support both Fechner's Law and Stevens' Law. Furthermore, numerous other studies have reported neither a logarithmic nor a power function, but a sigmoid function (see Lipetz, 1971).

So far, we have discussed only those studies in which animals have served as subjects. Since both Fechner's Law and Stevens' Law have been formulated to explain the relationship between stimuli and the sensations aroused by them in humans, it is surprising that any of the foregoing data should be accepted as evidence for the validity of these laws. If these physiological measures correlate with conscious sensations, then they must certainly be the sensations of the animals from whom the data were recorded. Putting aside the question of whether animals even have conscious experience, it must still be concluded that this data is inappropriate for evaluating Fechner's



Law and/or Stevens' Law. The only psychophysical laws this type of data might be used to support are those that might evolve from animal behavioral psychophysics a la Blough (1966). However, for those predisposed to making the numerous metaphysical assumptions necessary for such cross-species comparisons, the above animal physiological data has been presented. For those not so disposed, the following data may seem more pertinent.

The acceptance of animal physiological data to support the psychophysical laws has been fostered, in some part, by the difficulty of obtaining comparable data from humans. However, recent studies have made headway in this area, and if one accepts a psychophysiological parallelism, the results of these studies can be brought to bear on the problem at hand. Due to the obvious difficulty of recording directly from the nervous system in man, most of these studies have employed measures obtained through external electrodes, most commonly — cortical evoked potentials (CER's). Keidel and Spreng (1965) measured the amplitude of one of the slow components of the cortical wave to three types of stimuli — tones, electric current, and vibration. They reported that the responses to all three types of stimuli were power functions of the intensity. Ehrenberger, Finkenzeller, Keidel, and Plattig (1966) replicated this first study, but used only vibration as the stimulus. Their results confirmed the earlier findings. Loewenich and Finkenzeller (1967)

found that the CER to flashes of light was a power function of stimulus intensity, while Plattig (1967) found the CER to electrical stimulation of the tongue to exhibit the same relationship. Similar results have been found by David, Bowers, and Hirsh (1968) for the CER to electrical shock to the skin, and by Franzen and Offenloch (1969) for the CER to tactile stimulation of the fingers. Although all of these studies report power functions, even Stevens (1970a) admits that CER measures are difficult to interpret, as they represent a summation of neuroelectric potentials that may have greatly different origins. As such, it is not clear what stage of stimulus information processing is being tapped.

A somewhat less ambiguous electrophysiological measure which has been recorded from humans has produced slightly different results. Borg, Diamant, Strom, and Zotterman (1967a, b, 1968) have recorded the summated response in the chorda tympani of patients undergoing inner ear operations. Magnitude estimates of the same gustatory stimuli as used in the experiment were obtained from the same patients on previous days. Although the magnitude estimates for salt, sucrose, and acid were fit well by power functions, the neural data were often fit better by logarithmic functions (Zotterman, 1971). Thus, it appears that although CER data from humans are usually a power function of intensity, measures of electrical activity in the afferent nerves seem to be a logarithmic function.

There are two interesting aspects of both the animal and human results. First is the fact that in most of those studies that have found power functions, the exponents of the power functions rarely match the corresponding exponents found by psychophysical methods (see Rosner and Goff, 1967; Sato, 1971). This discrepancy casts doubt on Stevens' claim that the value of the psychophysical exponents refer to end-organ characteristics, because if they did, they should certainly be represented in the nervous system. Secondly, if one looks at both the animal and human data as represented in Tables I and II, there will be noticed a surprising correspondence between the form of the intensity function and where in the central nervous system the electrophysiological measure was recorded. A majority of those studies that have reported logarithmic functions have recorded from peripheral parts of the nervous system, while a majority of those that have reported power functions have recorded from more central parts. This apparent regularity has led MacKay (1963) to postulate that the transduction of energy at the receptor is logarithmic and that this signal is carried in the afferent nerves to a central "comparator." Here the signal is balanced against a centrally generated signal. If this central signal is also logarithmic, then the result is an overall power function. Marimont (1962) has also proposed a similar exponentiating mechanism in the CNS which would transform peripheral logarithmic functions into power



Table 1 Electrophysiological studies with animals that have been cited to support either the Fechnerian logarithmic law or the Stevensonian power law.

Author(s)	Electrophysiological Measure	Function
Adrian & Matthews (1927)	spike frequency in optic nerve of eel	log
Matthews (1931)	spike frequency in frog muscle spindle	log
Hartline & Graham (1932)	spike frequency in nerve fiber from eccentric cell of Limulus	log
Galambos & Davis (1943)	spike frequency in single auditory fibers of guinea pig	log
Katz (1950)	receptor potential and spike frequency in muscle spindle of frog	log
Tasaki (1954)	spike frequency in single auditory fibers of guinea pig	log
Granit (1955)	spike frequency in lateral line organ of eel	log
Rushton (1959) of the data from Fourtes (1959)	spike frequency in optic nerve of Limulus	log
Pfaffman, et al. (1961)	integrated potentials from chorda tympani and medulla of rat	log
Desmedt (1962)	massed response of the cochlear nerve of cat	log
DeValois, et al. (1962)	spike frequency in single cells in lateral geniculate of monkey	log
Nomoto, et al. (1964)	spike frequency in first-order auditory neurons of monkey	log
Yamada (1965)	integrated potentials in glossopharyngeal nerve of rabbit and rat	log
Teas, et al. (1962)	amplitude of action potential in auditory nerve of guinea pig	power

cont.

Table I (continued)

Author(s)	Electrophysiological Measure	Function
Mountcastle et al (1963)	impulse frequency in single neurons in ventobasal thalamic nuclei of monkey	power
Poggio & Mountcastle (1963)	impulse frequency in single neurons in ventrobasal thalamic nuclei of monkey	power
DeValois, et al. (1965) of earlier data --- DeValois et al. (1962)	spike frequency in single cells in lateral geniculate of monkey	power
Boudreau (1965)	amplitude of action potential in superior olivary complex of cat	power
Werner & Mountcastle (1965)	impulse frequency in Iggo touch corpuscle axons of monkey	power
Vatter (1966)	evoked-potentials in visual cortex of squirrel	power
Easter (1968)	impulse frequency in ganglion cells of goldfish	power
Dodge, et al. (1970)	amplitude of generator potential in the eye of Limulus	power

Table II Electrophysiological studies with humans that have been cited to support either the Fechnerian logarithmic law or the Stevensonian power law.

Author(s)	Electrophysiological Measure	Function
Borg, et al. (1967)	summated response in chorda tympani to salt and sucrose stimulation	log
Keidel & Spreng (1965)	CER to tone, electric shock, and vibration	power
Ehrenberger, et al (1966)	CER to vibration	power
Loewenich & Finkenzeller (1967)	CER to light flashes	power
Plattig (1967)	CER to electrical stimulation of tongue	power
Davis, et al. (1968)	CER to tone	power
Beck & Rosner (1968)	CER to electric shock	power
Franzen & Offenloch (1969)	CER to tactile stimulation	power



functions. Thus, both Mackay's model and Marimont's model closely resemble the two-stage models of psychophysical functioning proposed by Ekman and Treisman and mentioned earlier. All of these models predict a peripheral logarithmic function and a more central power function. As such, they suggest that Fechner's Law and Stevens' Law are not mutually exclusive, but that they simply describe different levels of processing.

### Evidence from Response Latency Studies

The last major line of evidence which bears on the psychophysical laws concerns response latencies to stimulation. Most of this evidence comes from studies of response latencies (both behavioral and electrophysiological) to visual stimulation. Human visual reaction time has long been known to be a negatively decreasing function of stimulus intensity (Cattell, 1885; Berger, 1886, Froeberg, 1907, Pieron, 1920). However, as intensity increases, latency soon reaches an irreducible minimum value. This asymptotic value presumably represents the minimum duration necessary for receptor processes, neural conduction, and efferent processes (Pieron, 1920; Woodworth and Schlosberg, 1956; Vaughan, Costa, and Gilden, 1966). The total reaction time minus the "irreducible minimum" ( $L_0$ ) is known as the "reducible margin" ( $L - L_0$ ), and represents the effect of stimulus intensity on latency. Pieron (1952) has claimed that the reducible margin is closely related to subjective brightness, while Vaughan (1966) has extended

this relationship to conclude that response speed (inverse of the reducible margin) is directly proportional to brightness. As such, the function relating visual latency to intensity may be used to assess the validity of the psychophysical laws.

As reported by Pieron (1952) numerous animal studies have determined that latency is a negative logarithmic function of intensity. However, for humans, Liang and Pieron (1947), using the Pulfrich effect, have found that visual latency is a power function of intensity with an exponent of  $-1/3$ . Bartlett and Maclead (1954) have disagreed with Pieron. Using simple reaction times, they found visual latency to be an inverse logarithmic function of intensity. Recently, Vaughan and Hull (1965), Vaughan (1966), Vaughan, Costa and Gilden (1966) and Mansfield (1970) have claimed that both simple reaction time and latency of the visual-evoked cortical potential are power functions of stimulus intensity, with exponent values of  $-1/3$ . The above visual latency data, coupled with the report by Luce and Green (1973) that older auditory latency data (Chocholle, 1940; McGill, 1963) also seem to fit power functions, have led to a renewed interest in the study of reaction times for psychophysical scaling.

In some sense, latency of responding is a rather unique method for scaling sensations. First of all, since reaction times are assumed to be relatively free of the

effects of learning, they avoid the criticism that Warren has raised against many scaling methods; namely, that their results reflect learned relationships among the stimuli. Secondly, this response mode affords the advantage of wide subject applicability and cross-group comparisons. Unlike either the partition scaling or direct ratio scaling procedures, the subject need not have a command of the number system nor any complex cognitive facilities. Thus, children, retardates, and animals can serve as subjects. Yet, unlike electrophysiological measures, there is no difficulty in obtaining data from normal, human, waking subjects.

This latter point, concerning wide subject applicability, raises an important question. It is a question about the type of methodology commonly used in human psychophysics, and more importantly, the type of methodology not commonly used.

Human psychophysics had its birth in the midst of the Structuralist paradigm, when introspection was regarded as the primary method for investigating "mental elements." Not surprisingly, therefore, early psychophysicists relied on methods that were, for the most part, introspectionist. With the advent of Behaviorism, most branches of experimental psychology rejected consciousness as an appropriate method of investigation. Psychophysicists, with their goal of measuring conscious sensation, could not accept the Behaviorist doctrine and still remain a viable science.



As a result, human psychophysics had to develop outside the mainstream of experimental psychology. Though its methods changed somewhat, it still retained the introspectionist flavor. This is evidenced even by present Stevensian methods of scaling, in which the subject "assigns numbers in such a way that they reflect his subjective impressions" (Stevens, 1971, p. 428). Clearly, the task is one of introspection.

Yet, psychophysics has been carried out within the Behaviorist tradition, although not until fairly recently, and not with humans, but with animals. Early attempts at measuring animal sensory processes employed Pavlovian conditioning techniques (Brown, 1936, 1937). These techniques, coupled with the development of operant conditioning procedures and emphasis on "stimulus control of responding," have led to a branch of experimental learning that, justifiably, is called "animal psychophysics." This discipline employs a multitude of scaling methods that parallel those used in human psychophysics, but obviously, avoid verbal responses. Some of these, such as stimulus generalization of responding, conditioned suppression, and response latency, could readily be applied to human subjects also. But due to the historical and philosophical schism between human and animal psychophysics, this has not, in general, been the case. It is for this reason, also, that the work on human response latency is important. It is here that one can begin to develop the link between human

and animal psychophysical methods, and possibly lead the way to a more widespread use of these methods in human psychophysical scaling. In light of the above consideration and those to be discussed below, the present investigation will be concerned with the use of visual latency as a method for the scaling of brightness in humans.

### The Present Investigation

As has been shown, the method of summing j.n.d.'s usually produces results that support Fechner's logarithmic law, while the methods of direct ratio scaling usually produce results that support Stevens' power law. Other methods, such as partition scaling and electrophysiological recording produce results that can support either law, depending on the continuum being scaled or the physiological level at which the data are recorded. Response latency methods, although seemingly germane to the problem, have not been adequately exploited; and the data that are available have produced conflicting results.

Visual latency for brightness has been chosen for a number of reasons. First, brightness is a simple prosthetic continuum that has been scaled repeatedly by a number of different methods. Thus, comparison of the current results with other methods is a relatively simple matter. Secondly, and more importantly, most of the available data on response latencies have come from studies employing



visual stimulation, and hopefully, many of the methodological problems have been solved. Lastly, those studies of visual latency which have found a power function of intensity, have also shown that the value of the exponent of the function corresponds well with the exponent found with Stevensonian methods. If one accepts Stevens' Law as an accurate description of the growth of sensation, then visual latency data is an excellent source for demonstrating "exponent invariance" (Mansfield, 1970).

Before describing the present investigation, it is necessary to bring out a few particularly important points. First, most previous studies of visual latency have employed stimuli of extremely short duration. These stimuli have sometimes been as short as 10 msec. (Vaughan, et al., 1966). Thus, most of the durations have fallen well within the range for which either Bloch's Law or the Broca-Sulzer effect hold. It is interesting that while many of the studies that have used short duration stimuli have found power function relationships, Bartlett and Macleod (1954), using a much longer duration (575 msec.), have found a logarithmic relationship. Since most of the more recent studies have employed the short stimulus duration, the present study will re-examine the earlier results of Bartlett and Macleod, using a long duration. However, this study will extend their findings by examining the effects of long stimulus duration with a light-adapted subject.



Another important point concerns a matter of proper experimental procedure. Most, if not all, of the studies which have compared response latency functions with brightness functions have failed to obtain both measures from the same individual. Usually, response latency data obtained in one study are compared with brightness data from another study, using different subjects. This practice is exemplified in a paper by Luce and Green (1973). After replotting some early auditory latency data from Chocholle (1940) and determining that the latency - intensity function follows a power law, they state, "Since Chocholle did not obtain magnitude estimates, we have plotted his data as if the magnitude exponent were 0.3." They then use the linearity between Chocholle's response latency data and this "magnitude estimation data" as evidence for the proportionality between latency and brightness. Clearly they have made two major assumptions. Not only have they assumed that the brightness function of Chocholle's subjects would follow a power law, but furthermore, that the values of the exponents of those functions would be precisely 0.3. Detailed assumptions like these should not be made, especially in light of the findings by Teghtsoonian and Teghtsoonian (1971) that exponent values for magnitude estimates of apparent size are not well correlated, even within the same subject, for periods as short as 24 hours. It would appear that if one wants to

demonstrate a relationship between response latency and brightness, then both measures should be obtained simultaneously from the same subject. For this reason the present investigation will obtain both response latency data and magnitude estimation data from the same subject and within a single experimental session. Only one previous study (Geschieder and Wright, 1971) has employed this procedure, but in that study, choice reaction times were used.

The last point to be brought out concerns experimenter expectations and their effect on experimental findings. This point was raised earlier in regard to electrophysiological data. At that time, it was noted that Stevens (1970a) had attributed early reports of logarithmic functions to the fact that the physiologists were "expecting them." However, this criticism can also be applied to many contemporary psychophysicists and physiologists, who conclude that their data were "well fit" by power functions, but fail to publish any statistical measure of goodness-of-fit. Yet even when these measures are published, the "expectation effect" still enters. This is particularly exemplified by some recent studies of visual latency.

In visual latency studies, the data of concern is the reducible margin of latencies ( $L - L_0$ ). In order to determine this value, one must interpolate the irreducible minimum,  $L_0$ , from the raw latency data and subtract this value from the total latency ( $L$ ). Thus, the value of the

irreducible minimum can have a sizeable effect on the function relating  $L-L_0$  to intensity. This factor can be put to excellent use by an investigator expecting to find a particular set of results. All he need do is choose a value of  $L_0$ , such that it will improve the fit of the data to the function he expects to find. Thus, Vaughan, et al. (1966, p. 650) described their procedure for determining  $L_0$  this way: "We then assessed the adequacy of power functions for expressing the relation between reducible latency ( $L-L_0$ ) and stimulus intensity. The value of  $L_0$  producing the least residual was accepted as the best estimate." Likewise, Mansfield (1970, p. 80) makes the following statement: "The asymptotic latency,  $L_0$ , was chosen to maximize the product-moment correlation between the logarithm of those averages (average latencies) and the energy in the first 10 msec. expressed in decibels." Clearly, these procedures will produce an inflated value of the goodness-of-fit for power functions.

The above practice closely resembles one commonly used for determining  $\phi_0$  in Equation (9). This procedure was outlined by Stevens (1961, p. 26) in the following manner: "Needless to say, the 'effective' threshold ( $\phi_0$ ) cannot be measured very precisely. Consequently, it becomes expedient to take as the value of  $\phi_0$  the constant value whose subtraction from the stimulus values succeeds in rectifying the log-log plot of the magnitude function. Provided the constant value so chosen is a reasonable threshold value,



this procedure seems justified." The inherent bias in both the calculation of  $L_0$  and  $\phi_0$  casts doubt on any conclusions made concerning the data. Furthermore, the studies of Vaughan, et al., and of Mansfield, like most other studies of response latency which have reported power functions, do not report goodness-of-fit to logarithmic functions. It seems to be tacitly assumed that power functions will give the best fit to the data, and therefore, the problem is reduced to one of determining the best fitting form of the power function. For these reasons, the present research will examine fits of linear, logarithmic, and power functions to the latency and magnitude estimation data by a least square statistic. Furthermore, the asymptotic value of the raw latency data will be taken as the best estimate of  $L_0$ , and the adaptation intensity will be taken as the best estimate of  $\phi_0$ . No further assumptions will be made concerning either  $L_0$  or  $\phi_0$ .

### Experiment 1

#### Method

#### Subjects

Two males and two females (all right-handed) between the ages of 19 and 29 served as Ss. All were either graduate or undergraduate students at the University of Massachusetts and were used in full accordance with the rules set forth by the Subject Committee of that institution

and in accordance with the ethical standards maintained by the American Psychological Association. All Ss volunteered for participation and received no compensation.

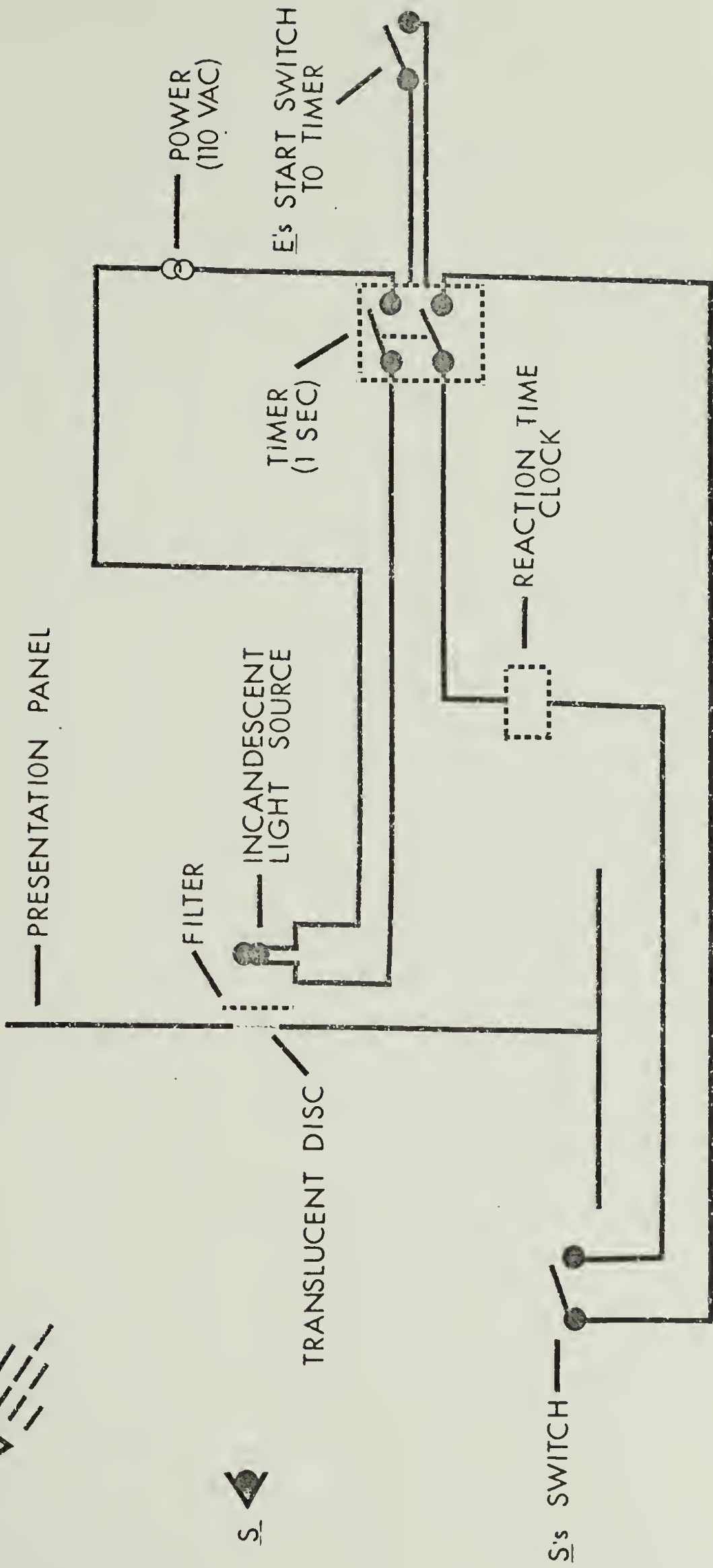
### Apparatus

Figure 1 shows a schematic representation of the optical and electronic apparatus. An electronic reaction time clock (Hunter, model 120A) was used to measure the latency between the onset of the visual stimulus and the subject's manual release of a telegraph key switch. Stimulus duration was controlled by an electronic timer (Hunter, model 111C), and stimulus intensity was varied by interposing Wratten neutral density filters between the light source and S. White noise (35dB) produced by a noise generator (Grason-Stadler, model 455C), was presented binaurally to S through earphones to mask the click of the stimulus switch.

The light source was a common incandescent 20-watt bulb located behind a white presentation panel or reduction screen. The light from the source projected through an aperture in the panel and illuminated a white translucent disk which served as the stimulus. The panel and disk were located 36 cm from S's eyes, and the stimulus subtended a visual angle of  $6^{\circ}$ . The stimulus intensities were 93.4, 85.1, 76.4, 67.5 and 60.7 dB re  $10^{-10}$  L (as measured by a Macbeth Illuminometer). The stimulus duration

Figure 1 Schematic diagram of the optical and electronic apparatus.





was kept constant at 1.0 sec. The adapting field of the presentation panel was illuminated by an incandescent source located behind S, and the adapting intensity of the field was 60.0 dB re  $10^{-10}$  L.

### Procedure

Ss were run for 5 sessions; one session on each of 5 consecutive days. Sessions 1, 2, and 3 were practice sessions, during which S performed only the reaction time task. Sessions 4 and 5 were the actual experimental sessions. These two differed only with respect to whether the reaction time task and magnitude estimation task were performed together or separately. The session during which they were performed together will, herein, be called the "simultaneous" condition. Likewise, the session during which they were performed separately will, herein, be called the "successive" condition. For two Ss, the simultaneous condition was session 4 and the successive condition was session 5. For the other two Ss, the conditions were reversed.

Practice Sessions. S sat at the apparatus and was asked to read the instructions (see Appendix for these and all other instructions used in this investigation). After reading the instructions, S positioned his head in a restraint and stared at the adapting field for 10 minutes, so as to enable stable reaction time measures independent of adaptation effects. Binocular stimulation and natural

pupils were employed.

Upon a verbal signal from E, S depressed his switch with his right thumb, and signalled to E that he was prepared for the stimulus. The stimulus was then presented from 1 to 3 seconds later, with the length of the foreperiod distributed exponentially so as to provide S with no information as to when the stimulus would occur (Luce and Green, 1973). After S released his switch, E recorded the latency and, after waiting the appropriate time, presented the next stimulus. Stimuli were presented in a quasi-random order with six presentations of each stimulus intensity. The interstimulus interval was 30 secs. (plus the interval of the foreperiod). During this time S continued to light-adapt to the background field.

Simultaneous Condition. In this condition, S made magnitude estimates of the brightness of the stimulus immediately after releasing his switch. Thus, both latency measures and magnitude estimates were recorded on each of the 30 stimulus presentations. No modulus was assigned for the magnitude estimates, and all other aspects of the procedure in this condition were the same as during practice sessions.

Successive Condition. In this condition, S made magnitude estimates to the full series of intensities either prior to or following the reaction time task. Thus, the procedure in this condition was the same as during practice sessions,



except that magnitude estimates of the brightness of the stimuli were obtained independently of the reaction times. The only other difference between this condition and the simultaneous condition was that the magnitude estimates were given for only 2 presentations of each stimulus intensity. This was done to eliminate the constraints often put on magnitude estimates by repeated judgments (Teghtsoonian and Teghtsoonian, 1971; Stevens, 1971). These constraints could not readily be eliminated in the simultaneous condition, since a relatively large number of presentations of each stimulus were necessary to obtain stable mean values of the reaction times.

## Results

### Effect of Condition on Reaction Time

Table III shows both the mean and the median reaction times for each stimulus intensity, subject and condition. The variance in the data is also shown, as represented by the standard deviation about the mean or the average deviation about the median.

It is apparent from this table that the reaction times in the simultaneous condition were, in general, much longer than those in the successive condition. This increase in reaction time was accompanied by an increase in the dispersion of the data, as evidenced by the larger values of the measures of variability. More importantly, though, the relationship between reaction time and stimulus intensity

Table III Mean ( $\bar{x}$ ) and median (Md) reaction times for each subject, condition, and stimulus. The standard deviation about the mean and the average absolute deviation about the median are given in parentheses. Each value is based on 6 stimulus presentations. Stimuli are labeled such that #1 is the most intense stimulus and #5 is the least intense.

S	Condition	Stimulus									
		1		2		3		4		5	
		$\bar{x}$	Md	$\bar{x}$	Md	$\bar{x}$	Md	$\bar{x}$	Md	$\bar{x}$	Md
DP	Success.	155.16 (20.55)	149.00 (14.50)	180.16 (24.04)	170.50 (18.83)	173.66 (13.50)	177.00 (10.00)	183.50 (30.84)	199.00 (21.16)	248.66 (26.43)	243.00 (23.33)
	Simult.	323.83 (108.90)	310.00 (97.50)	257.16 (84.53)	230.00 (68.50)	253.16 (89.08)	223.50 (63.50)	264.16 (75.88)	240.00 (60.83)	296.33 (66.15)	290.50 (61.33)
FS	Success.	193.16 (12.29)	194.00 (11.50)	194.00 (15.31)	189.00 (12.00)	219.50 (16.68)	216.50 (16.16)	237.16 (24.67)	242.00 (22.50)	285.00 (34.09)	284.50 (26.33)
	Simult.	622.66 (75.19)	618.00 (63.00)	597.83 (120.42)	564.00 (93.50)	652.16 (95.14)	660.00 (66.16)	533.66 (97.59)	511.50 (61.00)	548.33 (106.17)	501.50 (84.00)
RS	Success.	170.16 (19.23)	162.50 (15.16)	162.16 (6.48)	160.50 (5.16)	184.50 (12.10)	186.00 (9.50)	187.33 (19.51)	186.50 (14.66)	237.00 (61.11)	227.50 (43.66)
	Simult.	154.33 (21.71)	151.00 (16.66)	144.50 (16.67)	146.00 (12.50)	176.00 (20.35)	172.00 (16.19)	242.16 (94.39)	188.00 (64.83)	285.33 (66.95)	269.00 (55.00)
CM	Success.	164.00 (9.98)	162.00 (7.66)	172.00 (32.90)	167.00 (25.33)	186.50 (30.92)	184.50 (27.16)	200.66 (42.05)	197.50 (32.00)	222.83 (31.93)	211.50 (20.83)
	Simult.	186.00 (25.83)	177.50 (19.33)	179.83 (18.58)	187.00 (15.50)	182.16 (22.78)	189.00 (18.16)	219.33 (26.80)	227.50 (21.33)	245.33 (15.29)	250.50 (11.66)



during the simultaneous condition was atypical for at least two of the Ss. Figures 2 and 3 show the general form of this relationship during both the simultaneous and successive conditions for all four Ss. It is quite obvious that during the simultaneous condition, reaction times were not a negatively accelerated decreasing function of intensity for all Ss. Since these data were so atypical when compared with previous studies of reaction time, it was decided not to use the reaction time data obtained during the simultaneous condition. It seems that the attempt to simultaneously perform the reaction time and magnitude estimation tasks introduced a confounding variable which distorted the reaction times in a manner independent of intensity. However, it is interesting that the magnitude estimates in the simultaneous condition were not adversely affected, as will be shown in a later section.

#### Relationship of Reaction Time to Intensity

Figures 4, 5, 6, and 7 show median reaction time plotted against the logarithm of the intensity for each S during the successive condition. The asymptotic value ( $L_0$ ) of these raw latency data were estimated in order to determine the reducible margin of latencies,  $L-L_0$ , for each S. The estimated values of  $L_0$  were 148, 188, 159, and 161 msec. for Ss DP, FS, RS, and CM respectively.  $L-L_0$  values determined in this way were then plotted against stimulus intensity, which was specified as the intensity of the



Figure 2     Median reaction time as a function of stimulus intensity for all 4 Ss in the successive condition. Reaction times have been standardized so that the longest reaction time for each S is plotted on the ordinate at 1.0.

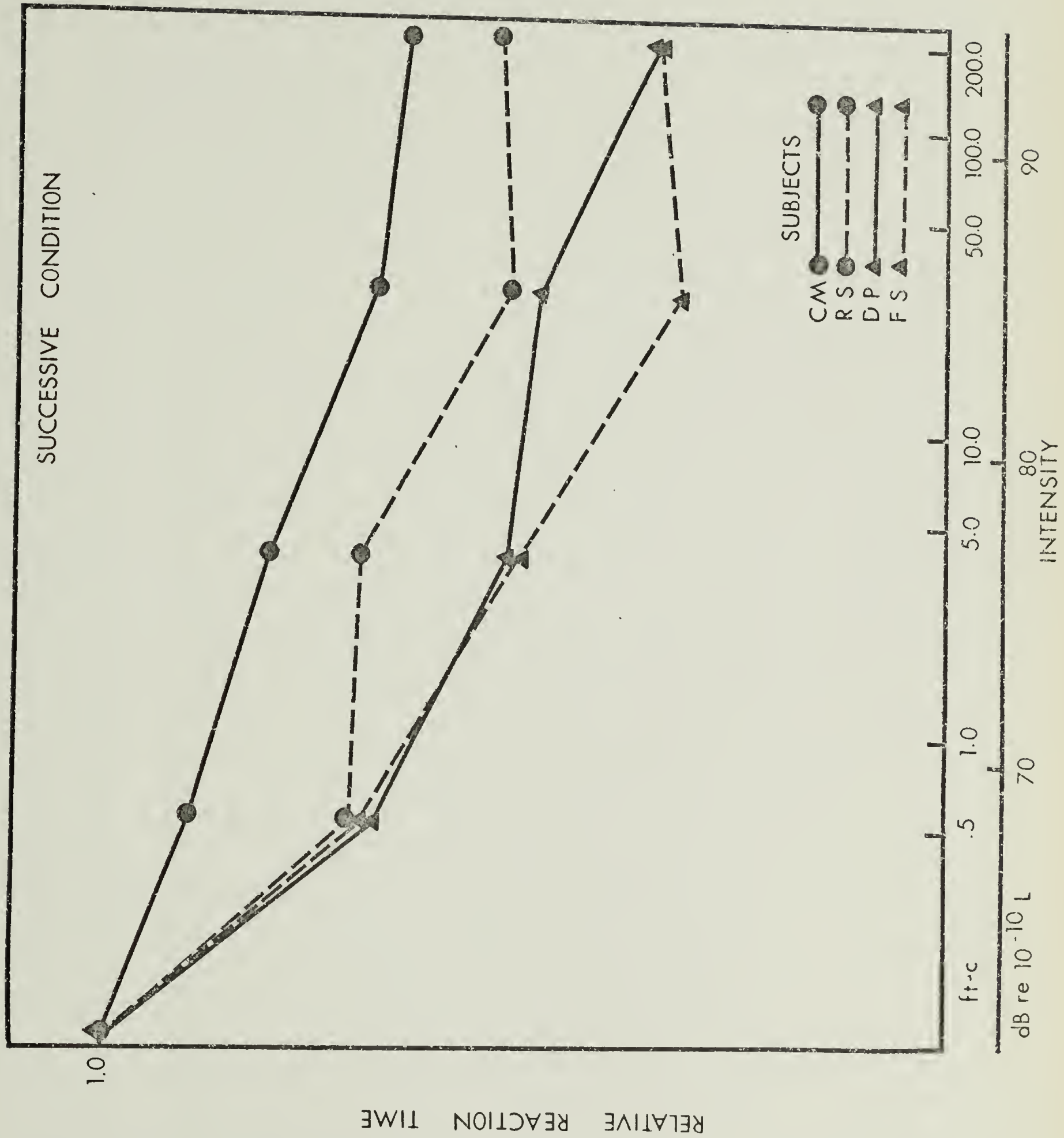


Figure 3 Median reaction time as a function of stimulus intensity for all 4 Ss in the simultaneous condition. Reaction times have been standardized so that the longest reaction time for each S is plotted on the ordinate at 1.0.



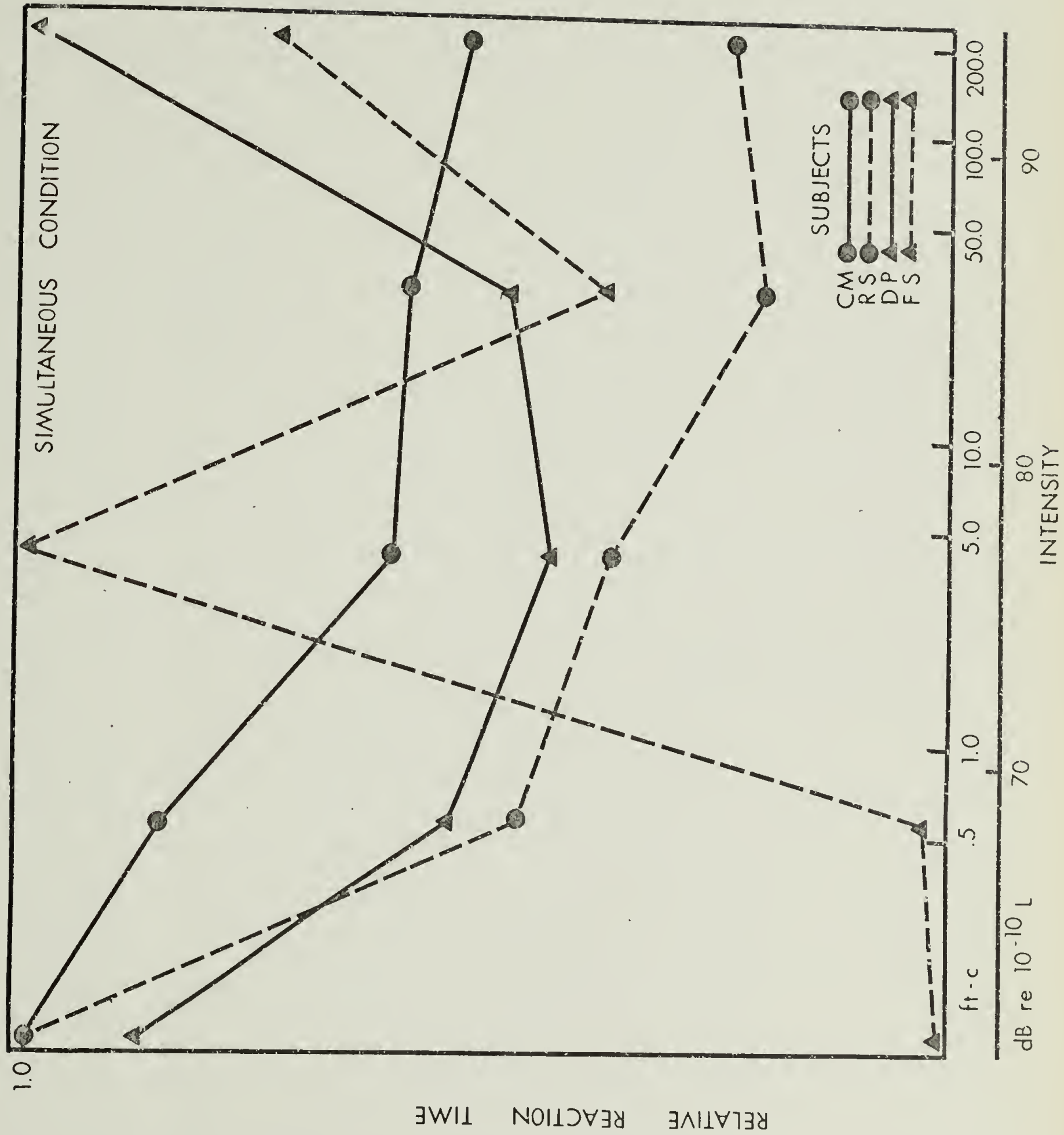


Figure 4 Median reaction time as a function of stimulus intensity for subject DP in the successive condition.

SUBJECT DP

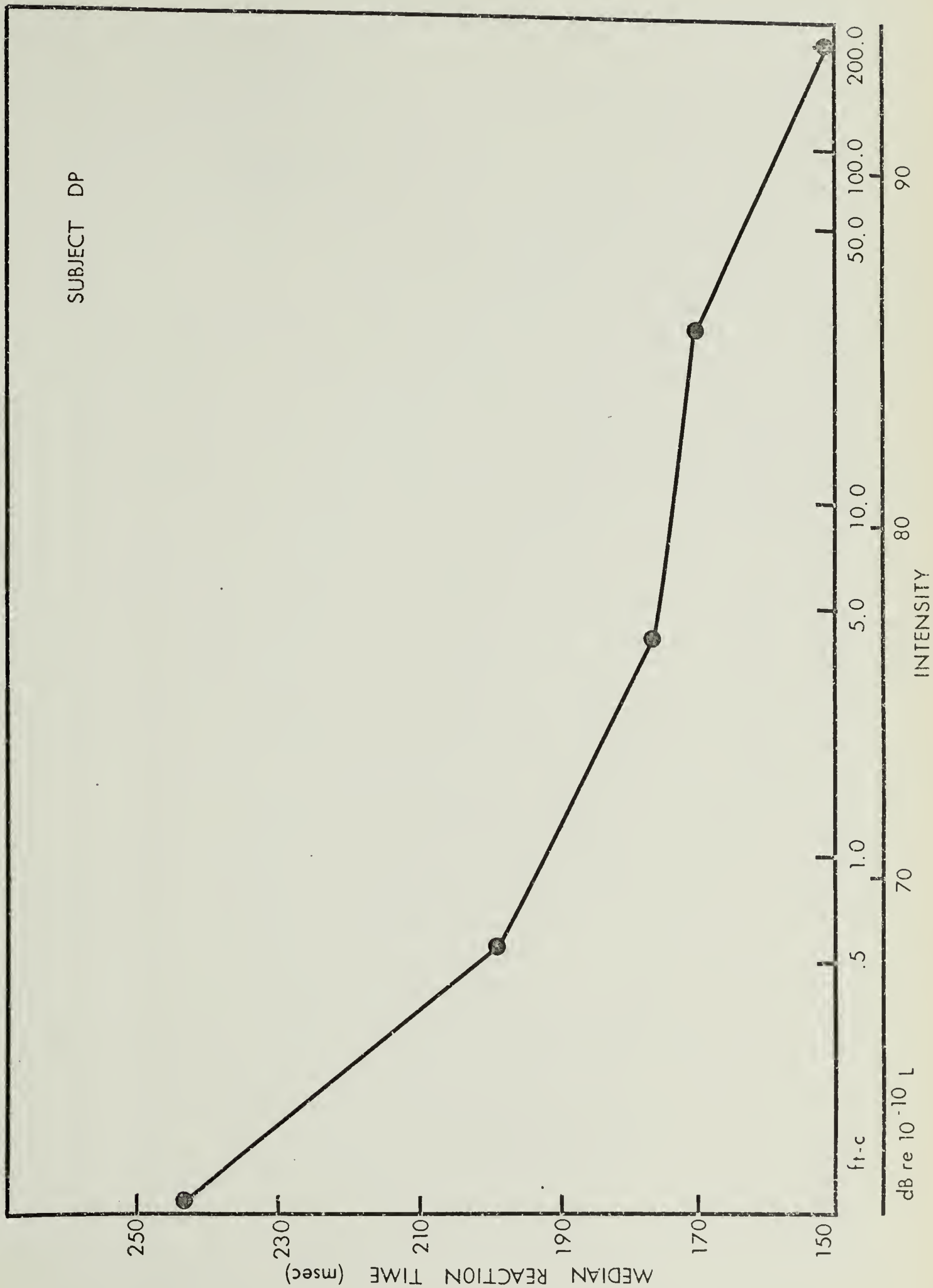




Figure 5 Median reaction time as a function of stimulus intensity for subject FS in the successive condition.

SUBJECT FS

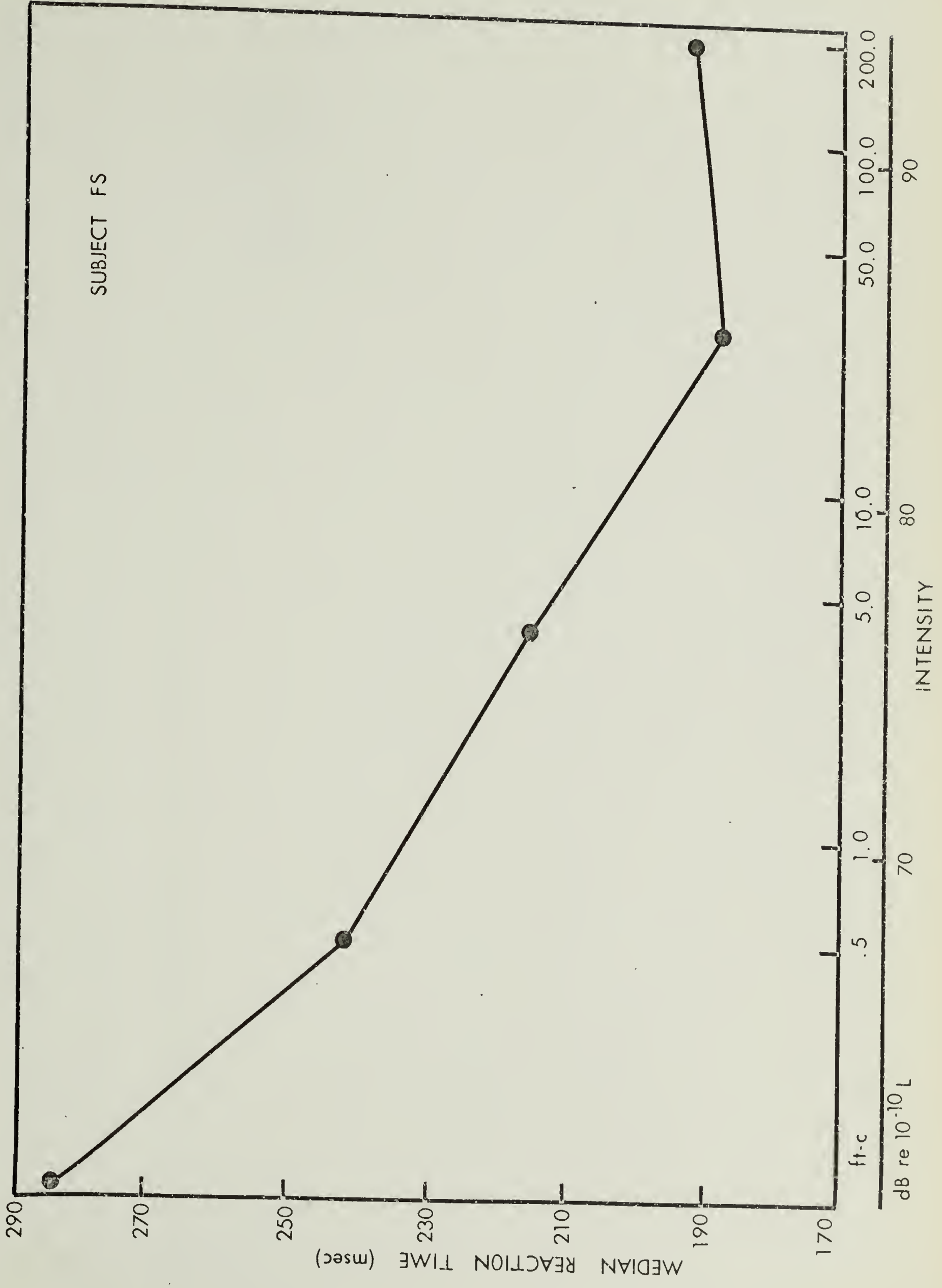


Figure 6    Median reaction time as a function of stimulus intensity for subject RS in the successive condition.



SUBJECT RS

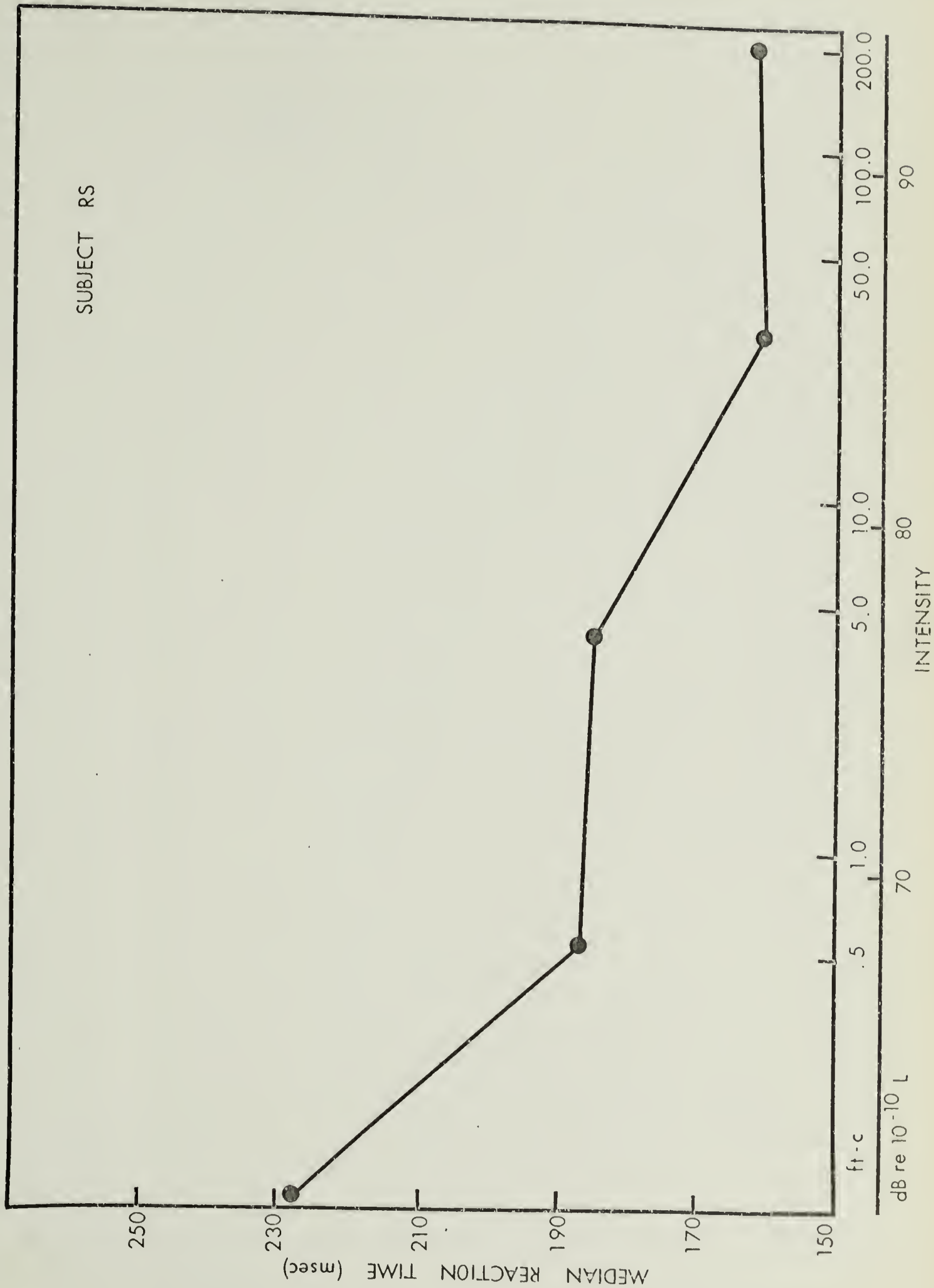
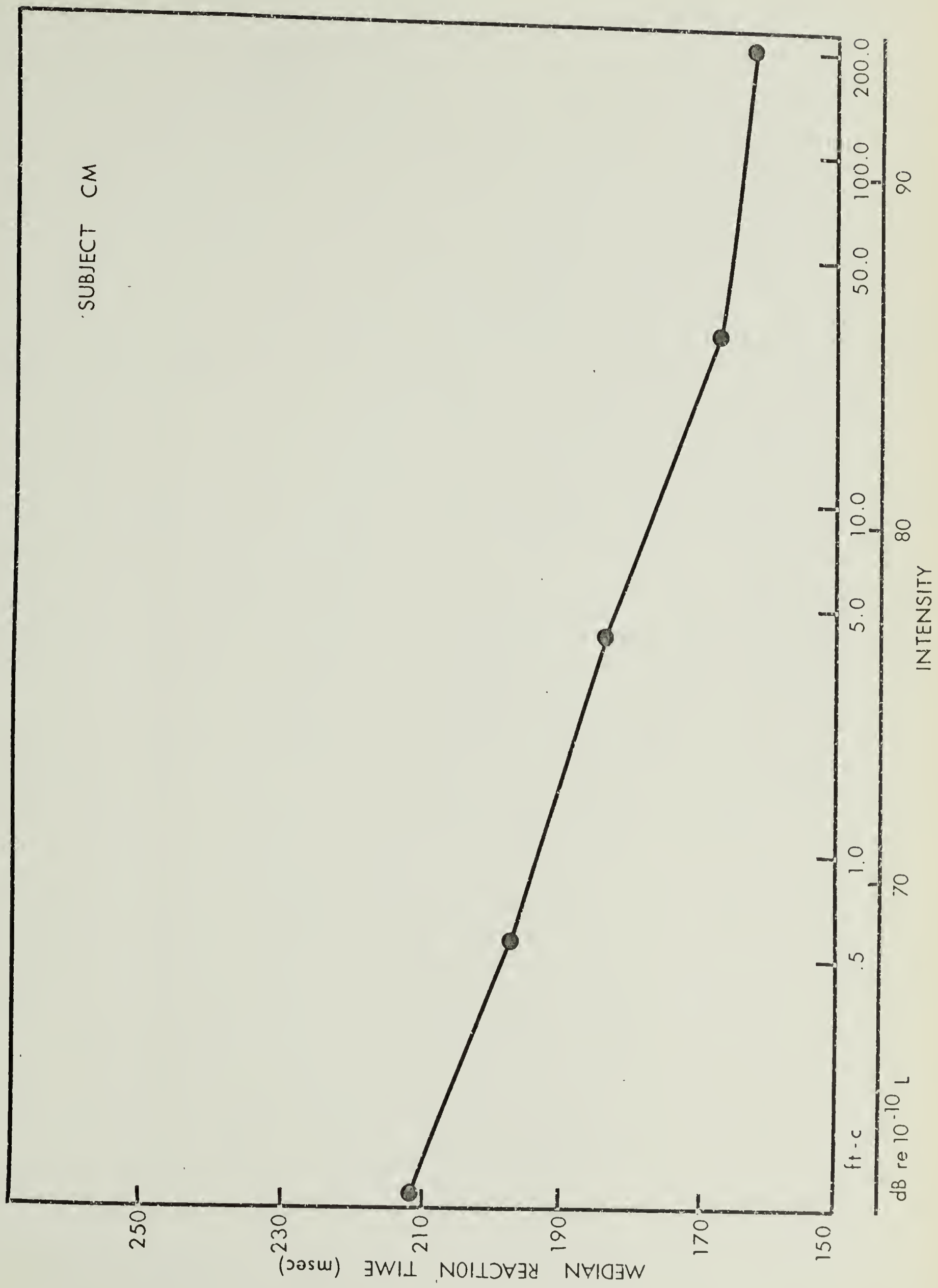


Figure 7 Median reaction time as a function of stimulus intensity for subject CM in the successive condition.

SUBJECT CM





stimulus minus the adapting intensity,  $I-I_0$ . Least square fits of linear, logarithmic, and power functions to these data were made with the aid of a computer program (Danielson, 1968). The coefficient of determination ( $r^2$ ) for each of these fits is shown in Table IV, along with the exponent of the best-fitting power function. The coefficient of determination was chosen as the measure of goodness-of-fit, because this measure also represents the percentage of variance explained by the function. For each  $r^2$  value, the probability level for getting an  $r^2$  value as large by chance, if no such relationship actually existed was determined by a t statistic (Croxtan, 1959, p. 312), and is also shown in Table IV. Mann-Whitney U tests of the  $r^2$  values presented in Table IV showed that, for the successive condition, a logarithmic function is a much better description of the relationship between  $L-L_0$  and  $I-I_0$  than either a linear function ( $p = .014$ ) or a power function ( $p = .014$ ).

One interesting aspect of the power functions is that the exponents range from  $-.38$  to  $-.40$  for all  $S$ s, and that these values are similar to those found by other investigators (Vaughan, et al., 1966; Mansfield, 1970).

#### Relationship of Magnitude Estimates to Intensity

Figures 8, 9, 10, and 11 show the geometric mean of the magnitude estimates (ME) plotted against the logarithm of the intensity for each  $S$  during the successive condition. Again specifying intensity as  $I-I_0$ , least square fits of linear, logarithmic, and power functions were made to these

Table IV Least square fits of linear, logarithmic, and power functions to the relationship between reaction time (L-Lo) and stimulus intensity ( $I-I_0$ ) for all 4 Ss in the successive condition.  $r^2$  is the coefficient of determination; p is the probability of a coefficient that large, given no such relationship actually existed; and n is the exponent of the best fitting power function.

Function		Subject			
		DP	FS	RS	CM
linear	$r^2$	.4508	.2929	.3020	.4916
	p<	.20	.40	.40	.20
log	$r^2$	.9696	.9418	.8999	.9791
	p<	.001	.001	.005	.001
power	$r^2$	.7271	.6583	.7706	.8167
	p<	.05	.10	.025	.02
	n	-.4040	-.4033	-.3894	-.3918

Figure 8    Geometric mean of magnitude estimates as a function of stimulus intensity for subject DP in the successive condition.



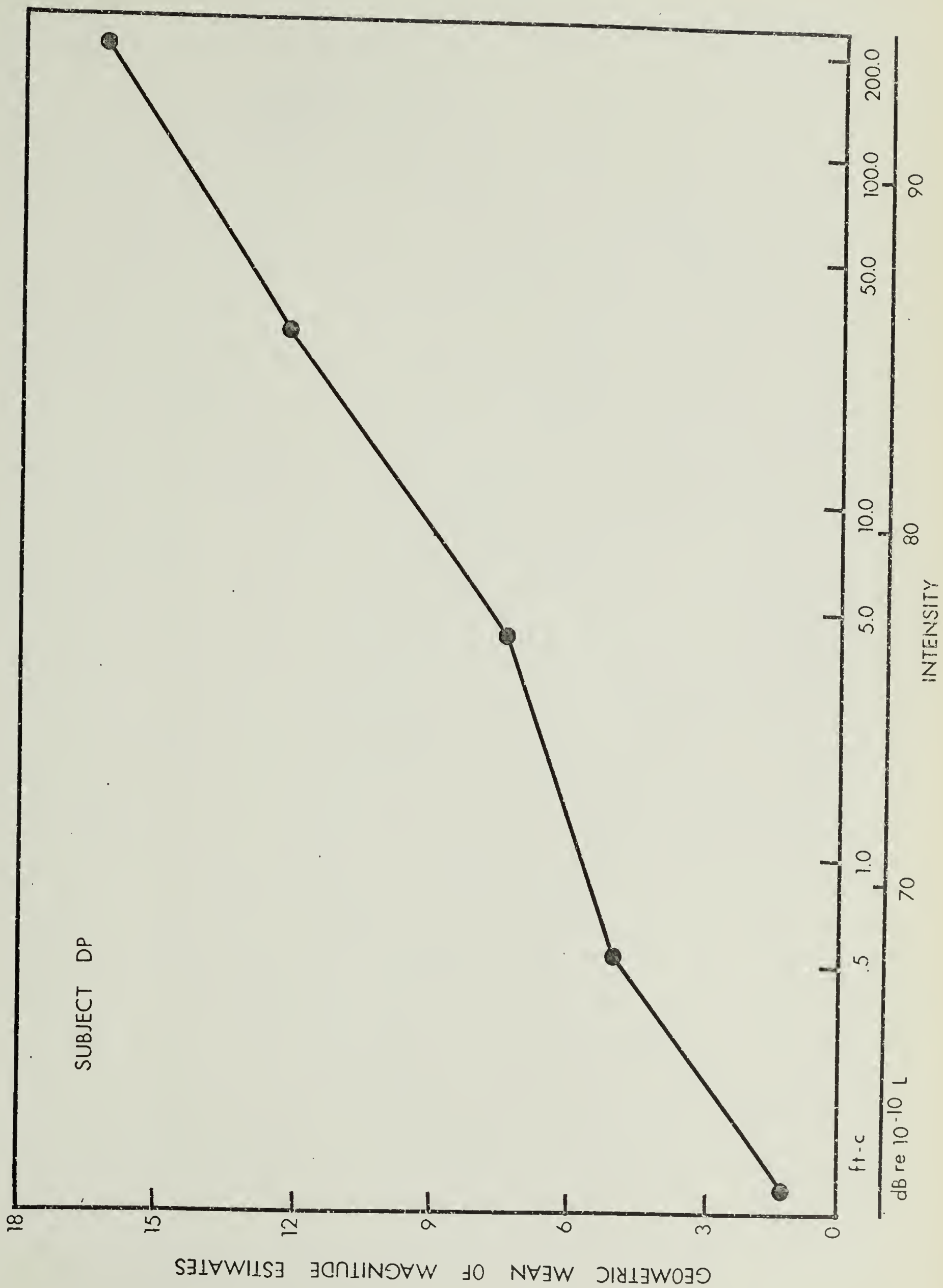


Figure 9    Geometric mean of magnitude estimates as a function of stimulus intensity for subject FS in the successive condition.

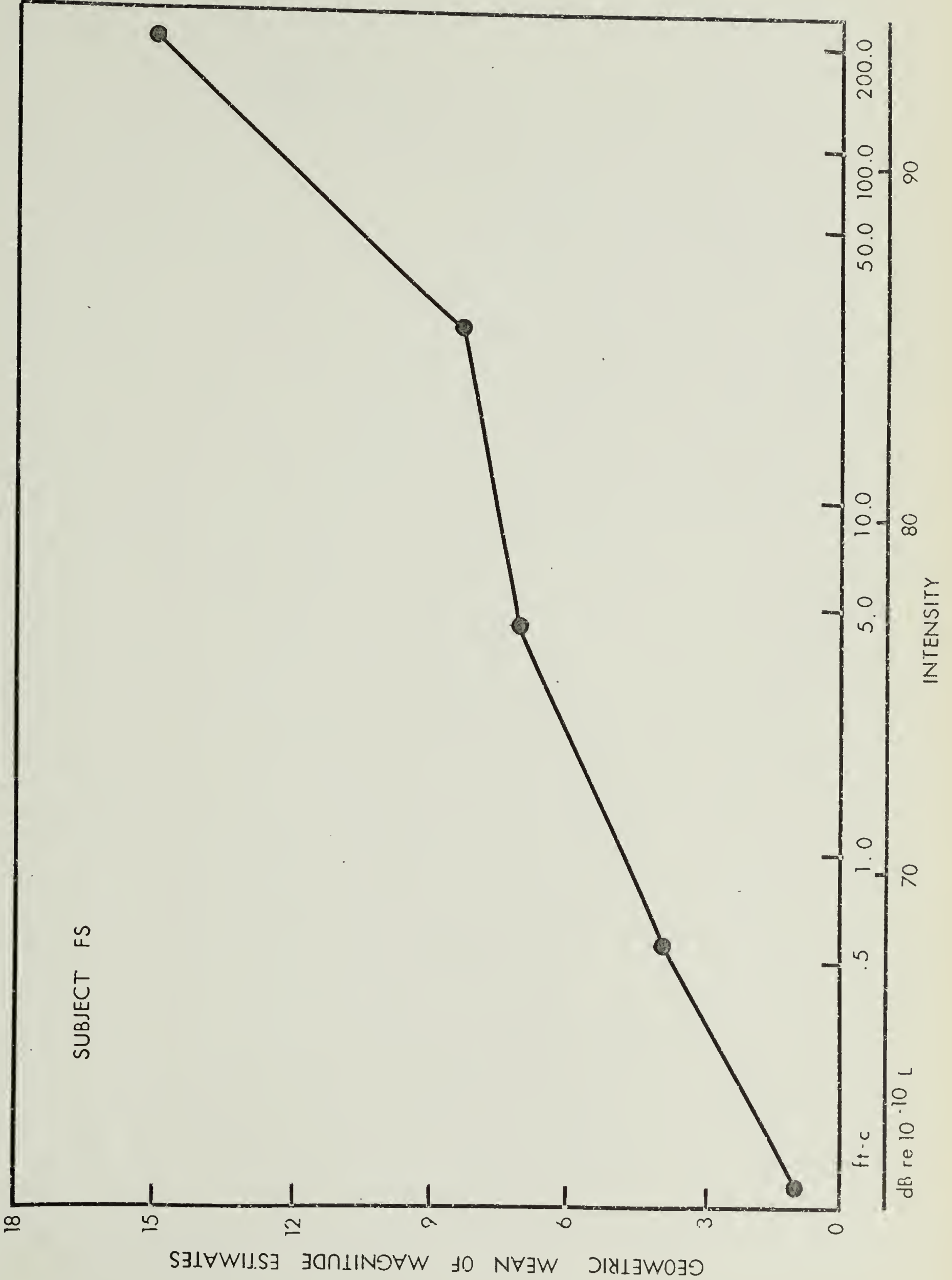




Figure 10    Geometric mean of magnitude estimates as a function of stimulus intensity for subject RS in the successive condition.

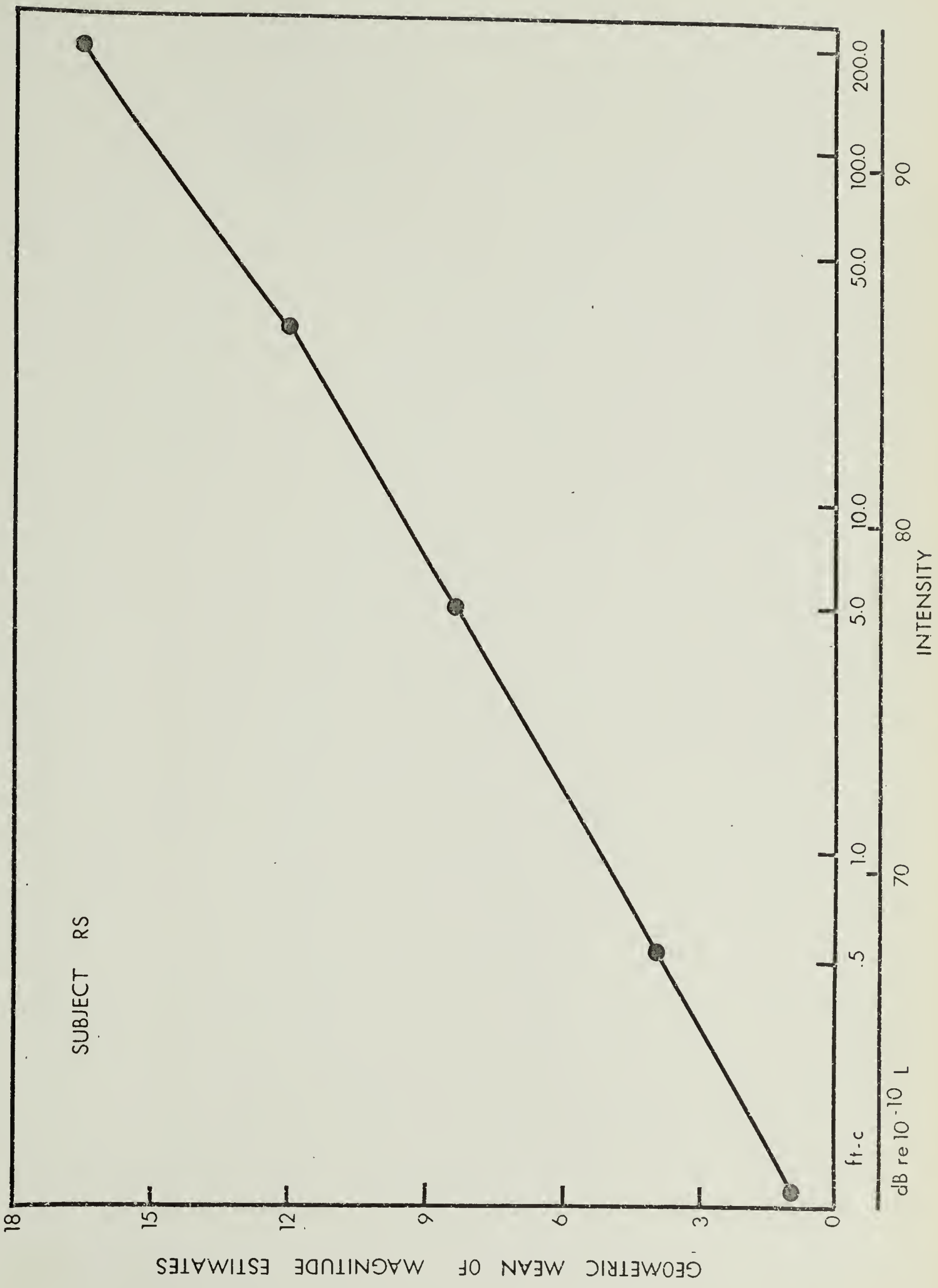
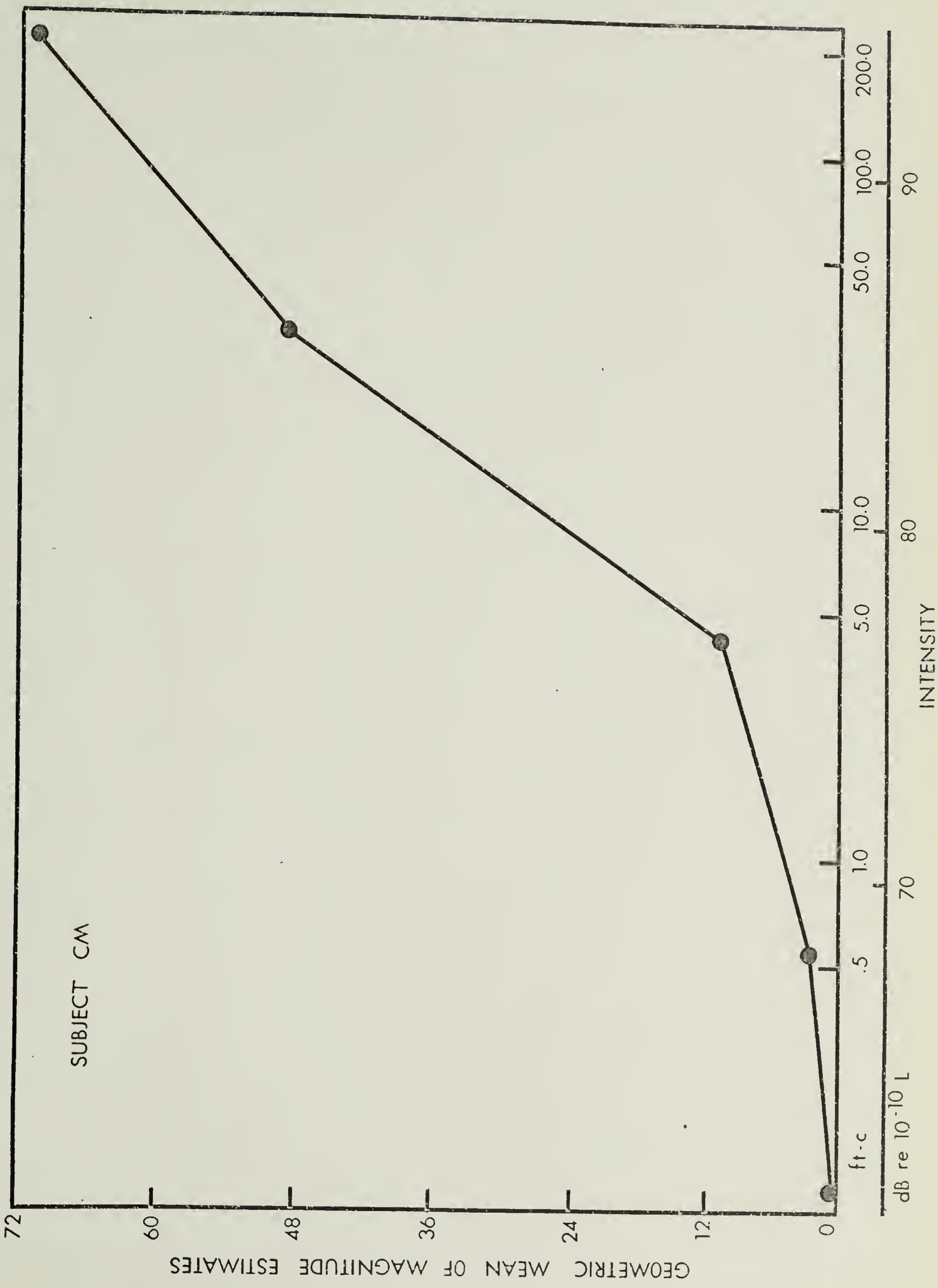


Figure 11    Geometric mean of magnitude estimates as a function of stimulus intensity for subject CM in the successive condition.





data, and the obtained values of  $r^2$  and  $p$  for each fit are shown in Table V, along with the exponent of the best fitting power function. Mann-Whitney U tests of the  $r^2$  values presented in Table V showed that, for the successive condition, a power function is a much better description of the relationship between ME and  $I-I_0$  than a linear function ( $p = .014$ ), and it is a somewhat better description than a logarithmic function ( $p = .057$ ).

Unlike the reaction time data, the magnitude estimates were not very adversely affected in the simultaneous condition. This is evidenced by the fits of the three functions to the relationship between ME and  $I-I_0$  for each  $\underline{S}$  during the simultaneous condition (Table VI). As in the successive condition, Mann-Whitney U tests of the  $r^2$  values showed that a power function is a much better fit to the relationship than a linear function ( $p = .029$ ), and it is a somewhat better description than a logarithmic function ( $p = .243$ ). Furthermore, the exponents for all  $\underline{S}$ s were correlated across conditions, with the value of the coefficient of determination being .9928 ( $p = .001$ ). It is also noteworthy that the absolute values of the exponent of the best fitting power functions ranged between .23 and .31 for three of the four  $\underline{S}$ s. These values are similar to those previously found by direct ratio methods. However, one  $\underline{S}$ , CM, had atypical exponents of .92 and .75 for the two conditions.

Table V Least square fits of linear, logarithmic, and power functions to the relationship between the geometric mean of the magnitude estimates and stimulus intensity ( $I-I_0$ ) for all 4 SS in the successive condition.  $r^2$  is the coefficient of determination;  $p$  is the probability of a coefficient that large, given no such relationship actually existed; and  $n$  is the exponent of the best fitting power function.

Function	Subject			
	DP	FS	RS	CM
linear	$r^2$	.7172	.7907	.6817
	$p<$	.10	.05	.10
log	$r^2$	.9477	.9094	.9573
	$p<$	.01	.02	.05
power	$r^2$	.9750	.9588	.9692
	$p<$	.005	.005	.02
	$n$	.2582	.2711	.3000
				.9234

Table VI Least square fits of linear, logarithmic, and power functions to the relationship between the geometric mean of the magnitude estimates and stimulus intensity ( $I-I_0$ ) for all 4  $\underline{S}$ s in the simultaneous condition.  $r^2$  is the coefficient of determination;  $p$  is the probability of a coefficient that large, given no such relationship actually existed; and  $n$  is the exponent of the best fitting power function.

Function	Subject			
	DP	FS	RS	CM
linear	$r^2$	.6999	.7344	.6188
	$p<$	.10	.10	.20
log	$r^2$	.9332	.9346	.9678
	$p<$	.01	.01	.005
power	$r^2$	.9562	.9695	.9575
	$p<$	.005	.005	.005
	$n$	.2335	.2406	.3086
				.7521



### Relationship between Reaction Times and Magnitude Estimates

Since reaction times were found to be a logarithmic function of intensity, while magnitude estimates were found to be a power function of intensity, it followed that reaction times were not linearly related to magnitude estimates.

Figures 12, 13, 14, and 15 show median reaction time ( $L-L_0$ ) plotted against the geometric mean of the magnitude estimates for each  $S$ . The coefficients of determination for the linearity of these two measures were low, with values of .72, .78, .82, and .86.

### Experiment 2

Due to the fact that subject CM had very atypical values for the exponent of the power function relating ME to  $I-I_0$ , it was decided to investigate this point further. It is known that the brightness exponent increases with increased light-adaptation (Stevens & Stevens, 1963), but the value rarely approaches that found for subject CM. To assure that this result was not an outcome of peculiarities in the methodology, 11 more  $S$ s were run on the magnitude estimation task only.

### Method

#### Subjects and Apparatus

$S$ s were from the same population as in Experiment 1, and the apparatus was the same.

Figure 12    Reaction time ( $L-L_0$ ) as a function of the geometric mean of the magnitude estimates for each stimulus. The data are for subject DP in the successive condition.

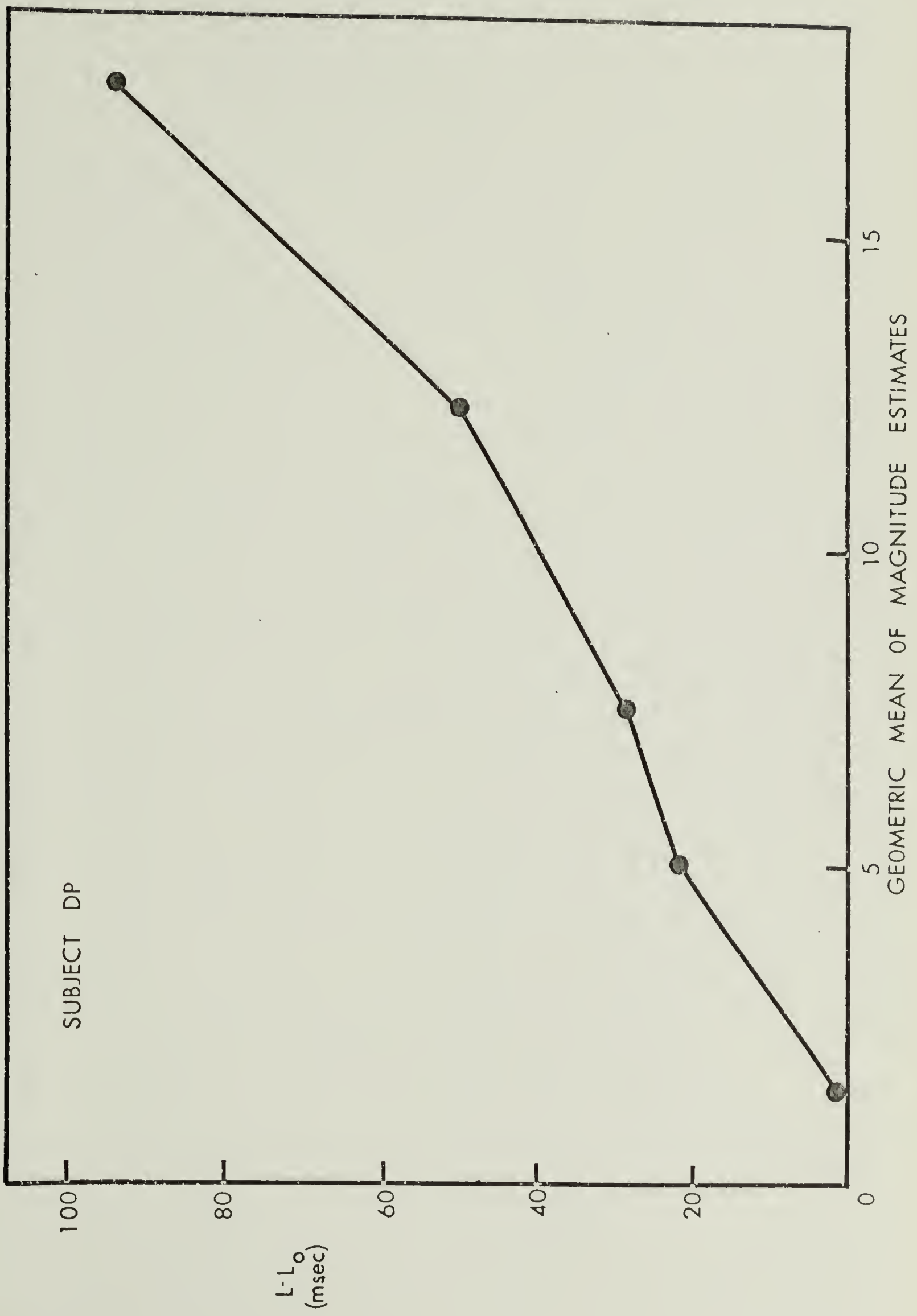


Figure 13    Reaction time ( $L-L_0$ ) as a function of the geometric mean of the magnitude estimates for each stimulus. The data are for subject FS in the successive condition.



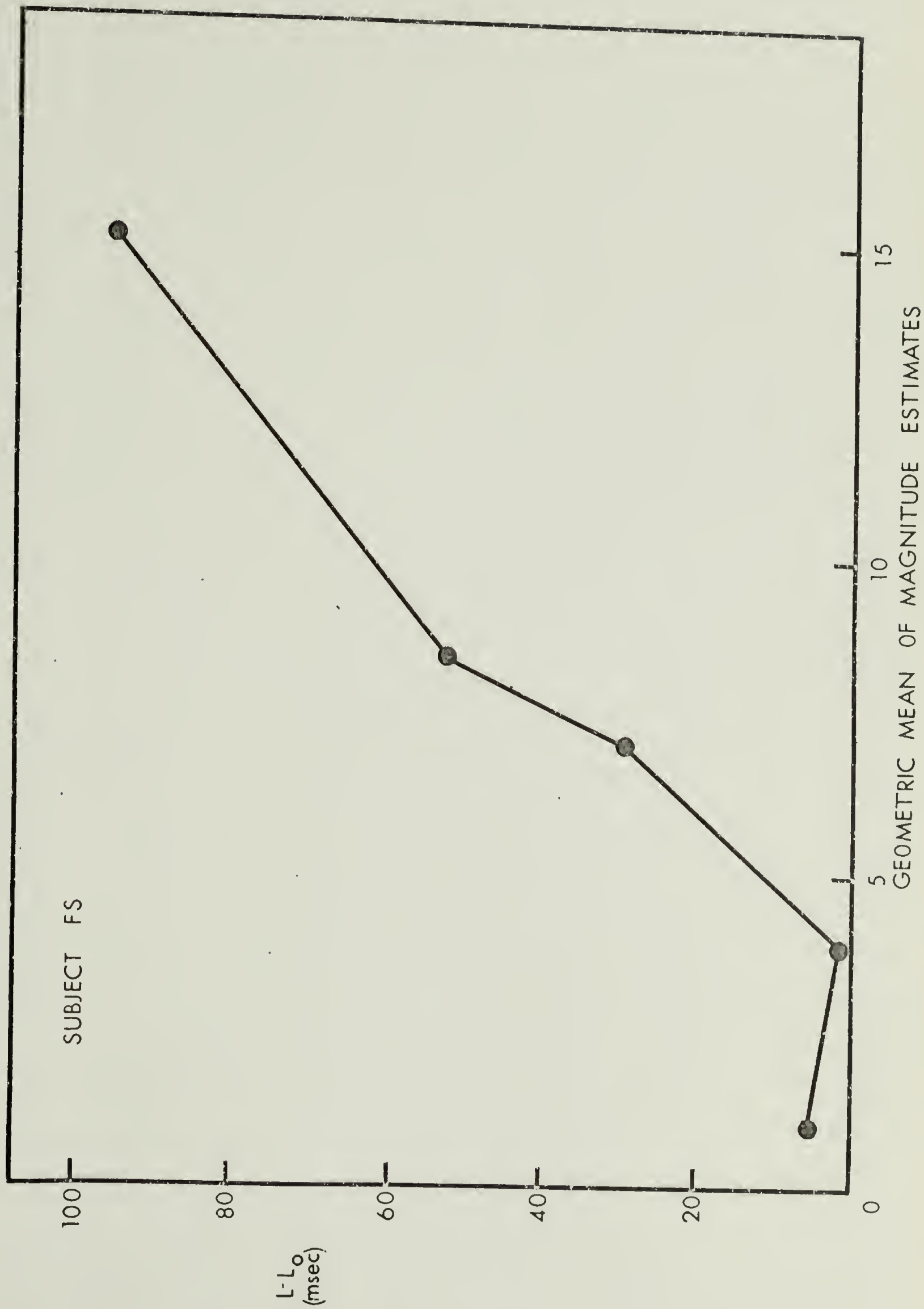


Figure 14      Reaction time ( $L-L_0$ ) as a function of the geometric mean of the magnitude estimates for each stimulus. The data are for subject RS in the successive condition.

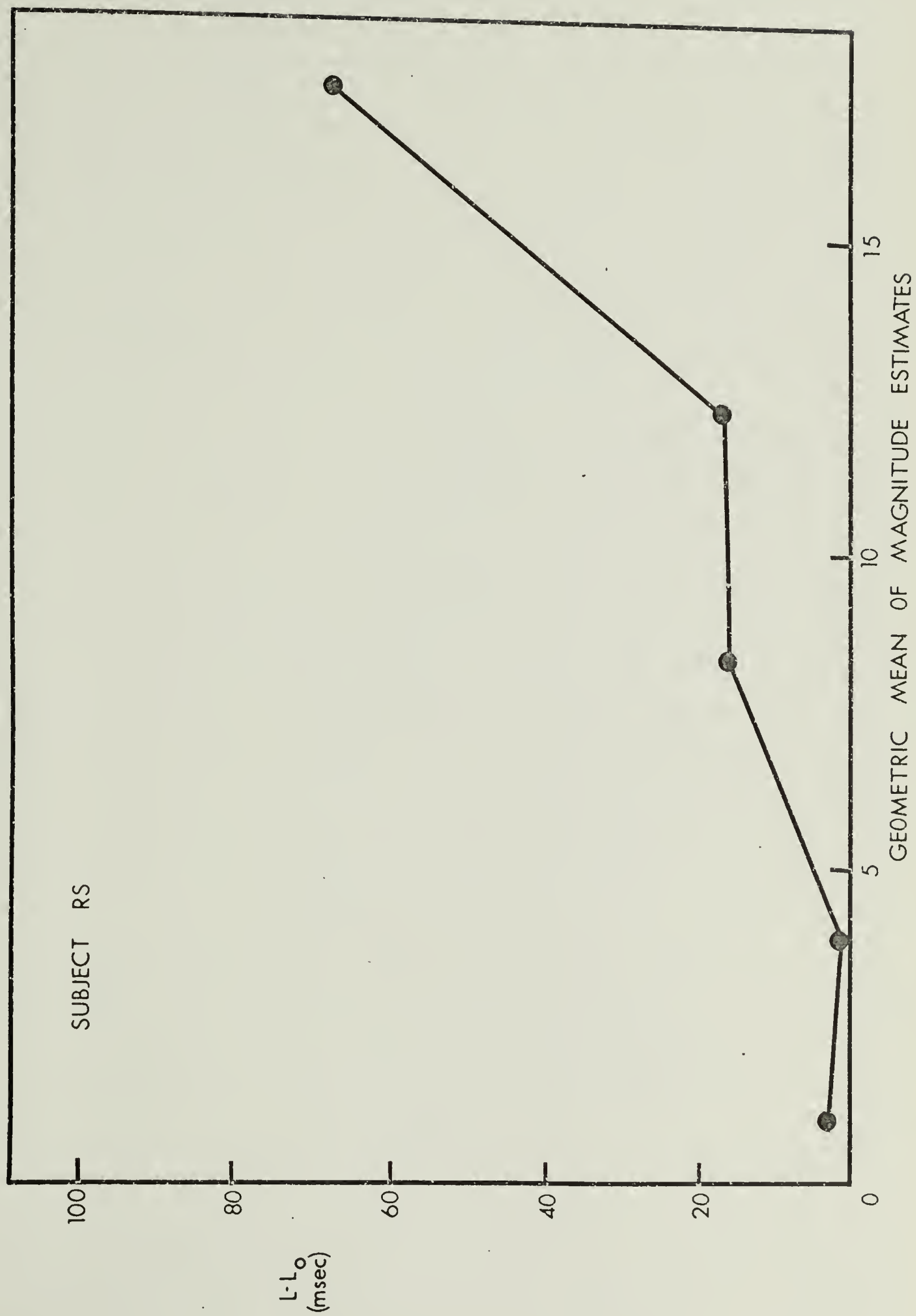
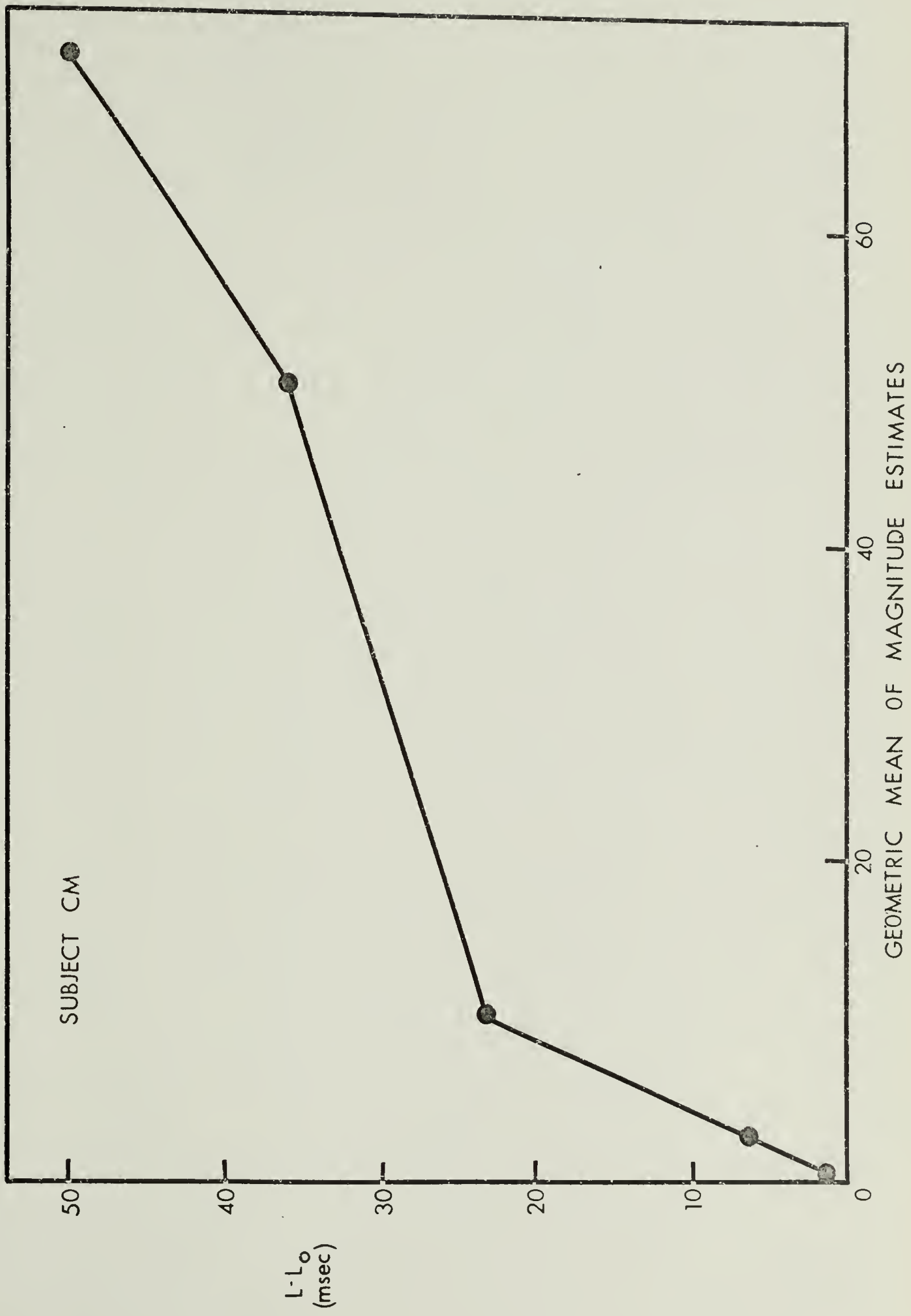


Figure 15    Reaction time ( $L-L_0$ ) as a function of the geometric mean of the magnitude estimates for each stimulus. The data are for subject CM in the successive condition.





## Procedure

Ss were run under the same conditions as in the last two sessions of Experiment 1, except that they did not perform the reaction time task. Five Ss gave six magnitude estimates for each stimulus intensity, as was the case in the simultaneous condition. Likewise, six Ss gave two magnitude estimates for each stimulus intensity, as was the case in the successive condition. Also, a second set of instructions which differed slightly from the first (see Appendix) was given randomly to 4 of the 11 Ss.

## Results

Table VII summarizes the data for each S. Mann-Whitney U tests done on the values of  $r^2$  showed that a power function is a much better fit to the relationship between ME and  $I-I_0$  than either a linear ( $p = .002$ ) or logarithmic ( $p = .05$ ) function, even though two Ss' data (Ss 2 and 10) were better fit by a logarithmic function. Furthermore, the best fitting power functions for all Ss had exponent values which ranged from .25 to .46. The instruction variable had no obvious effect. Thus, subject CM in Experiment 1 seems to be an anomalous case.

## Discussion

### Reaction Times During the Simultaneous Condition.

The disruption of the reaction times in the simultaneous condition was a surprising outcome of this research.

Table VII

Least square fits of linear, logarithmic, and power functions to the relationship between the geometric mean of the magnitude estimates and stimulus intensity ( $I-I_0$ ) for all 11 Ss in Experiment 2.  $r^2$  is the coefficient of determination;  $p$  is the probability of a coefficient that large, given no such relationship actually existed; and  $n$  is the exponent of the best fitting power function.

Function	Subjects											
	1	2	3	4	5	6	7	8	9	10	11	
linear	r <sup>2</sup>	.7895	.5769	.7560	.7968	.5832	.9054	.7615	.7534	.6796	.6650	.7967
	p<	.05	.20	.10	.05	.20	.02	.10	.10	.10	.10	.05
log	r <sup>2</sup>	.8990	.9958	.9105	.9048	.9360	.8063	.8973	.9294	.9140	.9793	.8701
	p<	.02	.001	.02	.02	.01	.05	.02	.01	.02	.005	.025
power	r <sup>2</sup>	.9825	.8389	.9858	.9644	.9521	.9395	.9581	.9778	.9802	.9404	.9824
	p<	.001	.05	.001	.005	.005	.01	.005	.005	.005	.01	.001
	n	.3526	.4270	.3191	.3740	.2895	.4687	.4218	.2503	.3306	.2621	.4528

It can be hypothesized that just prior to the onset of the stimulus, Ss were maintaining two different sets. One was a "motor set" for releasing the switch in response to the onset of the stimulus; the other was a "judgmental set" for assessing the magnitude of the sensation aroused by the stimulus. It would seem reasonable, therefore, to assume that the sets were competing, and the motor set lost, with the resultant disruption of the reaction times. This analysis of the situation is based on Ss' verbal reports following the experiment. Subject DP stated, "Before the light came on I tried to stay prepared to get a good look at it, so I could judge its brightness." Likewise, subject RS stated, "I don't feel as if I was paying as much attention to my finger as on other days." Both of these comments support the hypothesis that it was the presence of these two competing sets which was responsible for the disruption of the reaction times during the simultaneous condition.

Furthermore, it would appear to be difficult to control this disruptive effect, because some Ss are not aware of the effect, and others, who are aware of it cannot seem to control against it. This is evidenced by the comments of two Ss. Subject FS, whose reaction times in the simultaneous condition were longer by nearly 300%, stated that she was completely unaware of any change in the speed of her reaction times in that condition. Meanwhile, subjects DP and CM, who verbalized the fact that



their set to give magnitude estimates may have affected their reaction times, stated that it was almost impossible to divorce this set from their preparation for the stimulus onset. This is surprising in view of the fact that they knew that the stimulus remained present for some time following the release of their switch.

Whether the above analysis in terms of competing sets is correct or not, or if it is only one of a number of possible explanations, is irrelevant. Whatever the explanation, it is apparent that the reaction times in the simultaneous condition did not reflect solely a stimulus parameter, i.e. intensity. For this reason, these reaction times were not used in subsequent analyses of the data. The failure to obtain stable reaction times in this condition did not limit the results of this research, because reaction times and magnitude estimates to the same stimuli and within the same subject were recorded in the successive condition. These measures were recorded within a 45-60 min. period, and since it is assumed that these measures are stable characteristics of the individual, it is not likely that they would vary greatly within the time span of a single experimental session. Certainly the fact that both measures were obtained from the same  $\underline{S}$  is a significant improvement over earlier studies.

#### Reaction Time Versus Intensity During the Successive Condition.

The finding that reaction times ( $L-L_0$ ) are a negative logarithmic function of stimulus intensity ( $I-I_0$ ) confirms

the earlier results of Bartlett and Macleod (1954) and extends this relationship to the light-adapted S. It is interesting that both their research and the present research employed a long stimulus duration, 575 and 1000 msec., respectively. Those studies which have employed very short stimulus durations (Vaughan, 1966; Vaughan, et al, 1966; Mansfield, 1970) have reported latency data that are a power function of intensity. Thus, it appears that latency may be a logarithmic function of intensity when stimulus duration is long, but a power function of intensity when stimulus duration is short. No parametric study of possible changes in the form of latency functions with changes in stimulus duration has been undertaken, but such a study would be necessary in a complete analysis of latency data.

The present results, taken alone, lend support to Fechner's Law as an accurate description of the relationship between the magnitude of a sensation and the magnitude of the stimulus which aroused that sensation. However, taken together with the results of the magnitude estimation task (to be discussed below), they suggest support for Fechner's Law only as a description of peripheral processes.

One interesting aspect of the latency data was that the fits of power functions, although much poorer than the fits of logarithmic functions, had exponent values ranging between  $-.38$  and  $-.40$  for all 4 Ss. These values

are very similar to those found in previous studies which have reported power functions (Liang and Pieron, 1947; Vaughan, et al., 1966; Mansfield, 1970). Thus, if only power functions were fit to the present data, the results might be falsely interpreted as support for Stevens' Law and as confirmation of previous studies with regard to exponent values. These data point out the need to use an objective methodology that avoids the effect of what Stevens termed "experimenter expectation." This will be returned to in a later section entitled "Methodological Considerations."

#### Magnitude Estimates versus Intensity

The finding that magnitude estimates are a power function of stimulus intensity ( $I-I_0$ ) confirms numerous earlier studies by Stevens and his collaborators. Thus, taken alone, these results lend support to Stevens' Law as an accurate description of the relationship between the magnitude of a sensation and the magnitude of the stimulus which aroused that sensation. However, like the results of the reaction time data, this conclusion is not totally warranted. Given the above results for reaction times, it appears that Stevens' Law serves only as a description of central processes.

The fact that the exponents of the power functions in both the successive and simultaneous conditions for three of the four Ss ranged between .23 and .31, also supports previous findings of a value of about  $1/3$ . However,



subject CM's anomalous exponents (.92 and .75) and the subsequent results of Experiment 2 raise an interesting question about the ability of Ss to give numerical responses to represent their sensations and the inevitability of a resultant power function. From a total of 15 Ss who gave magnitude estimates in Experiments 1 and 2, the data of 13 of them were better fit by a power function. The other two (both in Experiment 2) were better fit by a logarithmic function. However, reports of ratio methods, such as magnitude estimation, resulting in logarithmic psychophysical functions are extremely rare. In fact, they are perhaps more rare than one would expect, given the mathematical similarity between a power function with an exponent less than 1.0 and a logarithmic function.

Two viable reasons exist for this failure to find reports of ratio methods which support Fechner's Law. The first is the fact that most investigators employing direct ratio methods assume that the resultant data will be best fit by a power function. Therefore, they do not bother to try to fit other functions to the data, but go on to deal with other aspects of the data, such as the continuum being scaled or the value of the exponent. The second possible reason is embodied in the "nomathetic imperative" (Stevens, 1971). This search for the simple laws governing nature requires the dismissal of occasional "aberrant" data on the ground that they lead one astray from the fundamental principles of concern to science.



This attitude is reflected in many of Stevens' writings and practices. Thus, he writes concerning Ss whose magnitude estimates do not follow a power law: "It appears that most intelligent, educated people can make these quantitative estimates in a consistent manner, but it is idle to assume that all people can do so. It is not surprising, therefore, that an occasional O in our experiments turns out to use numbers in curious ways" (Stevens, 1956, p. 18). Here Stevens seems to imply that Ss whose data do not follow a power law must use numbers in an unintelligent or uneducated manner. Likewise, when he (Stevens, Rogers, and Herrnstein, 1955) replicated and confirmed the results of an early scaling experiment (Laird, Taylor and Willie, 1932) which used ratio methods but found results inconsistent with his own, he simply concluded that that particular procedure should not be used. Thus, we see the nomathetic imperative screening both the data and the methods which are acceptable as evidence for Stevens' Law. The nomathetic imperative might serve as a valid justification for dismissing some data as aberrant, but only if such data occurs in only a few cases. However, if the data collected in this investigation is indicative of the entire population, then the fact that 2 out of 15 Ss' data for magnitude estimates were better fit by logarithmic functions, while one had an exceedingly large exponent, suggests that perhaps close to 20% of the population use numbers "curiously."

If this estimate is at all accurate, then it seems well worth the time to investigate the causes for these departures from "normality," and not to dismiss them so lightly.

### Methodological Considerations

Considering many of the aforementioned practices in analyzing data from psychophysical experiments, it appears that the methods of analysis used in such research are of an importance equal to the empirical findings. Unlike numerous earlier studies, the present investigation and the analysis of the data were not guided by an overriding theoretical assumption. The values of  $L_0$  were interpolated directly from Figs. 4-7, without consideration for a value which might give a better fit to a particular function. Likewise, the value of  $I_0$  was not chosen post-hoc, but was assigned the value of the background intensity prior to any fits of functions to the data. Lastly, linear, logarithmic, and power functions were all fit to the data with the coefficient of determination of the least square fit employed as the measure of goodness-of-fit. Thus no a priori assumption about the form of the function was made, nor was there any ambiguity about what was meant by a "good fit."

It should be obvious that all of the above practices are necessary if the conclusions are to be free of the effect of experimenter expectation. Yet these practices

appear to have been rarely, if ever, followed. For this reason, psychophysical studies which exhibit the practices representative of strong experimenter expectation should be viewed with care.

### Fechner's Law or Stevens' Law

The present investigation has confirmed the validity of Fechner's Law when reaction time is used as the response mode. Likewise, it has confirmed the validity of Stevens' Law when numerical magnitude estimation is used as the response mode. These results, rather than being discordant, are quite consistent, given the great difference in the forms of the responses. As pointed out by Phillips (1964), and cited earlier, they are really quite logically consistent. Furthermore, these results fit well into various two-stage models of psychophysical processing.

It will be remembered that Garner (1954), Attneave (1962), Ekman (1964), and Treisman (1964a, b) have proposed models in which the psychophysical function can be viewed as the product of two transformations. The first transduces the physical energy of the stimulus into a sensation magnitude, and the second transforms this sensation magnitude into a response magnitude. Garner and Attneave have suggested that both of these transformations are power functions, while Ekman and Treisman have suggested that the input function is logarithmic and the output function is exponential. If the input function is associated with characteristics of physiological processes occurring early in the



receptor-effector chain and the output function is associated with processes occurring later in this chain, then the results of the present investigation lend support to the models of Ekman and Treisman.

On the basis of previous studies (Kuffler, 1953; Bishop, Burke, and Davis, 1962), it has been shown that visual reaction times are characteristic of the duration of retinal processes. The results for  $S_s$  in the present investigation indicate that the duration of these peripheral processes are related logarithmically to stimulus intensity. As such, they support the contention of a logarithmic input function as proposed by Ekman and Treisman. The fact that the magnitude estimates of these same  $S$ 's are related to intensity by a power function indicates that responses representative of more central processing undergo a further transformation. Although it is obvious that magnitude estimates are not simply transformed latencies, the fact that they are representative of more central processes lends descriptive support to the model. A more exact test of the model would involve the measurement of some variable that is represented both in the periphery and more centrally. In general, this limits us to physiological variables; but as pointed out earlier, such data also support the presence of a logarithmic function at the periphery and a power function more centrally.

In conclusion, then, it appears that the controversy between Fechner's Law and Stevens' Law is really a



pseudo-controversy. Looking back at Equation (1), it is clear that there are innumerable methods for determining the value on the left-hand side of the equation. Depending on what type of response is utilized by a given method, data can be obtained which support either a logarithmic or a power function. However, the important conclusion that presents itself is that those methods which utilize responses representing peripheral processes confirm Fechner's Law, while those that utilize responses representing central processes confirm Stevens' Law.

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## Appendix

Instructions for practice sessions and the reaction time task in the successive condition:

Your task in this experiment will be to respond as quickly as possible to a visual signal. On the table before you is a button. At the start of each trial, the experimenter will say "ready?". Upon hearing this, you are to depress the button with one finger of your right hand. Be sure that your hand is resting in a comfortable position before you start, and be sure to use the same finger and hand position throughout the experiment. When you are prepared for the visual signal, let the experimenter know by responding "ready". Some very short time later a light will appear in the disc in the center of the presentation board which is before you. As soon as you see the light, lift your finger off the button. Speed is important, so release the button as quickly as possible to the onset of the light. After releasing, do not put your finger back on the button until the next trial (When the experimenter says "ready?" again). The signal light will vary in brightness from trial to trial, so be sure to watch the disc closely during each trial.

If there are any questions, please ask them now.

Instructions for the magnitude estimation task in the successive condition and for seven Ss in Experiment 2:

Your task in this part of the experiment will be to estimate the brightness of lights. You will not need to operate the button during this time.

As on previous days, each trial will begin with the experimenter saying "ready?", and you will respond back "ready" when you are prepared for the signal. When the light appears you need do nothing but observe it. When the light goes out, you are to assign a number to the brightness of that light. You may assign any number which you feel appropriate to the brightness of the first light. However, be sure to make all subsequent judgments in relation to the first. That is, if you happen to assign the first brightness a value of 10, and on the next trial you are presented a light which appears twice as bright, then you should call that brightness 20; Likewise, if the second light appears one-half as bright as the first then you should call it 5, and so forth. Be sure to make each estimate in relation to the first, and assign each light a number proportional to the brightness as you perceive it. You may use fractions, whole numbers, decimals or anything you feel comfortable with.

If there are any questions, please ask them now.

Instructions for the simultaneous condition:

Your task in this part of the experiment will be to respond as quickly as possible to a visual signal and then to estimate the brightness of that signal. The procedure will be the same as on previous days.

Each trial will begin with the experimenter saying "ready?". Upon hearing this, you are to depress the button in the same manner as you have done on previous days. When you are prepared for the visual signal, respond by saying "ready". Some very short time later a light will appear in the disc in the center of the presentation board. As soon as you see the light, lift your finger off the button. Speed is important, so release the button as quickly as possible to the onset of the light. After releasing the button, wait for the light to go out. You are then to assign a number to the brightness of that light. You may assign any number which you feel appropriate to the brightness of the first light. However, be sure to make all subsequent judgments in relation to the first. That is, if you happen to assign a value of 10 to the brightness of the first light, and on the next trial you are presented a light which appears twice as bright, then you should call that brightness 20; likewise, if it appears one-half as bright as the first, then you should call it 5, and so forth. Be sure to make each estimate in relation to the first, and assign each light a number proportional to the brightness as you perceive it. You may use fractions, whole numbers, decimals, or anything you feel comfortable with.

If there are any questions, please ask them now.



Instructions for four Ss in Experiment 2

You will be presented with a series of stimuli in irregular order. Your task is to tell how bright they seem by assigning numbers to them. Call the first stimulus any number that seems to you appropriate. Then assign successive numbers in such a way that they reflect your subjective impression. For example, if a stimulus seems twice as bright, assign a number twice as large as the first. If it seems one-half as bright, assign a number one-half as large, and so forth. Use fractions, whole numbers, or decimals, but make each assignment proportional to the brightness as you perceive it.





