

The Psychophysical Power Law and Unilateral Spatial Neglect

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The relationship between objective measures and subjective experiences of sensory stimuli is described by a power law, $\psi = K\phi^\beta$, in which ψ represents the psychological value and ϕ the physical value. The constant (K) and the exponent (β) are empirically derived. This relationship is often assumed to correspond to properties of peripheral receptor sensory transduction. Patients with left-sided spatial neglect tend to bisect lines to the right of the objective midline. Line bisection bias was used as the dependent variable in how a patient with neglect and five normal subjects bisected lines of varying lengths. Analyzing these data as a power function accounted for over 99% of the variance in five different experimental conditions. The normal exponent matched the value expected from traditional psychophysical experiments of line length estimation, whereas the patient's exponent was diminished. The patient's data provide evidence for central nervous system participation in computations underlying psychophysical relationships. The notion that attentional and perceptual processes are closely linked was supported by the influence of attentional cuing on the power functions obtained in normal subjects. The descriptive precision of the power function uncovered qualitative variability in how normal subjects allocate attention across different spatial reference frames and demonstrated that this patient had a quantitative defect in directing attention across an allosteric reference frame, but a qualitative defect in directing attention across a viewer/environment reference frame.

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INTRODUCTION

With the publication of the *Elements of Psychophysics*, Gustav Fechner (1860) introduced the discipline of psychophysics, a study concerned with the relationship between objective measures and the subjective experience of sensory stimuli. Fechner's insight was that this relationship was systematic and could be mathematically described. He thought that this relationship was logarithmic, such that $\psi = \log \phi + k$, in which ψ represents the psychological value and ϕ the physical value of the stimuli being sensed. This specific formulation, known as Fechner's Law, was accepted for nearly a century, until Stevens and colleagues proposed that a power function, $\psi = K\phi^\beta$, better described the psychophysical relationship (Stevens, 1970). Power function relationships were discovered for subjective estimations in a variety of perceptual continua, including judgments of brightness, loudness, taste, smell, pressure, tactile roughness, visual length, and area (Stevens & Galanter, 1957). Additionally, for a particular kind of perceptual estimation, the same exponent was observed across normal subjects. For example, judgment of loudness is described by a power function with an exponent of .67 (Stevens, 1956). The systematic and internally consistent nature of these relationships, both within modality (common exponent) and across modalities (power function relationships), was frequently interpreted as a consequence of biologic properties of neurons dedicated to sensory processing (Stevens, 1970, 1972). Despite a few exceptions to this emphasis on the role of the peripheral nervous system, as exemplified by MacKay's (1963) theoretical model postulating a central nervous system comparator involved in nonlinear transformations of information, only recently (Marshall & Halligan, 1990) has the effect of central nervous system damage on psychophysical judgments been considered. However, our current knowledge of how the central nervous system participates in the formulation of psychophysical relationships is limited.

Individuals with the syndrome of unilateral spatial neglect fail to orient toward, respond to, or act upon stimuli in space contralateral to their lesion (Heilman, Watson, & Valenstein, 1985). On drawing tasks they may draw parts of figures, when asked to make marks through targets scattered on sheets of paper they preferentially cancel ipsilesional targets, and when asked to bisect horizontal lines they transect lines in the ipsilesional side of the objective midline. We have recently observed that on cancellation tasks, the number of targets patients with unilateral neglect cancel may be related to the number of stimuli present by a power function (Chatterjee, Mennemeier, & Heilman, 1992). This observation raised the possibility that there might be cognitive operations common to cancellation tasks and psychophysical judgments. Yet, despite the formal similarity of both relationships and the fact that a subject must be "aware"

of a stimulus to consciously estimate its magnitude, for several reasons the relationship between cancellation tasks and psychophysical judgments is obscure. It is unclear how serially acting upon individual targets, as is done in canceling targets, is cognitively similar to subjective estimations of fixed sensory stimuli. The respective tasks use different kinds of stimuli and require different responses from subjects making direct comparisons difficult. Although it is self-evident that the performance by neglect patients is abnormal on cancellation tasks, direct comparison of a power function established for a patient with neglect to performance by normal subjects is impossible. Normal subjects would perform at a ceiling level by canceling all the targets, precluding description by a power function. Because of the inherent difficulties equating tasks and the inability to make appropriate comparisons to normal performance, cancellation tasks do not easily allow assessment of the role of central nervous system structures in psychophysical relationships.

In contrast to cancellation tasks, line bisections may be a more appropriate task to examine whether behavior in unilateral neglect may be interpreted in psychophysical terms. Line bisection tasks are commonly used to assess neglect patients, and the method of sensory bisection has been used as a scaling method to derive power functions in traditional psychophysical experiments (Stevens, 1958). Previous investigations report that the exponent in the power function of estimations of line length is very close to 1 (Stevens & Guirao, 1963). Performance by neglect patients could then be directly compared to normal performance.

In this respect, we address the following questions. (1) Can line bisection performance in a patient with left-sided neglect be described by a power function, and if so, with what level of precision? (2) How well does the power function obtained from line bisections by normal subjects compare to the expected exponent of 1 as derived by psychophysical experiments of line length estimations? (3) Does central nervous system damage impair psychophysical judgments? (4) By providing two empirical quantitative parameters (the constant and the exponent), does analyzing line bisection data as a power function offer a useful method of measurement with which to probe issues of theoretic interest? In an attempt to use the power function in such a way, we looked at effects of attentional cueing and hemispatial placement on line bisection, since there are conflicting published reports about the respective effects of these conditions. These data will be interpreted in the context of current discussions of different frames of reference through which attention may be mediated.

Heilman and Valenstein (1979) reported that patients with neglect made larger errors in bisecting lines when lines were placed in left hemi-space than when placed in right. However, attentional cueing to the left or right side of lines by having them read a letter placed at either end prior to bisecting, did not affect performance. Subsequently, Riddoch and Hum-

phreys (1983) reported opposite results. They did not find differences in bisections based on spatial placement, but did find effects of attentional cueing. The conflicting results of these two reports have not been adequately reconciled, although Halligan and Marshall (1989) have suggested that cueing might be maximally effective in patients with visual field defects, since only 2/6 of Heilman and Valenstein's patients had field defects as compared to 5/5 of Riddoch and Humphrey's patients. An alternative explanation might be buried in the fact that in both studies errors were collapsed across different line lengths to obtain average errors. Since the publication of those reports, it has been appreciated that errors may vary systematically with line length (Bisiach, Bulgarelli, Sterzi, & Vallar, 1983; Butter, Mark, & Heilman, 1988; Halligan & Marshall, 1988). Collapsing errors across varying line lengths might obscure important differences. The power function incorporates changes in error magnitudes across different line lengths and might provide additional fidelity with which to reexamine the effects of spatial placement and attentional cueing on line bisections.

SUBJECTS

Patient

The patient was a 66-year-old right-handed man with a history of hypertension. On the morning of his stroke, he acutely became weak on the left side. His wife noticed his apparent unconcern regarding his condition. She remarked that he did not comb his hair on the left side, or eat food placed to his left during the first week after his stroke. After a month he was transferred to the Gainesville Veterans Administration Rehabilitation Service and was tested on 3 consecutive days. At that time he had mild distal weakness in his left hand and arm and did not have a persistent eye or head deviation, or a visual field defect to bedside confrontational testing. He demonstrated visual and tactile extinction. He omitted left-sided items when copying drawings. Computer tomography scan revealed a stroke in the distribution of his right middle cerebral artery (Fig. 1). Using the lesion localization technique described by Damasio and Damasio (Damasio & Damasio, 1989), his lesion involved the superior temporal gyrus, portions of premotor (area 6) and rolandic cortex, substantial portions of supramarginal gyrus, and anterior portions of the angular gyrus.

Control Subjects

Five control subjects were tested, average age 65.4, range 61 to 72. Two were volunteers, and three were non-brain-impaired inpatients. None of the control subjects had histories of having had a stroke, psychi-

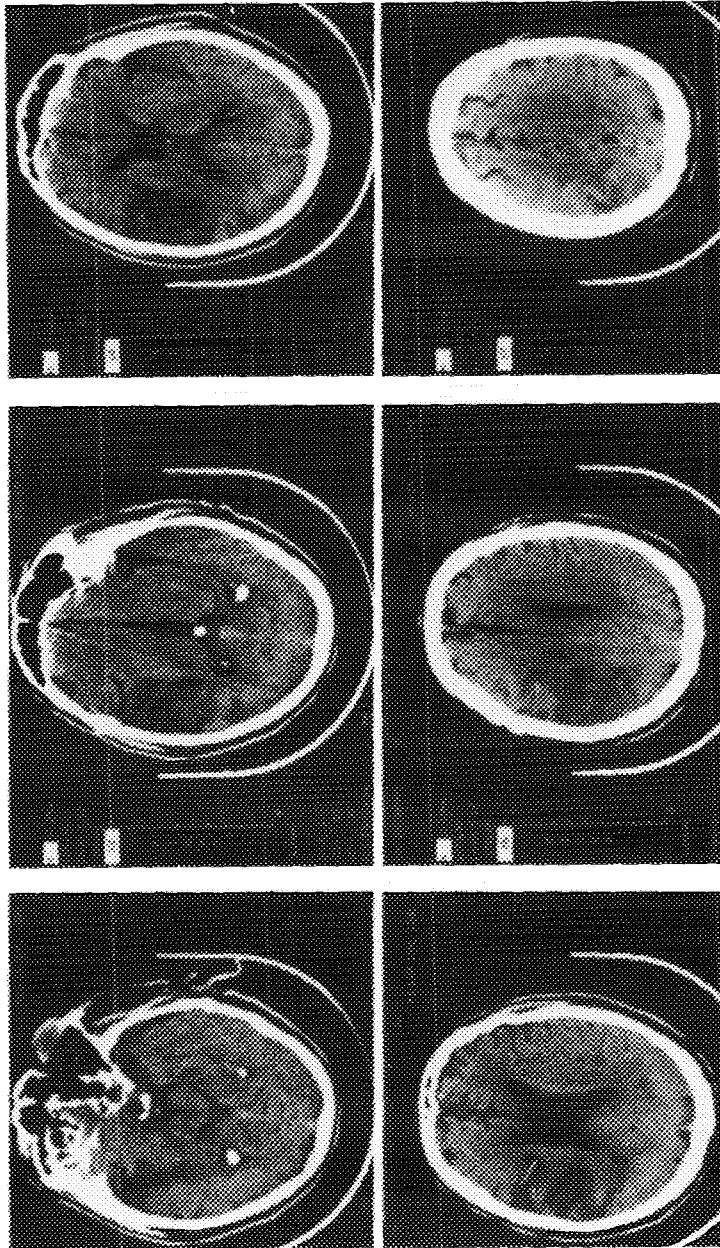


FIG. 1. CT scan demonstrating right hemisphere infarct.

atric illness, or were on psychoactive medications. They all had normal neurological examinations and did not demonstrate any evidence of neglect on drawing, copying, or cancellation tasks. Each normal subject was tested on a single day.

METHODS

Materials

Subjects bisected lines, with their right hand, that were 2, 4, 8, 16, 23, or 32 cm long and 1 mm wide. These lines were placed in the center of a sheet 21.59 cm (8.5 inches) \times 35.56 cm (14.0 inches). Lines were placed on a table in front of the subjects such that they were horizontally oriented and centered on the subjects' midsagittal plane. Approximate distance from the subjects' eyes to the surface of the table was 40 cm. Each trial consisted of random presentations of each of the differing line lengths, resulting in 6 bisections per trial. Each subject performed 10 trials, or 10 bisections per line length for a total of 60 bisections per experimental condition.

Analysis

The length of presented lines were considered the independent measure. Twice the distance from the right end of the line to the point of transection was considered the dependent measure. Both measures were logarithmically transformed to allow regression analysis from which a power function is easily derived. The regression line obtained (iv) is mathematically equivalent to a power function (i) as shown below:

- (i) $\psi = K\phi^\beta$
- (ii) $\log \psi = \log (K\phi^\beta)$
- (iii) $\log \psi = \log \phi^\beta + \log K$
- (iv) $\log \psi = \beta \log \phi + k$, which is in the form of
- (v) $y = mx + b$, the equation for a straight line.

As can be seen in these mathematically equivalent equations, the slope of the regression line obtained (iv) is identical to the exponent in the power function (i), and the constant of the power function is easily derived from the y axis intercept.

Experiment 1A: Determination of the Basic Power Function for Line Bisection in the Canonical Midsagittal Position

Lines were placed centered on the midsagittal plane with respect to subjects trunk and administered as described in the materials section.

Results. Raw data for bisection performances and power functions obtained are shown in Tables 1A and 1B, respectively. As would be expected, the patient tended to transect to the right of midline. Four of five normal controls transected to the left and one to the right of midline. Regression equations obtained for the patient (from which power functions were derived) and normal subjects accounted for greater than 99% of the variance in performance. The mean exponent for normal performance was .992 ($\pm .016$). The patient had an exponent of .962.

Discussion. Most of our normal subjects transected to the left of midline, although one transected to the right. These findings are consistent with the literature on line bisections by normals that suggests that although leftward errors are more common, there is inter-individual variability in the direction of errors (Manning, Halligan, & Marshall, 1990). The

TABLE 1A
Effects of Spatial Placement on Line Bisection

	Line length (cm)					
	2	4	8	16	23	32
Midsagittal						
Patient	1.0 (.1)	1.8 (.1)	3.5 (.3)	7.3 (.6)	10.5 (.9)	14.4 (1.2)
Control 1	1.0 (.1)	2.0 (.1)	4.1 (.2)	8.1 (.3)	11.7 (.4)	16.2 (.3)
Control 2	1.0 (0)	2.0 (.1)	4.0 (.1)	8.1 (.1)	11.7 (.5)	16.2 (.3)
Control 3	1.0 (0)	2.1 (0)	4.0 (.1)	7.4 (.4)	11.1 (.4)	15.8 (.3)
Control 4	1.1 (0)	2.1 (0)	4.0 (.1)	8.3 (.1)	11.8 (.4)	16.4 (.2)
Control 5	1.1 (0)	2.0 (.1)	4.2 (.2)	8.3 (.3)	11.5 (.5)	16.1 (.6)
Left space						
Patient	.9 (.1)	1.7 (.1)	3.4 (.2)	6.4 (.5)	9.9 (.6)	13.6 (.6)
Control 1	1.0 (.1)	2.1 (.1)	4.1 (.1)	8.0 (.3)	11.7 (.4)	16.1 (.4)
Control 2	1.0 (0)	2.0 (0)	4.0 (.2)	8.1 (.1)	11.6 (.3)	16.4 (.3)
Control 3	1.1 (0)	2.1 (.1)	3.9 (.2)	7.4 (.3)	10.8 (.4)	15.5 (.4)
Control 4	1.1 (.1)	2.1 (.1)	3.9 (.1)	7.7 (.3)	11.6 (.4)	15.7 (.3)
Control 5	1.1 (0)	2.0 (.1)	4.2 (.2)	8.3 (.2)	11.5 (.3)	16.1 (.5)
Right space						
Patient	1.0 (0)	2.0 (.1)	3.6 (.3)	7.5 (.6)	11.0 (.4)	13.9 (1.3)
Control 1	.9 (0)	1.9 (0)	4.1 (.2)	8.2 (.3)	11.7 (.4)	16.8 (.2)
Control 2	1.0 (0)	2.0 (.1)	4.1 (.1)	8.3 (.3)	11.9 (.4)	16.7 (.5)
Control 3	1.0 (.1)	1.9 (.1)	3.8 (.1)	7.5 (.3)	10.6 (.3)	15.3 (.4)
Control 4	1.1 (.1)	1.9 (.1)	3.9 (.1)	7.6 (.3)	11.4 (.6)	15.9 (.5)
Control 5	1.1 (0)	2.1 (.1)	4.2 (.2)	8.4 (.3)	11.9 (.5)	16.6 (.7)

Note. Measurements represent the length of the segment from the right end of the line to the point of transection. Standard deviations are in parentheses.

TABLE 1B
Effects of Spatial Placement on Power Functions Derived from Line Bisection Data

	Left space	Midsagittal	Right space	F ratio _(4,174)
Patient	.921(L) ^{0.968}	1.002(L) ^{0.962}	1.026(L) ^{0.961}	10.93 (<i>p</i> < .001)
Control 1	1.020(L) ^{0.997}	0.956(L) ^{1.021}	.876(L) ^{1.055}	18.62 (<i>p</i> < .001)
Control 2	1.014(L) ^{1.000}	1.023(L) ^{0.997}	.976(L) ^{1.019}	3.26 (NS)
Control 3	1.080(L) ^{0.956}	1.039(L) ^{0.977}	.958(L) ^{0.994}	13.65 (<i>p</i> < .001)
Control 4	1.054(L) ^{0.977}	1.057(L) ^{0.989}	1.017(L) ^{0.986}	9.86 (<i>p</i> < .001)
Control 5	1.068(L) ^{0.983}	1.085(L) ^{0.975}	1.054(L) ^{0.995}	2.67 (NS)

Note. L, line length. *p* values obtained from testing for differences between regression lines with a Bonferroni adjustment for multiple comparisons.

power function was remarkably precise in accounting for greater than 99% of the variance. Our patient demonstrated a diminished exponent, whereas averaging across the normal subjects, an exponent very close to the expected exponent of 1 was obtained. Line bisection was comparable to other methodologies used to obtain power functions for estimation of line length by normal subjects.

Experiment 1B: Determination of the Effects of Hemi-spatial Placement on Line Bisections

Lines were placed either 20 cm to the left or 20 cm to the right of the midsagittal plane, and trials were presented in counterbalanced blocks (right or left) in an ABBABAAB... manner, for a total of 20 blocks, or 10 blocks per condition.

Results. Raw data for bisection performance and the power functions obtained are shown in Tables 1A and 1B, respectively. Regression equations obtained for the patient (from which power functions were derived) and normal subjects accounted for greater than 99% of the variance in performance. The patient showed a pattern of performance that was qualitatively different from that of normals (Figs. 2a and 2b). The exponent in the patient's performance remained relatively unchanged across the different spatial locations, but the constant was lower in left space than in right. All five subjects had higher exponents in right space than in left and lower constants in right space than in left ($p = .03$). When viewed as multiple single case studies, 3/5 subjects were significantly influenced by spatial location of stimuli.

Discussion. Again the power function was highly precise in describing data. A qualitative difference was found in how the patient's performance changed with respect to varying spatial location when compared to normal performance.

Experiment 2: Determination of the Effects of Attentional Cueing on Line Bisection

Lines were placed in a midsagittal position. Each line had a letter placed either at the left or right end of the line. Subjects were required to read the letter out loud before bisecting the line. Presentation of trials for both conditions, left cue or right cue, were blocked in an ABBABAAB manner.

Results. Raw data for bisection performance and the power functions obtained are shown in Tables 2A and 2B, respectively. Regression equations obtained for the patient (from which power functions were derived) and normal subjects accounted for greater than 99% of the variance in performance in all conditions. When cued to the right the patient's exponent decreased and constant increased whereas when cued to the left, the patient's exponent increased and constant decreased (Figs. 3a and 3b). The same pattern was observed in the normal performance. When viewed as a group, all five normal subjects had lower exponents when cued to the right than when cued to the left ($p = .03$), and when analyzed as multiple single cases 3/5 normal subjects were significantly influenced by attentional cues.

Discussion. Again the power function was highly precise in describing data. As can be seen in Fig. 3, the pattern demonstrated by the patient with neglect was similar to that demonstrated by normal subjects, except that the response to attentional cues was exaggerated.

GENERAL DISCUSSION

The patient described here demonstrated typical signs of unilateral neglect. He had extinction to simultaneous visual and tactile stimulation,

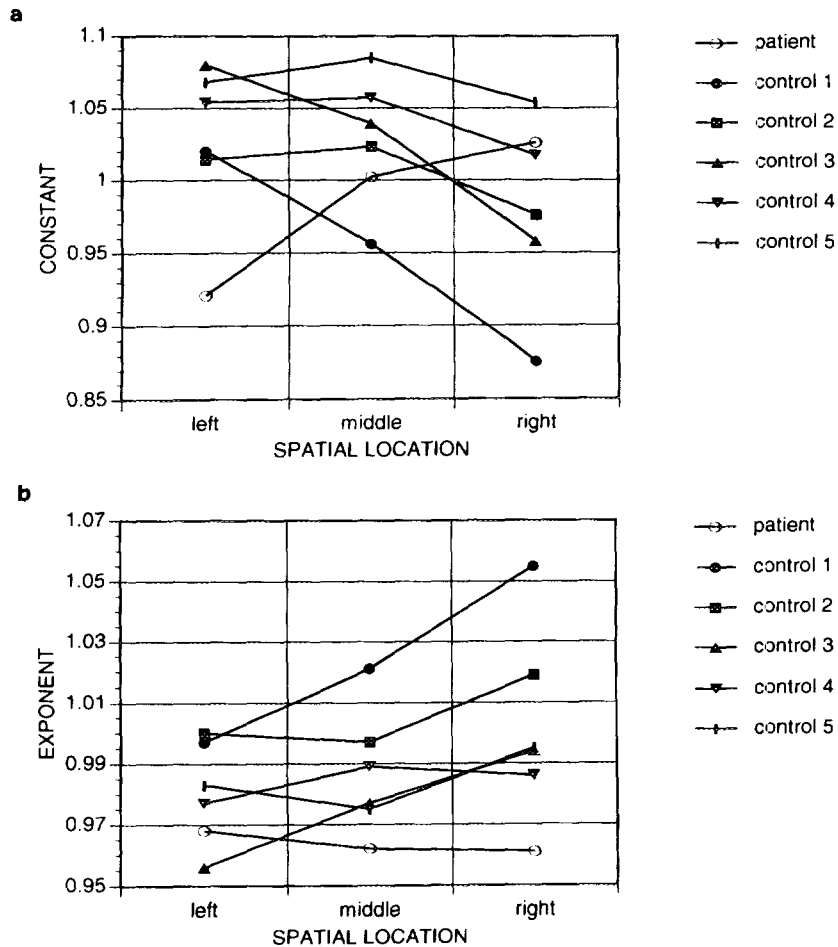


FIG. 2. (a) The effect of varying spatial location on the constant of the power function. (b) The effect of varying spatial location on the exponent of the power function.

omitted left-sided items when copying drawings, and bisected lines to the right of midline. His CT scan demonstrated a right hemisphere stroke involving peri-sylvian regions, notably much of the supramarginal gyrus and portions of the angular gyrus. There are no atypical features in the clinical presentation of this patient that obviously sets him apart from the common presentation of unilateral spatial neglect.

The first goal of this study was to determine if line bisection data from a patient with left-sided neglect and normal subjects could be described by a power function, and if so with what degree of precision. The power function accounted for greater than 99% of the variance in performance of the patient and five age-matched controls in five different experimental

TABLE 2A
Effects of Attentional Cueing on Line Bisection

	Line length (cm)					
	2	4	8	16	23	32
Left cue						
Patient	.9 (.1)	1.9 (0)	3.9 (.2)	7.9 (.5)	10.9 (.6)	15.0 (.6)
Control 1	1.0 (0)	2.0 (.1)	4.1 (.1)	8.1 (.3)	12.0 (.6)	16.5 (.3)
Control 2	.9 (0)	1.9 (0)	3.9 (.2)	7.9 (.2)	11.9 (.4)	16.4 (.5)
Control 3	1.0 (0)	2.0 (.1)	3.9 (0)	7.2 (.3)	10.8 (.4)	15.2 (.5)
Control 4	1.0 (0)	1.9 (.1)	3.8 (.1)	7.5 (.3)	11.6 (.2)	15.9 (.3)
Control 5	1.1 (.1)	2.0 (.1)	4.1 (.2)	8.4 (.3)	12.7 (.5)	16.8 (.6)
Right cue						
Patient	1.0 (.1)	1.9 (.1)	3.6 (.2)	6.5 (.3)	9.7 (.3)	13.3 (.7)
Control 1	1.0 (.1)	1.9 (.1)	3.9 (.2)	7.8 (.2)	11.5 (.4)	16.2 (.4)
Control 2	1.1 (0)	2.0 (.1)	3.9 (.1)	8.1 (.2)	11.5 (.3)	15.2 (.2)
Control 3	1.1 (0)	2.1 (.1)	3.9 (.1)	7.4 (.3)	10.6 (.5)	14.8 (.5)
Control 4	1.0 (0)	2.0 (.1)	3.8 (.2)	7.9 (.1)	11.4 (.2)	15.1 (.3)
Control 5	1.1 (.1)	2.0 (.1)	3.9 (.2)	7.7 (.2)	11.6 (.4)	15.4 (.2)

Note. Measurements represent the length of the segment from the right end of the line to the point of transection. Standard deviations are in parentheses.

conditions, demonstrating remarkable precision in capturing how these subjects performed. Additionally, we wished to learn if bisections, as a method of determining the power function in normal subjects matched power functions established for estimations of line length derived from traditional psychophysical experiments. In the midsagittal non-cued condition, the five subjects had an average exponent of 0.992 ($\pm .016$) and across all experimental conditions had an average exponent of .995 ($\pm .023$), closely approximating the expected exponent of 1.00. Thus, line bisections provide a comparable measure of the psychophysical power law describing estimations of linear extent. The diminished exponent ob-

TABLE 2B
Effects of Attentional Cueing on Power Functions Derived from Line Bisection Data

	Left cue	Right cue	F ratio _(2,116)
Patient	.937(L) ^{1.006}	1.058(L) ^{0.921}	53.25 ($p < .001$)
Control 1	.963(L) ^{1.021}	.961(L) ^{1.011}	5.88 ($p < .03$)
Control 2	.904(L) ^{1.037}	1.011(L) ^{0.972}	46.75 ($p < .001$)
Control 3	1.048(L) ^{0.963}	1.073(L) ^{0.952}	1.01 (NS)
Control 4	.973(L) ^{1.001}	.991(L) ^{0.992}	.79 (NS)
Control 5	1.022(L) ^{1.012}	1.033(L) ^{0.980}	26.63 ($p < .001$)

Note. L, line length. p values obtained from testing for differences between regression lines, with a Bonferroni adjustment for multiple comparisons.

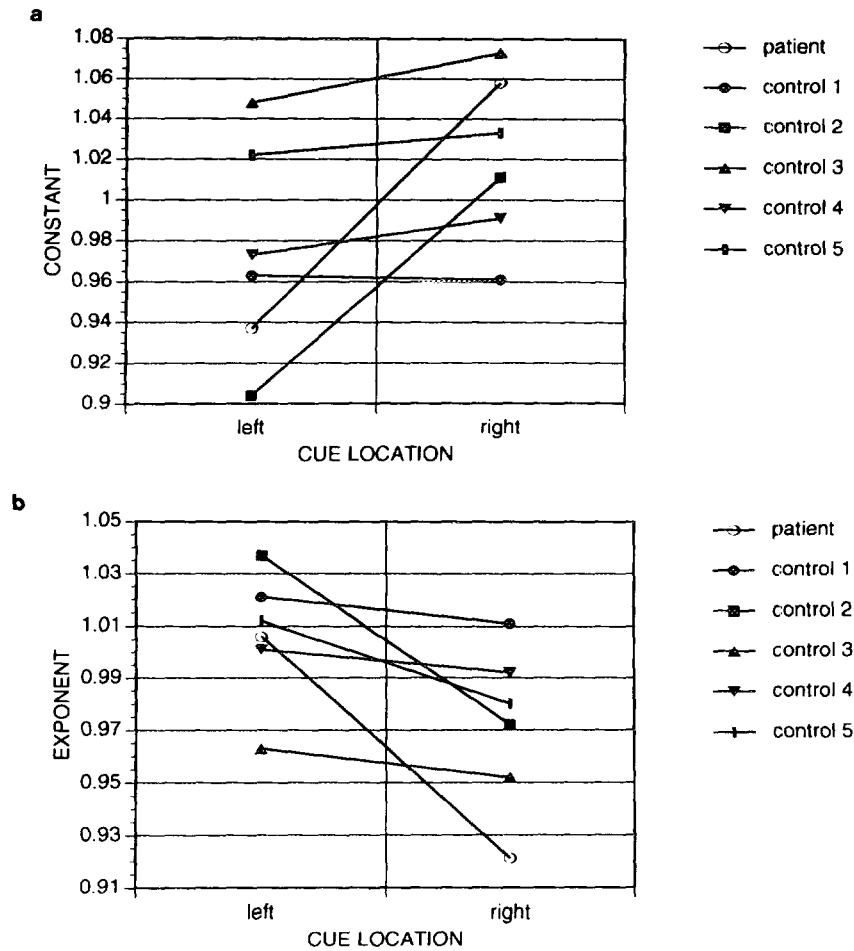


FIG. 3. (a) The effect of attentional cues on the constant of the power function. (b) The effect of attentional cues on the exponent of the power function.

served in the patient's performance was presumably induced by his central nervous system lesion. Therefore, it is at the very least an oversimplification and perhaps incorrect to think that the exponent in the power function for psychophysical judgments of linear extension corresponds to sensory transductions at peripheral receptors. If only linear transformations occur centrally, then one would expect a central lesion to result in an unchanged exponent and perhaps a reduced constant. Damage to the right hemisphere, in this patient, diminished the exponent. The right hemisphere (perhaps the parietal lobe) must either be directly involved in non-linear stimulus transformations or have non-linear modulating in-

fluences on ascending sensory inputs in the process of estimating line lengths.

We are not the first to suggest that psychophysical principles may apply to behavior in unilateral neglect. Marshall and Halligan (1990) have reported systematic relationships between error magnitudes and line lengths in performance by patients with neglect. They interpret their findings by using the concept of a Weber fraction. In the judgment of the mid-position of a line, it is hypothesized that there is a segment with which a subject is unable to perceive a difference between the lengths of the line segments on either side. This segment, the Weber fraction, increases with longer line lengths. They propose that patients with neglect have abnormally large Weber fractions. These patients scan lines from right to left, and when they approach the right boundary of the Weber fraction, or the 'zone of indifference' they bisect the line. Since they still adhere to the psychophysical principle of a Weber fraction, despite having an abnormally large one, their errors are systematically related to line length (Manning et al., 1990).

Given the reports of Marshall and Halligan, one could question if there is a point to interpreting line bisection data as an abnormal power function rather than an abnormal Weber fraction. Both interpretations have considerable similarities. Both establish links to psychophysical principles and suggest that there are similarities between neglect and normal performance. In their conception, the abnormality demonstrated by patients with neglect is a larger Weber fraction, and in ours a decreased exponent. Marshall and Halligan's linear regression of bisection errors on line length have negative constants which indicate transections to the left of midline for short lines, whereas constants greater than 1 obtained in the power function indicate the point at which transections to the left occur. Both interpretations remain formal descriptions of data and thereby establish constraints on behavior, but do not constitute explanations of behavior. Each respective interpretation does not explain why the Weber fraction is enlarged or the exponent diminished in patients with neglect. Both methods have high degrees of descriptive precision, often accounting for greater than 99% of the variance in performance. However, there may be heuristic advantages to interpreting data in terms of a power function rather than the Weber fraction. The two quantitative empiric parameters of the power function, the exponent and constant, may be observed for systematic changes under a variety of experimental conditions. Such changes might potentially shed light on issues of theoretic interest. As an example of the heuristic use of the power function, we examined how varying attentional cues and spatial placement of stimuli affects line bisection performance.

Varying attentional cues and spatial location of stimuli did not influence transections by the patient in similar ways, particularly when compared

to normal performance. When the patient was cued to the right the exponent of the power function decreased and the constant increased relative to when being cued to the left. Normal subjects performed with a similar pattern (Fig. 3). Attentional cues appeared to have had an exaggerated influence on how this patient bisected lines. In contrast, two observations demonstrated that varying spatial placement influenced his performance in a way qualitatively different than normal. First, in the patient, the constant was lowest in left space, whereas in the normal subjects the constant was consistently lowest in right hemisphere (Fig. 3a). Second, the relationship between the exponent and constant within the observed power functions across different conditions appeared to be different for the patient than it was for normal subjects. Normal subjects seemed to demonstrate an inverse relationship between the constant and exponent (Fig. 4). When the exponent decreased, the constant increased. The patient also demonstrated this inverse relationship between constant and exponent when his performance was influenced by attentional cues (Fig. 4b). However, this relationship was no longer evident in the condition of varying spatial location (Fig. 4a). Thus, describing data as a power function helped uncover both quantitative and qualitative differences from normal performance.

Our data raises some issues of theoretic interest. The first is the relationship between attention and perception. In examining how normal subjects bisect lines, Milner and co-workers (1992) have suggested that the perception of lines is inextricably linked to how attention is directed to them. Our data independently support this claim. The normal subjects when analyzed as a group, and 3/5 when analyzed as multiple single case studies, were influenced by explicit attentional cueing to the right or left end of the line. Since the power function is a measure of perception of linear extent, these data support the notion of perceptual processes being yoked to attentional ones. These findings also confirm an underlying assumption in neglect research, that a directional attentional disturbance may result in mis-bisection of lines.

A second issue of theoretic interest raised by these data is how attention is allocated in space. Spatial frames of reference have been discussed in terms of object-centered, viewer-centered and environment-centered coordinate systems (Marr, 1982; Feldman, 1985; Farah, Brun, Wong, Wallace, & Carpenter, 1990). Object-centered or allocentric coordinates refer to intrinsic spatial properties of an object itself. Viewer-centered or egocentric reference frames refer to the spatial location of an object relative to the viewer. This reference frame may be retinocentric, head-centered, or body-centered. Environment-centered reference frame refers to an object's location in the environment. By varying spatial location of the lines, changes are made in both the viewer centered (to the subjects' left or right) and the environmental (location in room) reference

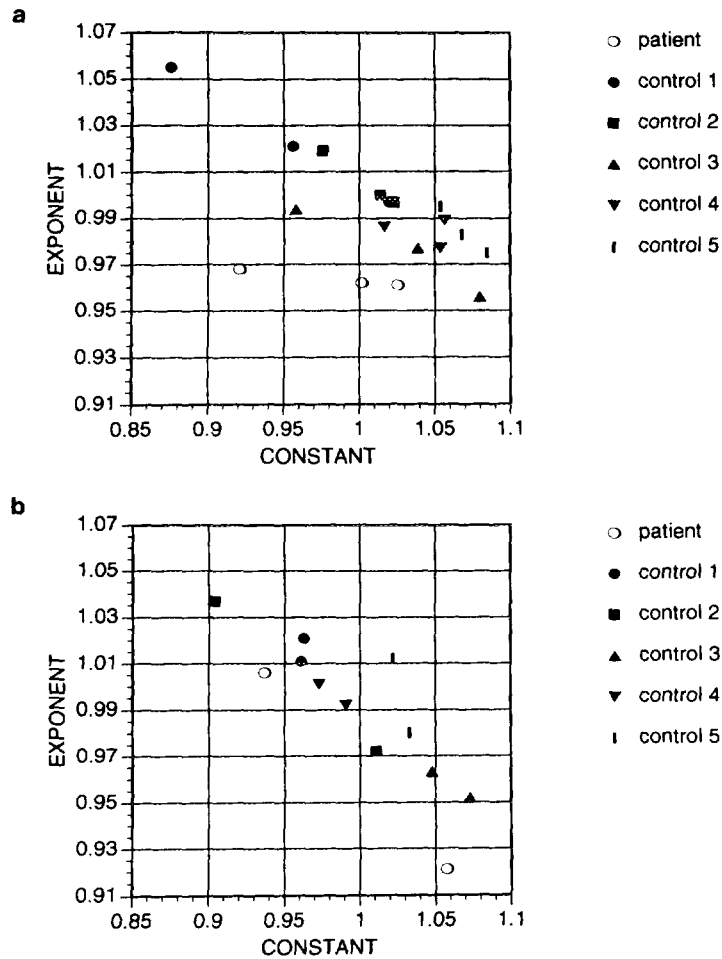


FIG. 4. (a) The relationship between the exponent and constant when varying spatial location. (b) The relationship between the exponent and constant when varying attentional cue.

frames. The object being attended in these experiments, horizontal lines are not changed, meaning that allocentric reference frames are held constant. In contrast, under conditions of attentional cueing, the location of the lines themselves do not vary with respect to viewer (mid-sagittal) and environment (same location in room). However, explicit attentional cueing either to the right or left end of the line manipulates how attention is directed on the line itself, or within an allocentric reference frame. Performance by normal subjects in this study provides evidence for the relative modularity of these reference frames. When viewed as single

cases, performance of 2/5 normal subjects were influenced when attention was directed across space in viewer/environmental coordinates and not when directed to the left or right of the line in allocentric coordinates, and 2/5 were influenced in the opposite way. One subject was susceptible to manipulations of both reference frames. Previous reports in line bisections by normal subjects have underscored individual variability. While most studies report that normal subjects transect lines to the left of midline (Bradshaw, Nathan, Nettleton, Wilson, & Pierson, 1987; Scarisbrick, Tweedy, & Kuslansky, 1987; Milner et al., 1992) some normal subjects transect to the right (Werth & Poppel, 1988; Manning et al., 1990). Consistent with these previous reports, four of our normal subjects bisected to the left of midline, and one bisected to the right. Our interpretation of the data using power functions, admittedly post hoc and somewhat speculative, extends the concept of individual variability in line bisection by suggesting that normal individuals may qualitatively differ in how attention is deployed within different reference frames.

The patient with neglect reported here, when compared to normal subjects had a qualitative defect in the condition of varying the allocation of attention across viewer/environmental reference frames, but not in the condition of directing attention across an allocentric frame. These results are consistent with Farah et al.'s (1990) finding, using completely different experimental paradigms that neglected fields were predominantly viewer and environment centered rather than object centered. We recognize that some patients may demonstrate qualitative defects in directing attention across allocentric reference frames and not viewer or environment centered reference frames.

In summary, our data demonstrate that line bisection may be analyzed in terms of the psychophysical power law with great precision. The neglect syndrome provides evidence that at least in estimations of line length, central nervous system structures participate in non-linear information processing, and "neuro-electric codes" established from response characteristics of peripheral receptors oversimplify cognitive operations corresponding to the psychophysical power law. The formal constraints on behavior made explicit by the power function have heuristic value in addressing theoretic issues. We provide evidence in support of links between attentional and perceptual processes. Our data also suggest that there may be qualitative differences in how normal subjects allocate attention across different spatial reference frames. Finally, the power function provides a method that distinguishes qualitative and quantitative abnormalities in performance by patients with unilateral neglect.

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