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13. ABSTRACT *(Maximum 200 words)*

Psychophysical studies of the processes underlying relative localization in human vision were conducted. Specifically, the focus of this granting period was characterizing the spatial characteristics of the units that encode spatial location. Evidence was found for a higher-order scaled representation of position in which the size of position integration areas scales with the distance being encoded. This scaling of the position integration areas was found to account well for the increase in separation discrimination thresholds with increasing separation. The position integration areas were shown not to integrate luminance, but were shown to depend on an initial spatial organization of the scene. The time course of the position integration was also investigated. Additional studies investigated the relationship between position integration and the Muller-Lyer illusion, and the effect of the spatial frequency of a masking stimulus (presented at termination of the separation discrimination stimulus) on separation discrimination thresholds.

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SPATIOTEMPORAL CHARACTERISTICS OF HUMAN VISUAL LOCALIZATION

Final Report on Grant AFOSR-91-0058
Covering the Period: 01 Oct 1990 to 31 Dec 1991

Date: 28 February 1992

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Research Objectives

The original contract, to SRI, with which this grant originated, stated the following research objectives:

We propose to conduct psychophysical research, together with the necessary and appropriate theoretical development, on the three topics listed below..

(1) Test and explore the theory that spatial-interval discrimination thresholds can be determined at any of several stages of processing, the precise stage depending on the details of the stimulus. Specifically,we will seek those conditions that cannot be accounted for by linear spatial filters.

(2) Explore the source of the exposure duration effect in localization judgments, by investigating its dependence on both the spatial frequency content and retinal eccentricity of the stimulus, and by relating these results to properties of the spatial filters as revealed in analogous contrast-detection experiments.

(3) Investigate the spatial characteristics of the receptive fields underlying the proximal localization mechanism and relate them to those of the linear spatial filters.

During the 14 months covered by this report, our research focused on the last topic, the first two having been substantively investigated during the two prior years' research. Our considerable progress in characterizing the receptive fields underlying localization is detailed below and in the accompanying draft manuscript.

Status of Research Effort

Introduction

Our research during this granting period, October, 1990 through December, 1991, focused strongly on the effect of a third line on the perceived separation of a target pair. This finding led to a major study in which the position integration areas were defined and demonstrated and the relationship established between the size of these areas and the increase in separation discrimination thresholds with increasing separation. The results of this central study are given in the attached draft manuscript.

Other studies were also begun which focused on specific aspects of this major result. These are reported briefly below. They are all in progress.

Spatial Organization and Position Integration

We have found that the effect of the flanking line on perceived target separation is dependent on the spatial characteristics of the targets and flanking line as well as on their proximity to one another. Thus, in addition to indicating the spatial extent of the area over which position information is integrated, this flanking line effect may also tell us what portions of the visual scene are being treated as a unit by the visual system in its initial attempts to organize the scene.

The spatial organization implied by the flanking line effect is not the obvious one. For example, making the flanking line of opposite contrast polarity to the target lines (in a black, white, white arrangement) leaves the effect unchanged or slightly diminished - depending on the observer – even though free-viewing of the stimulus suggests that the targets would segregate from the flanking line much more strongly in this case.

Interestingly, making the upper target of opposite contrast polarity to the other two bars (in a white, black, white arrangement), causes the effect of the flanking line to be eliminated altogether. Making the bottom line black (a white, white, black arrangement) results in a small but significant effect of the flanking line. Reducing the saliency of the flanking line when it is black (with white targets) by adding another black flanking line above it (black, black, white, white) does not change the effect. These results are only exploratory, but they demonstrate the dependence of the flanking line effect on the perceptual organization of the stimulus. We are continuing to explore these effects.

Time Course of Flanking Line Effect

An undergraduate student working in our laboratory, Irene Snyder, took on the task of examining the temporal interactions that occur when a pair of target bars is embedded in an array of four background bars that are identical to the targets. Her results on this were inconsistent across observers. (We suspect that, when the exposure duration is brief, the task of determining the perceived separation between a pair of embedded targets may sometimes be done by judging the overall density of the display instead.) So Irene adopted another approach. She focused on the time course of the effect of the single flanking line on perceived separation. The results of this study were nicely robust and intriguing. She has written them up as her honors thesis and will be presenting them at the 1992 ARVO meeting.

Irene used a 0.75° mean target separation and presented the flanking line at half of that separation, a value at which a large effect of the flanking line had been obtained in the original studies. She manipulated the stimulus-onset-asynchrony (SOA) between the flanking line and the target lines. The target lines were always on for 100 ms and the flanking line was on until the targets were turned off. Thus, the exposure duration of the flanking line was varied. Irene used SOA's of -500 to +100 ms. At an SOA of -500 ms, the flanking lines preceded the target lines by 500 ms. At +100 ms SOA, the flanking lines never appeared (because they terminated simultaneously with the target lines). Her results are shown in Fig. 1. The flanking line increased the perceived separation between the targets by a roughly constant amount when the onset of the flanking line was within about 100 ms of the onset of the targets. At longer SOA's the effect of the flanking line was diminished. So, given enough time, observers were able to disregard the flanking line, at least to some extent (one observer had a residual effect). However, when the flanking line onset was near the target-line onset, its effect was as large as if the targets and flanking line were simultaneous.

This research is currently being continued, using a fixed duration for the flanking line to assess the role of its perceived contrast in determining the magnitude of the effect at negative SOA's. At positive SOA's, perceived contrast cannot be responsible for the effect because the effect of the flanking line increases as its duration decreases, opposite of what would be expected on the basis of its perceived contrast. Our other studies have shown that a perceived difference in contrast between the target and flanking line does not, by itself, appreciably attenuate the effect of the flanking line. However, if the perceived contrast of the flanking line is very low, its effect must be diminished.

Variation of Position Integration Areas with Eccentricity

Having established that the position integration areas increase in size with increasing separation to be encoded, we sought to determine whether this increase was tied to the separation per se or to the retinal eccentricity of the targets. Our previous research had shown that retinal eccentricity played a role in, but was not alone sufficient to account for, the increase in separation discrimination thresholds with separation.

To ascertain the role of eccentricity in the increase in position integration areas, we repeated the flanking line experiment with peripheral presentation. The horizontal lines were presented, roughly centered on the horizontal meridian, at 1.5 degrees eccentricity. The mean target separation was 0.75°. Our goal was to determine whether the maximum effect of the flanking line occurred at about .4°, a distance consistent with the separation, or at about 1.2°, consistent with the eccentricity. Instead of either possibility we found that two of three observers tested showed a reversal of the direction of the effect. Instead of being perceptually expanded, the target separation was perceptually decreased by the presence of the flanking line. This clearly is an area in need of further investigation, and we are pursuing it.

Flanking Line Between the Target Lines

Exploring further the nature of the position integration areas, we presented the "flanking" or background line between the targets. Data were obtained from two observers. Their data are shown in Fig. 2. The background line was also presented outside the target lines, as in the previous experiment, to replicate the basic effect with these observers. When the background line lay between the target lines, its effect was not consistent across observers. For both observers, the perceived separation was diminished slightly when the background line was inside the target pair and very near the top target. When the background line was farther from the top target, it caused a perceptual expansion of separation and a perceptual diminution for the other.

We speculate that there are two conflicting forces controlling these data, position integration causes the target separation to be perceptually reduced by the presence of the background line, whereas the addition of objects between the targets causes their separation to be perceptually expanded. This latter effect is hypothesized on the basis of previous reports that filling in the region between two objects with other objects increases the target perceived separation. Although this latter effect appears to be well-known, we have not been able to find data on the subject and are attempting to demonstrate it ourselves using different stimuli. That work is in progress.

Muller-Lyer Illusion

The expansive flanking line results we obtained were reminiscent of the Muller-Lyer illusion. As an independent project, Scott Hadden – who working as a full-time research assistant with us until April 1991– explored this possible parallel. The display apparatus we had available at the time could not create Muller-Lyer arrows, so Scott made hundreds of cards for use in a tachistoscope the Psychology Department had available. He measured the magnitude of the effect with 100 and 500 ms exposure durations to see if it decreases over time as the flanking line effect does. It does not. We conclude that position integration is not a primary component of the Muller-Lyer illusion. The incorporation of the temporal dimension in this study enabled us to determine whether the two phenomena had a common origin without extensive modeling or parametric investigation.

Masking

Accurate manipulation of the temporal domain requires that we mask the stimulus at its termination. However, creation of an effective mask is not always a trivial task. We have done extensive studies on the effects of various masks on performance, checking to ensure that we have not influenced the conclusions drawn by our choice of masks, and generally trying to understand the site of masking in separation discrimination tasks. We have found that separation discrimination thresholds for a pair of bar targets are elevated most when the mask is a set of bars similar to the targets. Masking by spatial frequency gratings is also effective, with the peak masking effect occurring at a low spatial frequency (0.75 cycles/degree) and varying slightlair of bar targets are elevated most when the mask is a set of bars similar to the targets. Masking by spatial frequency gratings is also effective, with the peak masking effect occurring at a low spatial frequency (0.75 cycles/degree) and varying slightly but significantly with the separation and width of the targets. We believe that masking is occurring at several sites in these experiments.

Professional Personnel

Christina A. Burbeck, Ph. D., Principal Investigator

Yue-Lin Li, Graduate Student in Psychology

Scott Hadden, Laboratory Assistant (Worked on this project for one year between undergraduate studies and entering Medical School.)

Bryan Morse, Graduate Student in Computer Science

Other Collaborators

Jonathan Marshall, Ph.D., Assistant Professor of Computer Science

Stephen Pizer, Ph.D., Professor of Computer Science

Jannick Rolland, Ph.D., Research Associate in Computer Science

Dan Ariely, Graduate Student in Psychology

Irene Snyder, Undergraduate Student in Psychology

Papers Submitted, Manuscripts In Preparation, and Manuscripts Planned

Burbeck, Christina A., "Separation Discrimination in Context", submitted to Vision Research.

Burbeck, Christina A., "Position Integration Area: A Higher-Order Scaled Spatial Representation" to be submitted to Journal of the Optical Society of America A. (Manuscript in prepation, draft included in this report.)

Hadden, Scott and Burbeck, Christina A., "No Position Integration in the Muller-Lyer Illusion", to be submitted to Vision Research. (Manuscript planned.)

Burbeck, Christina A. and Snyder, K. Irene, "Spatio-temporal Integration of Position Information", to be submitted to Vision Research. (Manuscript planned.)

Presentations

Burbeck, Christina A., "Temporal Development of Perceived Spatial Relationships," Association for Research in Vision and Ophthalmology Annual Meeting, Sarasota, Florida, May, 1991.

Burbeck, Christina A., "Scale and Context in the Encoding of Visual Size or Separation", invited presentation, Buys Ballot Laboratory, State University Utrecht, the Netherlands, September, 1991.

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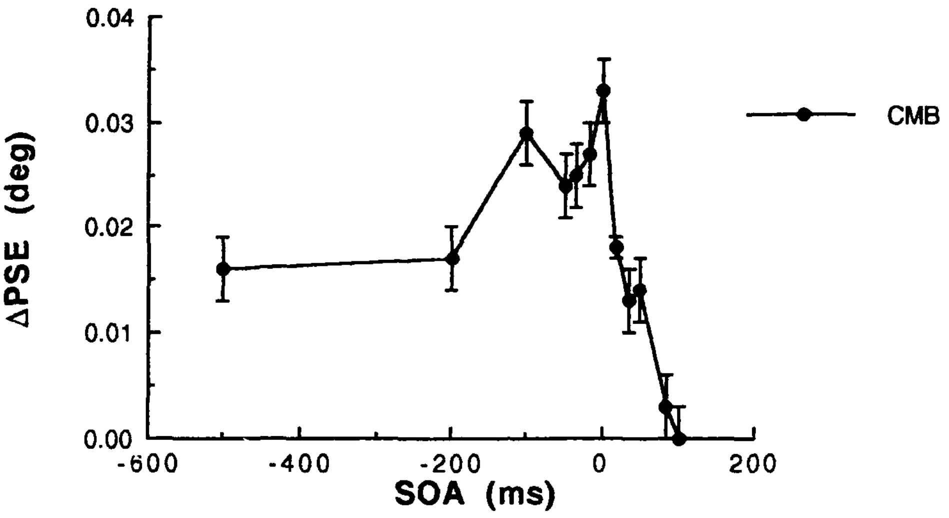

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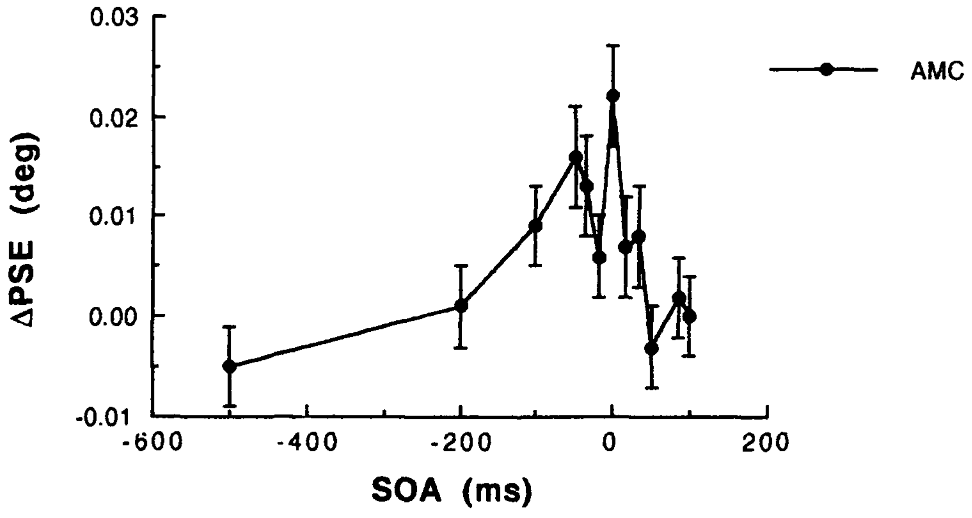

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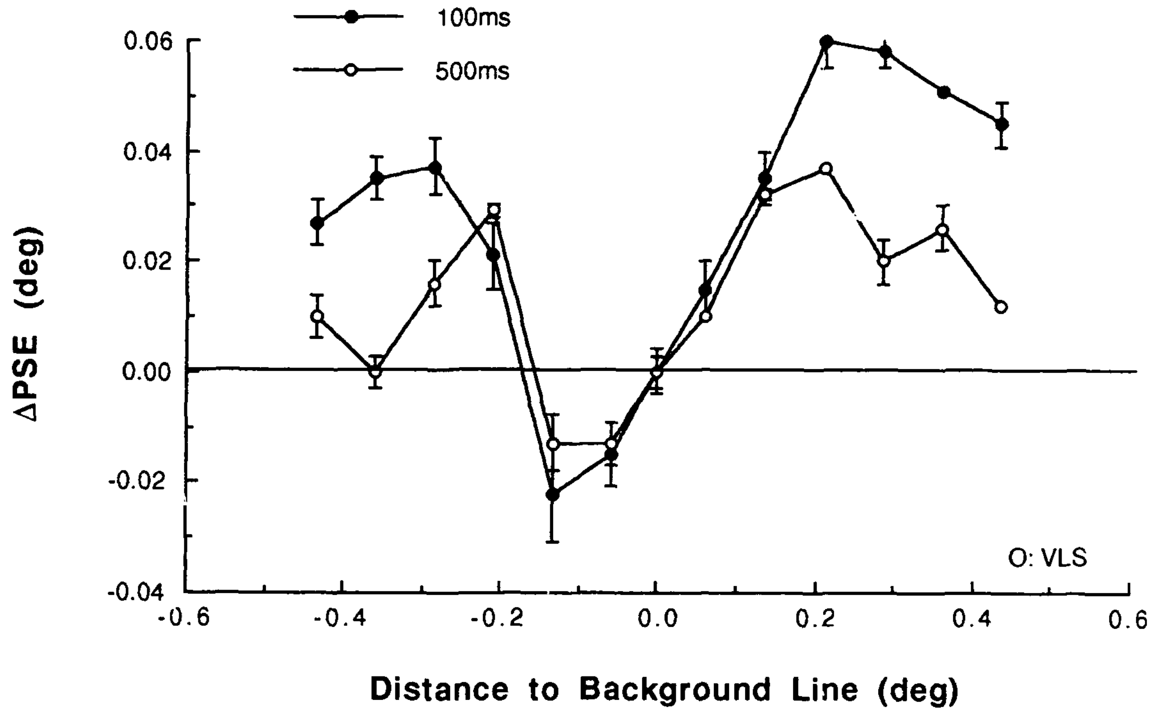
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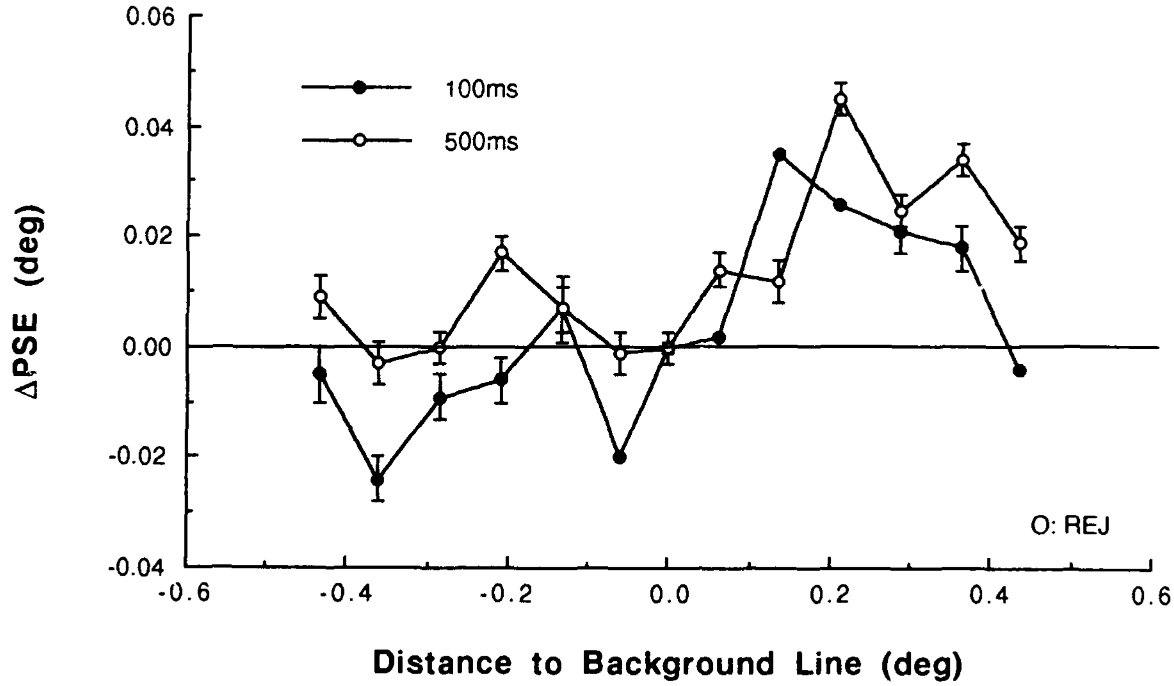
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-0.2
0.0
0.2
0.4
0.6
Distance to Background Line (deg)

Draft manuscript detailing major results of this funding year:

Position Integration Area:
A Higher-Order, Scaled, Spatial Representation

Position Integration Area:
A Higher-Order, Scaled Spatial Representation

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Abstract

Perhaps the most basic fact about human visual encoding of relative spatial position is that the length or separation discrimination threshold increases with the mean length or separation being judged. In this study, the cause of this increase was investigated by measuring the effect of a parallel flanking line on the perceived separation of a pair of target lines. Perceived target separation was increased by the presence of the flanking line whenever the distance to the flanking line was less than the mean target separation. Modeling this effect as the product of a weighting function and the distance to the flanking line, we inferred the size of the position integration area. The increase in the position integration area with increasing separation was found to account well for the concomitant increase in separation discrimination thresholds.

Introduction

Well over a century ago, Volkmann reported that the threshold for length discrimination increases as the reference length increases. This behavior has been referred to as Weber's law for length, Weber's law stating that the discrimination threshold is proportional to the value of the referent, or $\Delta x \sim x$. This fundamental fact about length or distance judgments has been replicated repeatedly in the years since, under a wide variety of stimuli and paradigms. In 1923, Wolfe summarized the results of 19 of those studies in tabular form. All results were reported in terms of the sizes of the object distances, i.e., in mm. For ten of those studies with a sufficient number of values reported, viewing distances were also reported, enabling us to convert those results into degrees of visual angle, for more convenient comparison to one another and to more recent studies. The results of this conversion are shown in Fig. 1. The agreement between the results of the various studies is impressive. Discrimination thresholds are consistently found to be approximately proportional to the mean length, L. Thus, $\Delta L/L$is nearly constant, over a large range of separations, yielding a constant Weber fraction for length or size. More recent studies have confirmed the original result using a wide range of stimuli and conditions (e.g., Westheimer and McKee, 1977), and have focused attention once again on the problem.

There are many instances of Weber's law type behavior in sensation, and explanations often focus on the variability of the signal itself (e.g., see Laming, 1986; Norwich, 1987). For example, when measuring luminance increment detection thresholds, the variability of quantal noise increases as the intensity of the light increases, thereby requiring a larger difference in intensity to reach the same signal to noise ratio. In the case of separation judgments, there is no such co-variation in the stimulus itself: the intrinsic variability of the signal is independent of the separation. Therefore, an alternative type of explanation must be found to account for Weber's law for length.

There are two general classes of model appropriate to explain Weber's law for length. They will be referred to here as distance models and scale models. In distance models, error increases with increasing length because there is a neural process that must traverse the distance between the targets. In the course of that traverse, error accumulates. For example, a step-counting algorithm that consists of the sum of n independent steps results in variability increasing as the 0.5 power of n, i.e., as the 0.5 power of the length. If there is some correlation between the steps, the power is larger (between 0.5 and 1). Supporting this class of model is the finding that when the targets in a separation discrimination task are presented on an isoeccentric arc, so that retinal inhomogeneity is not a factor, thresholds increase as the 0.65 power of s (Burbeck and Yap, 1990). Thus, a step-counting algorithm with some small correlation between the steps could be consistent with the isoeccentric data.

The second general class of models emphasizes the scale of the task. Scale models are based on the hypothesis that the area over which information about position is acquired increases with increasing separation. The spatial frequency models that have been proposed to account for separation discrimination thresholds at very small separations (Klein and Levi, 1985; Wilson, 1986) are an example of this class of model. In these models, smaller separations are encoded by units tuned to higher spatial frequencies and larger separations are encoded by units tuned to lower spatial frequencies. The smaller receptive fields of the higher spatial frequency units provide more precise information about separation than do the larger receptive fields of the lower spatial frequency units, yielding smaller thresholds for smaller separations.

Another example of a scale model of separation discrimination is based on two stages of spatial filtering (Burbeck, 1987). It will be referred to as the recursive filters model. In it, the response space of an initial set of scaled units (like the spatial frequency channels in the models described above) is operated on by a second, similar set of scaled units that are insensitive to the source of response in the initial set, caring only about its location. The insensitivity to the source of the signal is required to account for data showing such insensitivity in separation discrimination thresholds (Burbeck, 1987, Toet and Koenderink, 1988,). This insensitivity can be model as a rectifying nonlinearity between the two filtering stages. To account for Weber's law for size, larger separations are encoded by larger receptive fields, and smaller separations by smaller receptive fields. The problem of extracting position information from an initial stage of filters has been addressed by Watt and Morgan (1984) in their MIRAGE model. Similar problems have also been encountered and addressed in texture discrimination (Fogel and Sagi, 1989).

A third type of scale model one might consider replaces the connected and convex receptive fields that constitute the second stage of the recursive filters model with linked pairs of receptive fields. These linked fields would be modeled as being insensitive to the source of excitation from the initial stage, caring only about the location of the excitation, as in the recursive filters model, to better account for the data. The linked fields would have the additional property that they would be insensitive to activity between the target areas. In such a model, the size of the linked fields in the second stage would increase with increasing length of the link between them. This scaling would yield Weber's law.

In all of the scale models, Weber's law is a result of the area over which information about target position is integrated increasing with increasing separation between the targets. This is an efficient method of coding separation information.

In the research reported here, we consider the general question: Does the area over which position information is acquired increase with increasing separation, and if it does, can that account for the increase in separation discrimination thresholds with increasing separation? To measure the area over which position information is integrated, we added an extraneous background line to the standard two-line separation discrimination task and measured the range over which it had an effect on the perceived target separation. This approach is directly analogous to the classical approach to inferring the spatial summation area for luminance integration (e.g. Fiorentini and Mazzantini, 1966).

Methods

The observers all had normal or correctable to normal vision. Three of the five observers were naive regarding the purpose of the experiment. Of the other two, one, observer NLB, was a laboratory assistant who was knowledgeable about the goals of the study, and the other, STH, is the second author.

The stimuli were displayed on a CRT monitor, with a mean luminance of 26 ft.L, which was controlled by computer. The display measured 20 cm by 39.4 cm. Additional details of the apparatus are given elsewhere (Burbeck, 1986). Viewing was monocular with the observer's preferred eye. The room was dark except for the illumination provided by the display screen. Viewing distance was maintained by a head rest.

A two interval, forced choice, method of constant stimuli was used with pairs of stimuli, as illustrated in Fig. 2. In the first temporal test interval, the stimulus consisted of three horizontal lines. The top line was designated to be the background line; the middle and bottom lines were the targets whose separation was to be judged. The observer was told to ignore the background line and to judge the separation between the target lines. In the second temporal test interval, the stimulus was two horizontal target lines, like those presented in the first interval, but with a slightly larger or slightly smaller separation than the target separation presented in the first interval. The average of the target separations presented in the first and second interval was constant in a given experimental session. Thus, for example, when the separation in the first interval was slightly larger than the mean, that in the second interval was slightly smaller. The observer's task was to report which interval contained the larger target separation. No right/wrong feedback was given.

The time course of the stimulus presentation was as sketched in Fig. 3. The exposure duration of the test stimuli was either 100 or 500 ms. A horizontal sine-wave grating mask followed termination of the test stimulus. It had a contrast of 90% and completely covered the portion of the screen occupied previously by the test stimulus. The spatial frequency of the masking grating for observers ALM and SMS was 16.7 cy/deg at the 0.75 and 1.5° separations and 4.2 for the 3.0° separation. For the other three observers, it was 8.3 cy/deg for the two smallest separations, and 2.8 for the large separation. The two-line reference stimulus was presented for 500 ms for observers ALM and SMS and for 100 ms for observers NLB, STH and VLS.

The mean separation between the targets was 0.75, 1.5 or 3.0°. These values were achieved by a combination of changing viewing distance and changing target separation. The viewing distance for the 0.75 and 1.5° separations was 220 cm, and for the 3.0° separation, it was 110cm. The target and background bars subtended 0.12° by 0.75° at both viewing distances.

The distance between the background line and the upper target line (i.e., the distance between the top and middle lines in the three-line stimulus) was a parameter of the experiment. The distance to the background line was perturbed by a small amount (in the range ±10% of the mean separation) from trial to trial, to discourage the observer from basing his judgments on the ratio of the overall size of the three line stimulus to that of the two-line stimulus. The position of the entire stimulus on the display screen was also varied by a small amount from trial to trial, to discourage the observer from using the edges of the display as landmarks.

The data obtained were the percentage of trials in which the observer reported that the second separation was larger. This value was plotted against the difference between the separations in the second and first interval. The height of this function was near zero at the smallest negative values (i.e., when the second interval was considerably smaller than the first) and near 100 at the largest positive values (i.e, when the second interval was considerably larger than the first). Probit analysis was used on this function to determine both the threshold discriminable difference in separations and the point of subjective equality (PSE) for the two stimuli, i.e., the 50% point.

In control experiments, the background line was not presented. The PSE obtained in the control experiments yielded a measure of the observer's response bias (i.e., his tendency to respond preferentially first or second interval when there was no difference between the stimuli in the two intervals). This value was measured for each observer at each mean separation and each exposure duration tested. The response bias was subtracted from the PSE obtained in the experiments with the background line present to yield a measure of the change in the PSE caused by the background line. The control experiments were conducted in interleaved sessions with the primary experiments.

We focused our attention on relatively large separations to avoid the neural blurring that occurs at very small scales. For the same reason, we did not measure the effect of a background line located very near the target line. In all of the experiments reported here, all lines in each stimulus were clearly discriminable from one another.

Effect of Background Line on Perceived Target Separation

The first main finding of this study was that the perceived separation between the targets in the three-line stimulus was larger than that in the two-line stimulus. The presence of the background line increased the perceived separation between the targets even though the background line was clearly discriminable from the targets.

The subsequent findings relate to the manner in which this perceived increase varied with (A) the distance to the background bar, (B) the separation between the targets, and (C) the exposure duration of the stimulus.

A. Dependence on Distance to the Background

Fig. 4 shows the effect of the background line on the perceived separation of the target pair using an average target separation of 0.75° and an exposure duration of 100 ms, for one observer. Data for additional observers in this condition are shown in the subsequent section. Here the focus is on describing the basic phenomenon.

The horizontal axis in Fig. 4 (and in subsequent figures) is the distance between the top target line and the background line. (These values are the mean target-to-background line distances that were presented in individual sessions. The exact value presented on a given trial of a session varied randomly around the mean value by a small amount, as described in the methods section.) The vertical axis, labeled ΔPSE, represents the change in perceived separation between the target lines caused by addition of the background line. ΔPSE is the PSE calculated from the experiments using a background line (at the specified distance) minus the PSE calculated from the control experiments in which no background line was used.

The data in Fig. 4 show that the perceived target separation was increased by the presence of the background line whenever the distance to the background line was less than about 0.75°, which was the mean separation between the targets in this experiment. For distances larger than that, there was no reliable effect of the background line. The graph in Fig. 4 consists of two disconnected pieces. The initial study investigated distances up to about 1 deg. Because ΔPSE went negative at that value, a second study was done using larger distances to see if there was a repulsive effect. No systematic effect of the background line was found when the distance from the background line to the top target line exceeded 1°.

The largest effect of the background line occurred when the target-to-background-line distance was approximately half the separation between the targets.

B. Dependence on Mean Target Separation

Data on the effect of the background line was obtained with mean target separations of 1.5° and 3.0°, as well as the 0.75° shown for one observer in Fig. 4. Data for five observers at each of the three mean target separations are shown in Fig. 5. Exposure duration was 100 ms. The axes are as described above for Fig. 4.

The background line had a significant effect on the perceived separation of the target lines at all mean target separations tested. Furthermore, the distance at which the background line had its largest effect increased as the separation between the targets increased. Finally, the amplitude of the effect was constant or increased as target separation increased, depending on the observer.

C. Variation with Exposure Duration

To begin to assess the generality of the effect and to test the hypothesis that the visual system changes its operative spatial scale over time (Watt, 1987), we measured the effect of the background line with a stimulus duration of 500 ms. The target lines and flanking line had simultaneous onsets and terminations as in the original experiments. Fig. 6 shows the effect of the background line using a 500 ms exposure duration. The comparable data obtained with a 100 ms exposure duration are also plotted for comparison. Data are shown for two observers and two separations.

The background line increased the perceived target separation at this longer duration, as it did with the briefer presentation, but the magnitude of the effect was appreciably reduced when more time was available. Interestingly, the range of target-background distances over which the effect occurred did not change with exposure duration. The peak effects occur at similar distances for the two durations.

Summary of Experimental Findings

At all mean target separations tested, the perceived target separation was increased by the presence of the background line. Additionally, the value at which this effect was largest increased with increasing separation. Finally, the effect of the background line decreased with increasing exposure duration, but the location of the peak effect was the same for the two exposure durations tested.

Modeling the Increase in Perceived Target Separation

The data of Fig. 5 suggest that information about the relative location of a target is acquired over a fairly large window and that the size of that window increases with increasing separation between the targets. Can this increasing window size account for Weber's law for distance? To make that assessment, we need a mathematical description of the effect shown in those figures. We base that mathematical description on a simple model of the underlying process.

We model the effect of the background line on the perceived target separation as a shift in the effective location of the top target line. The effective location of the top target line is, in turn, modeled as a weighted average of the locations of the top target and background lines.

Specifically,

Let PS(d) = the perceived target separation in the presence of the background line at location d. Experimentally this is given by the point of subjective equality for the three-line and two-line stimuli.

Let ΔPS(d) = PS(d) - PS(0), the change in perceived target separation caused by the addition of the background line. PS(0) is the point of subjective equality for the stimuli in the two temporal intervals when there is no background line. The stimulus in the second interval is taken as the reference.

Let ELT(d) = the Effective Location of the Top target given the background line at location d, where effective location means only the location that supports the perceived separation. The location itself is not required to have a separate representation.

For convenience, and without loss of generality, we take the location of the top target line in the absence of a background line to be zero.

$$ELT(0) = 0 \qquad (1)$$

Let ELB = the Effective Location of the Bottom target, which we assume to be independent of the background line. ELB depends only on the separation between the targets.

By definition of ELT(d) and ELB,

$$PS(d) = ELT(d) - ELB$$

so

$$\Delta PS(d) = ELT(d) - ELT(0) \qquad (2)$$

By assumption, ELT(d) is a weighted average of the locations of the top target and the background bar. The location of the top target is zero and that of the background bar is d, so

$$ELT(d) = w(d) \cdot d, \qquad (3)$$

where w(d) is a weighting function, w: $R^+ \rightarrow [0,1]$.

Thus, from equations 1,2 and 3,

$$\Delta PS(d) = w(d) \cdot d.$$

For this model to be plausible, w(d) should be a smoothly decreasing function of d, i.e., the farther the background line is away from the top target, the less weight it should be given. Gaussian shaped distributions have frequently been used to model spatial integration windows (e.g., Koenderink, 1984) and that form appears to be consistent with physiologically defined receptive fields. We follow that tradition and model the weighting function, w(d), as a Gaussian type function centered on the top target (i.e., centered at a background-to-target distance of zero). Unlike in a statistical Gaussian distribution in which the area under the function must be one, the amplitude of this function is allowed to vary, consistent with our task or modeling a neural integration region. Because the center of the Gaussian is fixed at the top target in our model, there are still only two free variables for the function, the standard deviation and the amplitude.

To infer the weighting function from our data, recall that, by definition, $\Delta PS(d)$ is the ΔPSE of Fig. 5. Thus,

$$\Delta PSE(d) = w(d) \cdot d$$

implying

$$w(d) = \Delta PSE(d)/d.$$

The results of this calculation on the data of Fig. 5 are shown in Fig. 7. In general, w(d) decreases as the distance to the background bar increases, consistent with expectation.

In a few of the data sets, the effect of the background bar at the smallest value of d, i.e.,at the closest background-to-target distance, was too small to be consistent with a Gaussian model. Those data points were not included in the calculation of the best-fitting Gaussians because their inclusion caused the rest of the data to be very poorly fit by the Gaussian. The conditions for which this occurred are noted in the caption for Fig. 7. The possible theoretical significance of these points is considered in the Discussion section.

The best-fitting Gaussians were found using the curve-fitting feature of Cricket Graph software (squaring the x value and then using the exponential distribution). They are shown, superimposed on the data, in Fig. 7. On a few occasions, ΔPSE was slightly negative at large values of d. To accommodate the requirements of the curve-fitting program, these negative values were deleted from the data set for the purpose of curve fitting. All data points are shown in Fig. 7, and the points that were deleted are noted in the caption.

The curve-fitting procedure yielded an amplitude and a standard deviation or sigma for each data set. These values are given in Table 1 together with the r^2 values obtained from the curve fitting procedure. The amplitudes indicate the magnitude of the weighting function for each observer and condition. They showed no consistent patterns across observers.

The standard deviations are of primary interest to us because they capture the spatial range over which the flanking line has its effect, and thus, presumably, the range over which position information is being acquired. These values will be considered in detail in the next section.

Predicting Weber's Law for Size

As the integration area for position information increases, the precision with which position is encoded naturally decreases. Thus, the increasing sigmas listed in Table 1 predict that the separation discrimination thresholds should also increase. To determine whether that predicted increase matches the actual increase in separation discrimination thresholds with increasing separation, we compare the standard deviations of Table 1 with the corresponding separation discrimination thresholds, which were measured in the control experiments.

If the change in position integration area with increasing separation is solely responsible for the change in threshold, then the rate of change of the standard deviations should match the rate of change of the thresholds. The thresholds and standard deviations calculated from the flanking line effect are plotted together for each observer in Fig. 8. The standard deviations have been shifted vertically to facilitate comparison of the slopes of the two functions. The shift constant that was used is

$$\left(\prod_i \theta_i \Big/ \prod_i \sigma_i\right)^{1/3} \quad i=1,..3$$

where θ_i is the observer's threshold for the i^{th} separation and σ_i is the standard deviation calculated from his flanking line data. Use of this constant yields the best superposition of the data, facilitating visual comparison of the slopes of the functions.

There is strong agreement between the threshold data and position-integration-area function. The increase in position-integration area with increasing separation is sufficient to account for the main effect of separation on threshold. Recall that there were no free variables involved in this comparison. All parameter values came directly from the data.

The data are replotted in Fig. 9 on log-log-coordinates to better illustrate the similarity of the slopes across observers. It is this slope that is consistently reported to be near one. This figure also shows that the model fits the large separation data as well as it fits the small separation data, when the error is considered proportionally.

Luminance or Position Integration?

Badcock and Westheimer (1985) also used a flanking line paradigm with spatial position tasks and also found integration regions. Specifically, they used two spatial judgment paradigms. In one, a line was presented and then displaced laterally to a new position. The observer had to report the direction of the lateral jump. A flanking line was added when the target jumped. In a similar paradigm, they measured the effect of a flanking line on a vernier acuity task. In both tasks, the perceived location of the target was displaced toward the flanking line when the flanking line was of the same contrast polarity and sufficiently near the target. When the flanking line was of opposite contrast polarity or farther from the target, the perceived target location was displaced away from the flanking line, i. e., it was repulsed. The dependence on the relative contrast polarities of the target and flanking line when the distance to the flanking line was small suggested that the underlying mechanism for this effect could be luminance integration rather than position integration. The repulsion at larger distances was attributed by Badcock and Westheimer to a different mechanism, one that is responsible for some figural aftereffects. They did not measure the spatial range of the repulsion.

To determine whether luminance integration is a possible explanation for our effect, we too changed the contrast polarity of the flanking line. In this experiment, mean target separation was 0.75°, exposure duration was 100 ms, and the distance to the flanking line was 0.37°, a value chosen to give a large effect of the flanking line in the same-polarity condition. The results of this experiment for two observers are shown in Fig. 10. Also shown for comparison are data that were obtained (in interleaved sessions) with a same-contrast-polarity flanking line at the same distance.

When the contrast polarity of the flanking line was reversed, its effect was not reversed. Even the magnitude of the effect was unchanged for one observer. If luminance integration were responsible for the effect we observed with same-polarity target and flanking lines, then reversing the contrast polarity of the flanking line should have reversed the direction of the effect, as it did in the Badcock and Westheimer data at small target to flanking line distances. Instead, the effect remained strong and in the same direction. We conclude that the integration that is occurring is not luminance integration, but is, in fact, position integration. The direction of our effect is opposite to the effect that they found at larger distances. It may be significant that when the distance to the flanking line was at the small end of the range we measured, there was sometimes a marked decrease in the magnitude of the effect. This may have been caused by the repulsive effect seen in the Badcock and Westheimer study. The comparison is made difficult, however, both by the dissimilarity of the tasks and by the fact that the spatial scales of the tasks in their study are not known.

Discussion

The key problem in understanding separation discrimination thresholds is why thresholds increase with increasing separation. The results reported here identify a set of higher-order, scaled receptive fields, which we call position integration areas. The scale of the relevant position integration area increases with increasing target separation. This increase in the scale of the position integration area is sufficient to account for the increase in separation discrimination thresholds with separation. In short, Weber's Law for Size is accounted for by the scaling of position integration areas.

This finding strongly supports scale models of separation discrimination. Our finding that the effect of the flanking line is not reversed when its contrast polarity is reversed argues that the relevant scaled units are not those that operate on the luminance distribution. This conclusion is further supported by previous findings on the irrelevance of the internal spatial scale or luminance distribution of the individual targets. This leaves as possibilities scale models that operate on more abstract representations of the image, as described in the introduction.

The position integration process measured here is not strictly "bottom up" or automatic. If it were, the locations of the top target and the background line would have to be weighted equally and they are not. A heavier weight is assigned to the target even though the target differs from the background line only in its designation as target to the observer prior to the experiment. Further, the relative weight given to the background line decreases over time. The fact that the peak effect occurs at the same location for the 500 ms duration as it does for the 100 ms duration indicates that this selection process does not operate by restricting the spatial extent of the integration window. There is no evidence here for a coarse to fine scanning of the image. (As proposed by Watt, 1987). Instead, the relative weight given to the background line diminishes over time.

The identification of position integration areas that scale with the separation to be encoded can account for some recent intriguing results by Morgan, Hole, and

Glennerster (1990). They used two black dots as their targets in a separation discrimination task. Each dot was embedded in a cluster of white dots. When presented with a single cluster, the observers could easily tell whether the black dot was centered in the cluster of white dots. However, when two clusters were presented with one black dot in each, and the observers were asked to judge the separation between the black dots, they instead reported the separation between the clusters as a whole. This finding is readily explained in terms of scaled position integration areas. When a single cluster was presented, the relevant spatial scale was small – judging the offset of the black dot from the center of the cluster – and so the position integration area that was operative was small – small enough to detect the location of the single black dot. When two clusters were presented at a separation that was large relative to the dot size, the position integration areas that were used were also large relative to the dot size.

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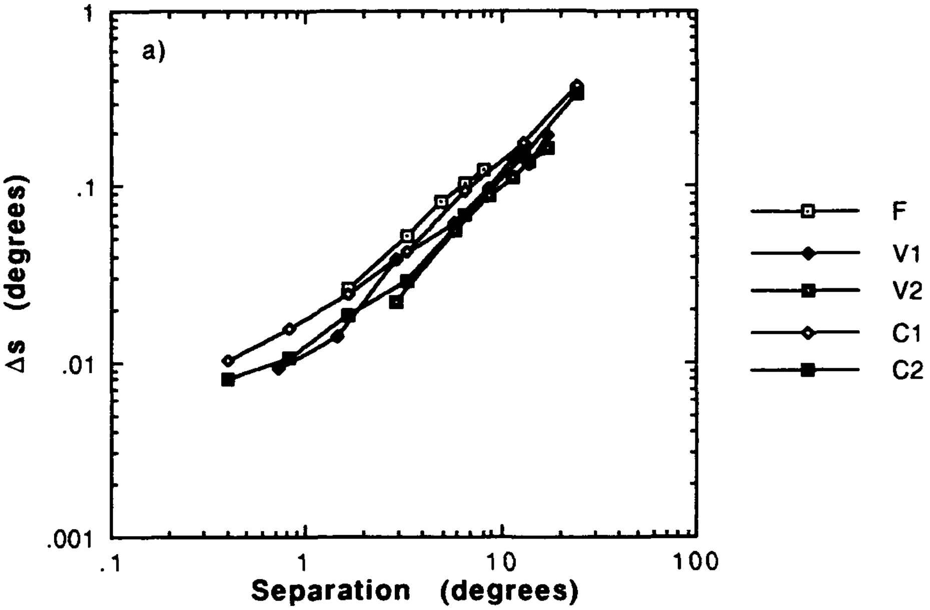
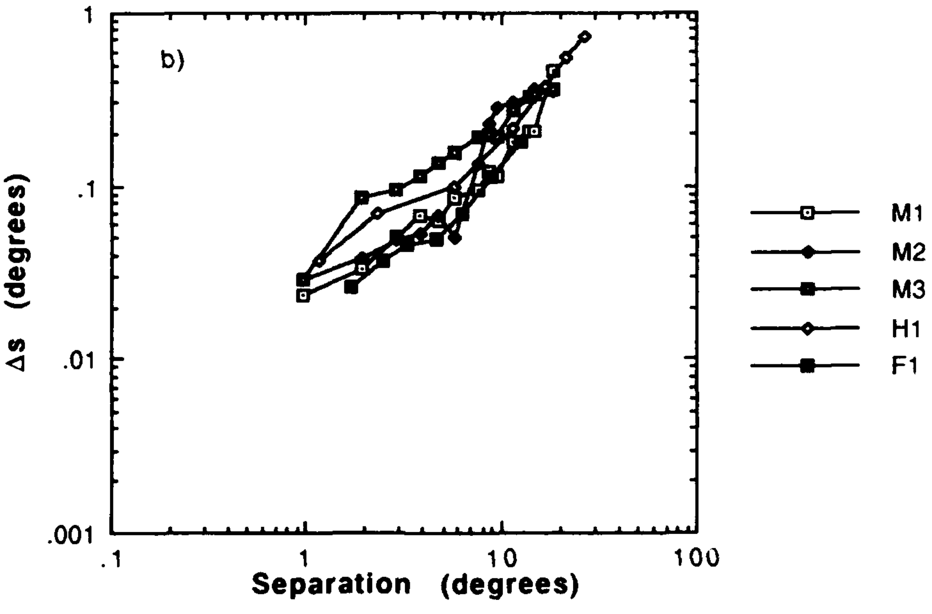
l



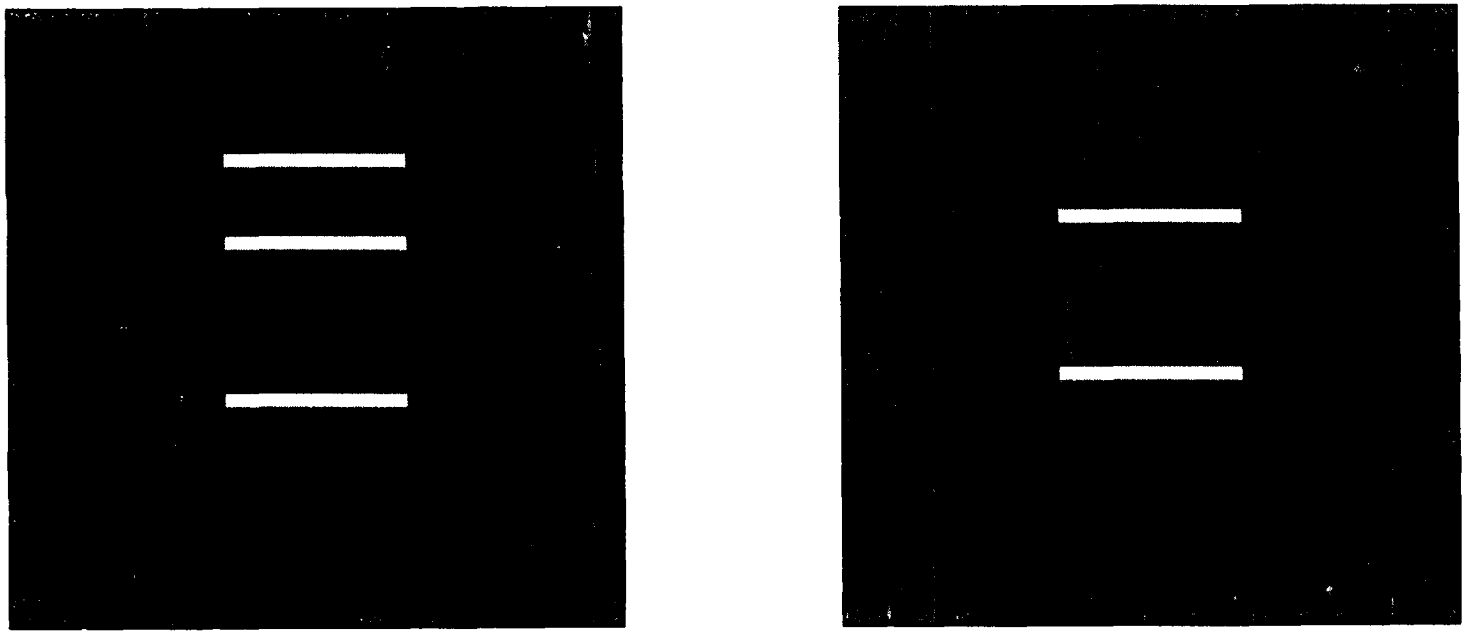
a)
Δs (degrees)
1
.1
.01
.001
.1
1
10
100
Separation (degrees)
F
V1
V2
C1
C2

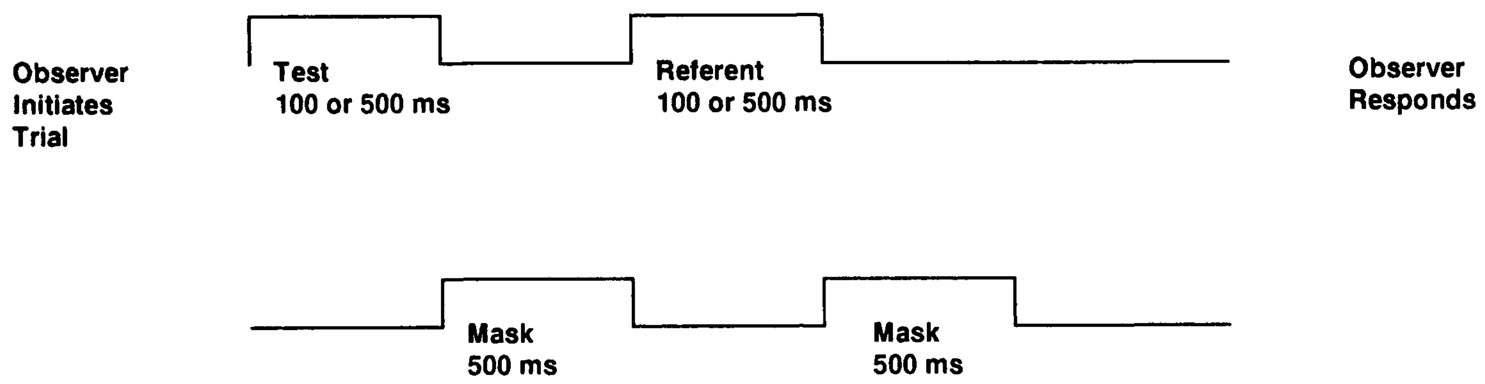


b)
Δs (degrees)
1
.1
.01
.001
.1
1
10
100
Separation (degrees)
M1
M2
M3
H1
F1

Test Interval

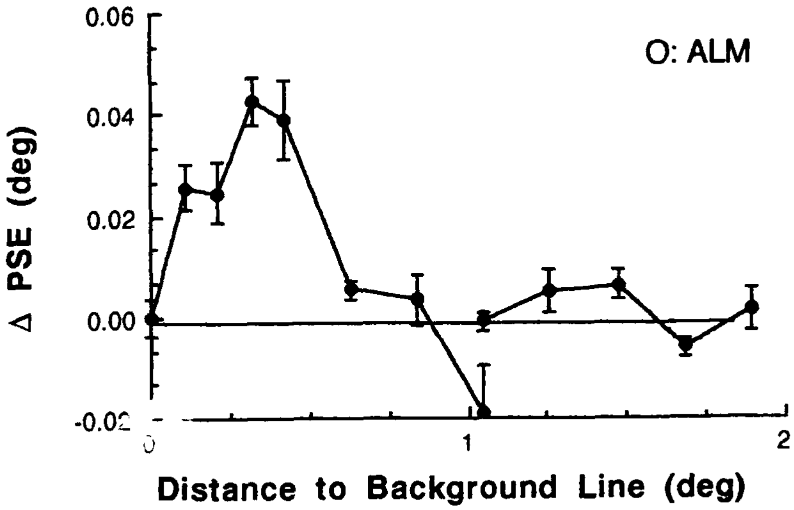
Reference Interval




Observer
Initiates
Trial
Test
100 or 500 ms
Referent
100 or 500 ms
Observer
Responds
Mask
500 ms
Mask
500 ms

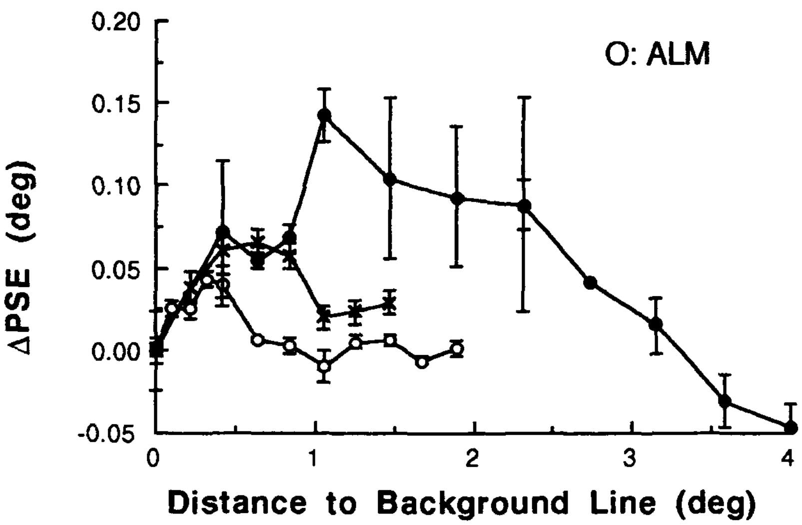
2

4



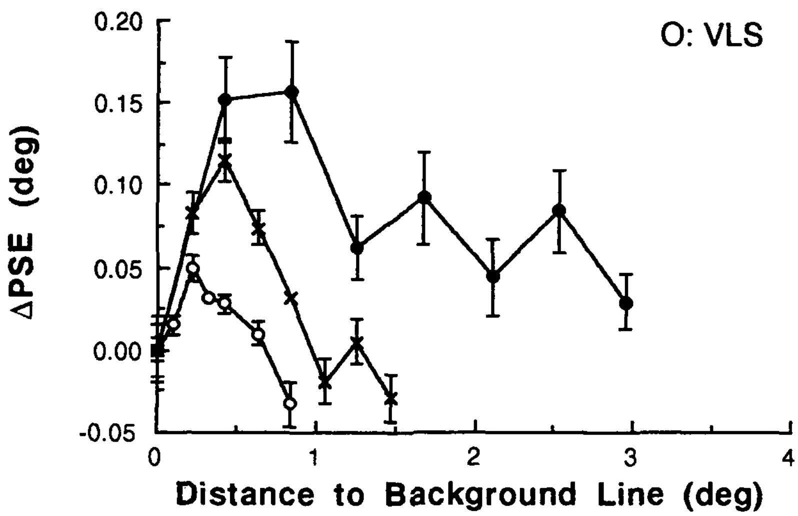
O: ALM
Δ PSE (deg)
0.06
0.04
0.02
0.00
-0.02
0
1
2
Distance to Background Line (deg)

5a



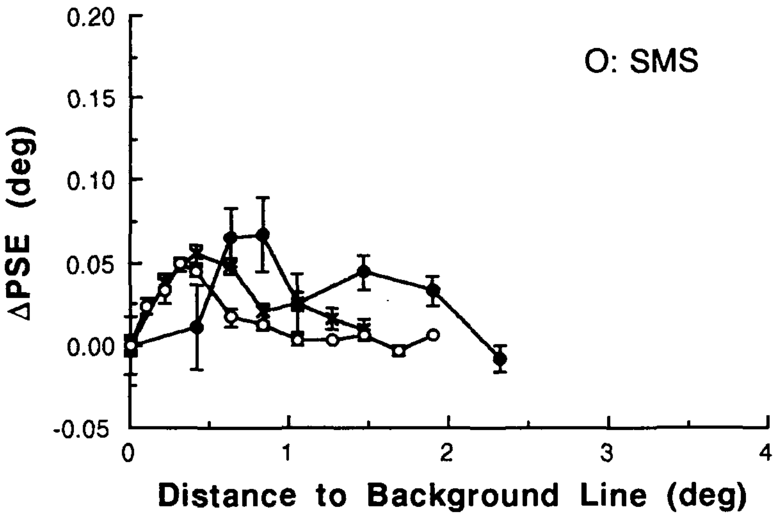
O: ALM
0.20
0.15
0.10
0.05
0.00
-0.05
ΔPSE (deg)
0
1
2
3
4
Distance to Background Line (deg)

5b

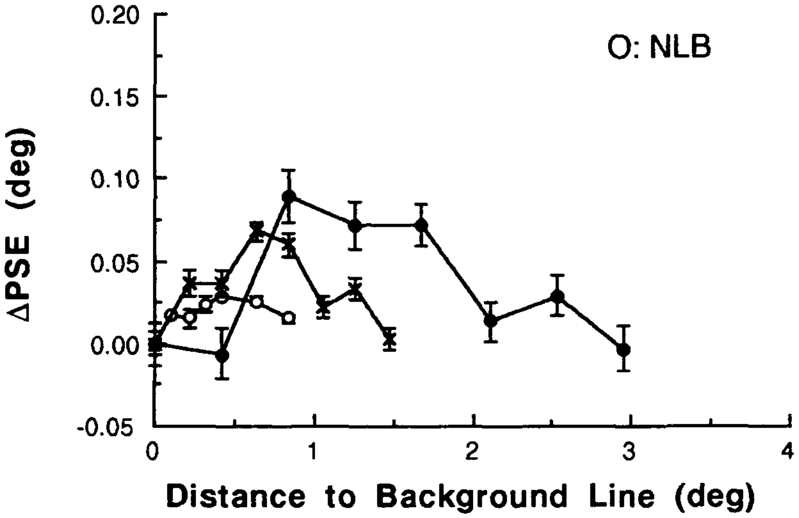


O: VLS
ΔPSE (deg)
0.20
0.15
0.10
0.05
0.00
-0.05
0
1
2
3
4
Distance to Background Line (deg)

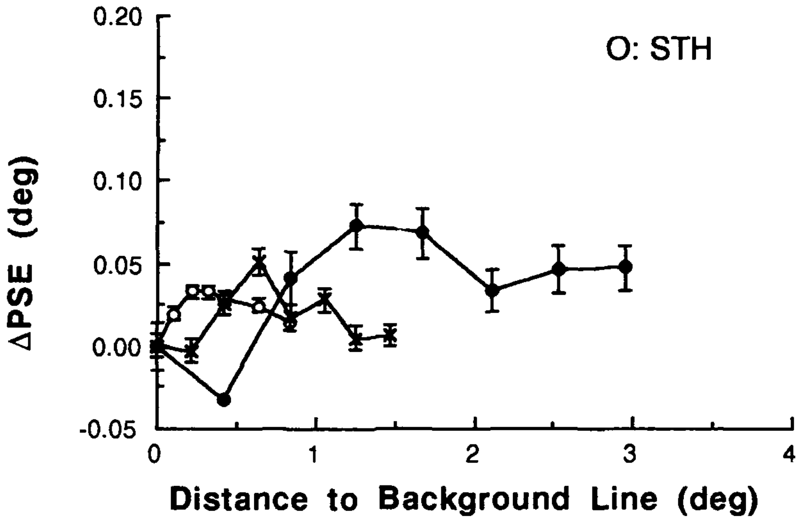
5c


O: SMS
0.20
0.15
0.10
0.05
0.00
-0.05
ΔPSE (deg)
0
1
2
3
4
Distance to Background Line (deg)

5d

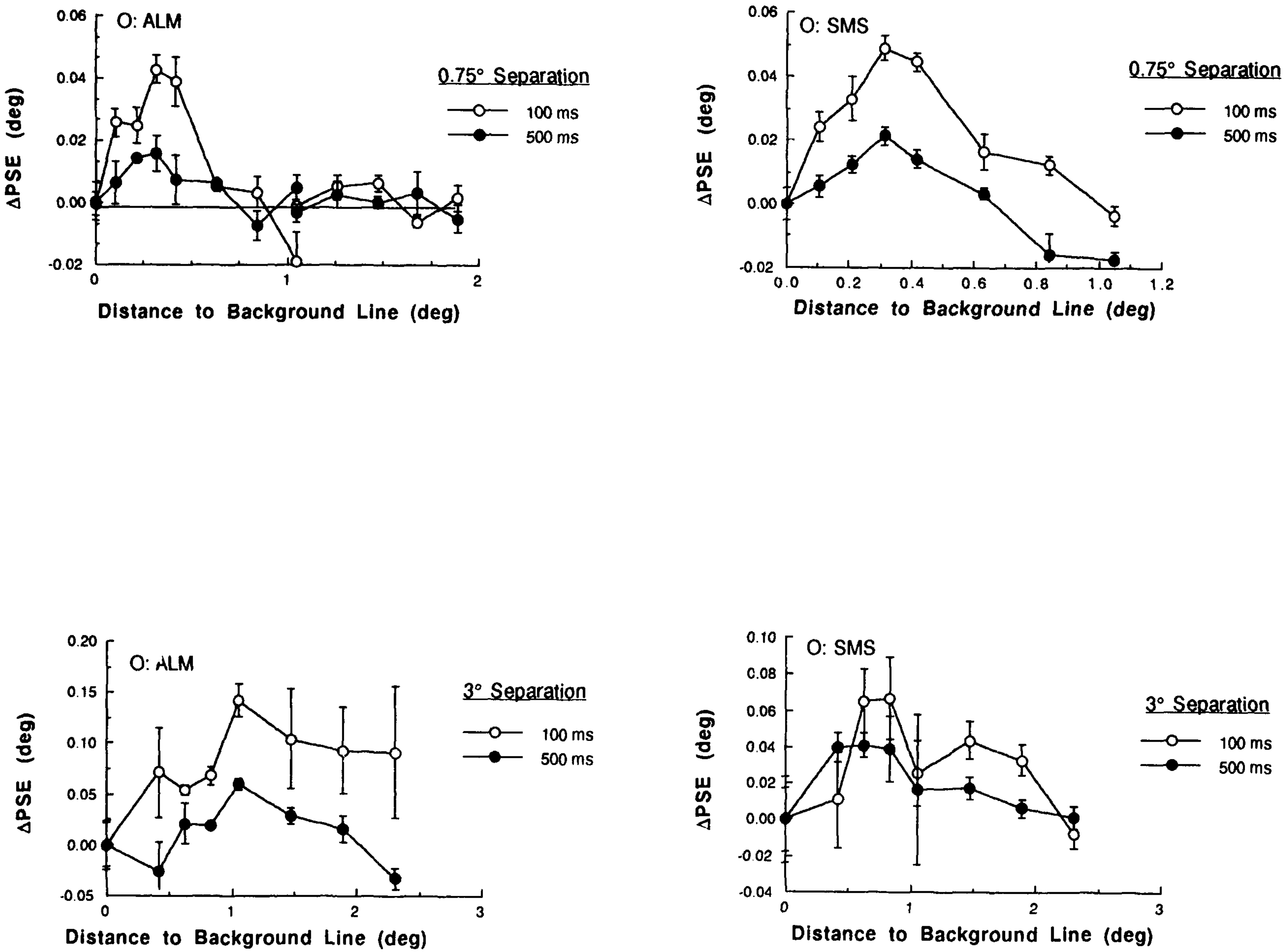

O: NLB
0.20
0.15
0.10
0.05
0.00
-0.05
ΔPSE (deg)
0
1
2
3
4
Distance to Background Line (deg)

5e



O: STH
0.20
0.15
0.10
0.05
0.00
-0.05
ΔPSE (deg)
0
1
2
3
4
Distance to Background Line (deg)

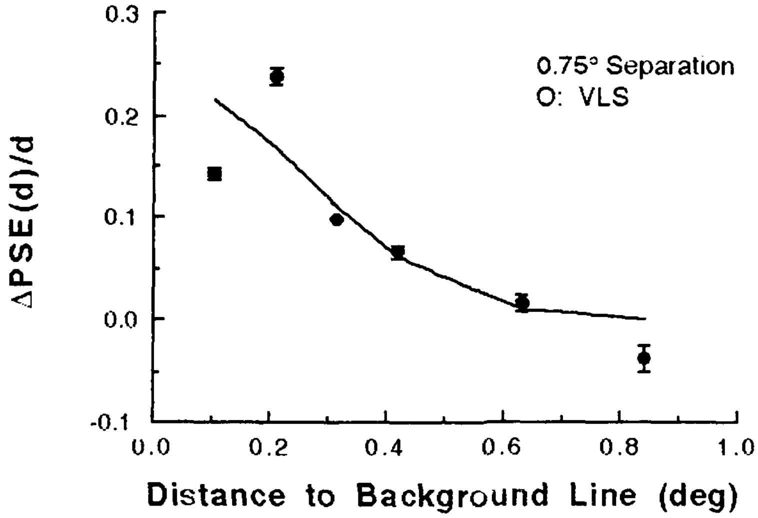
6

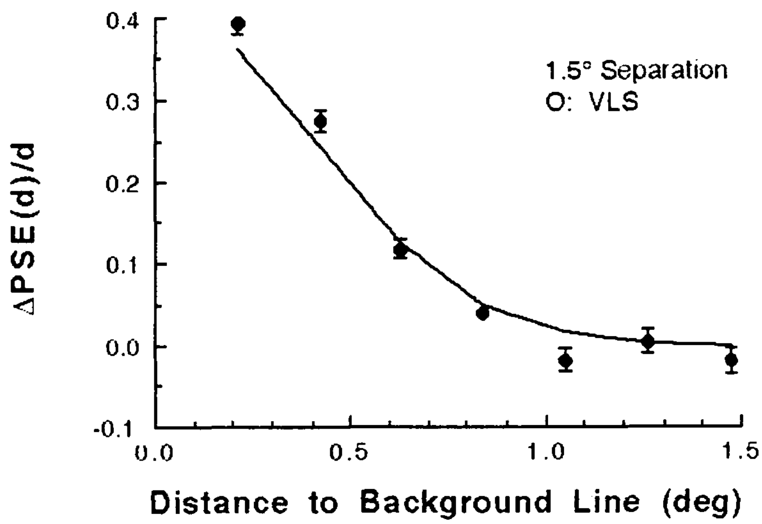


O: ALM
0.75° Separation
100 ms
500 ms
ΔPSE (deg)
Distance to Background Line (deg)
O: SMS
0.75° Separation
100 ms
500 ms
ΔPSE (deg)
Distance to Background Line (deg)
O: ALM
3° Separation
100 ms
500 ms
ΔPSE (deg)
Distance to Background Line (deg)
O: SMS
3° Separation
100 ms
500 ms
ΔPSE (deg)
Distance to Background Line (deg)

5

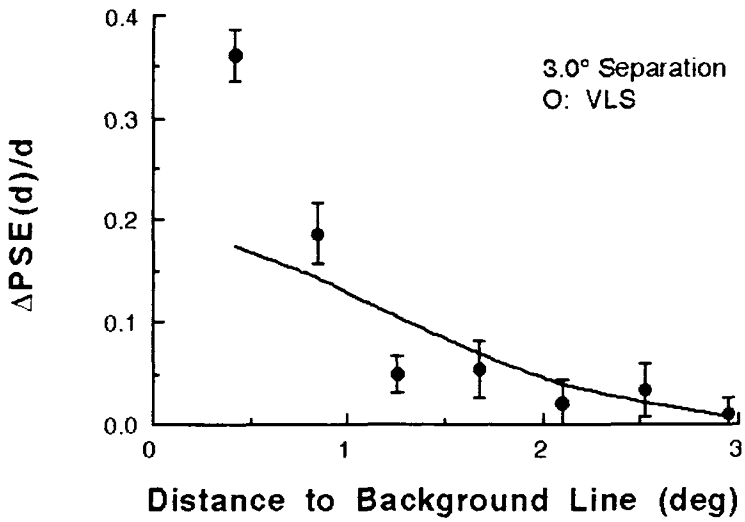
7a


0.75° Separation
O: VLS
ΔPSE(d)/d
0.3
0.2
0.1
0.0
-0.1
0.0
0.2
0.4
0.6
0.8
1.0
Distance to Background Line (deg)



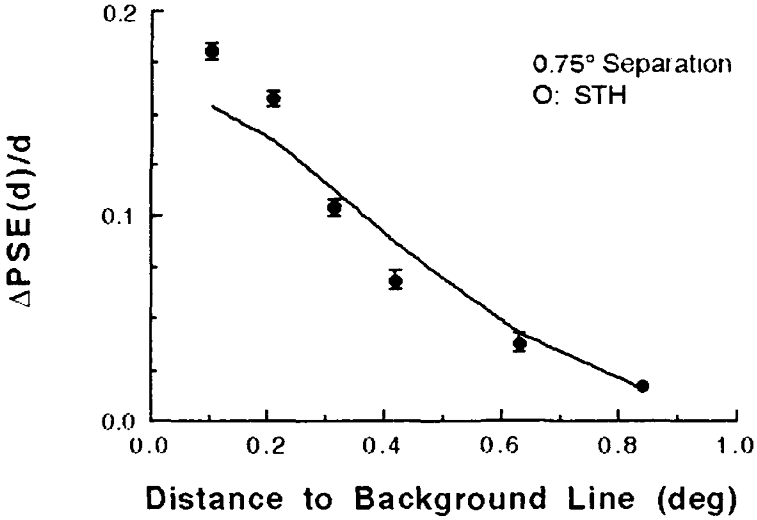
1.5° Separation
O: VLS
ΔPSE(d)/d
0.4
0.3
0.2
0.1
0.0
-0.1
0.0
0.5
1.0
1.5
Distance to Background Line (deg)

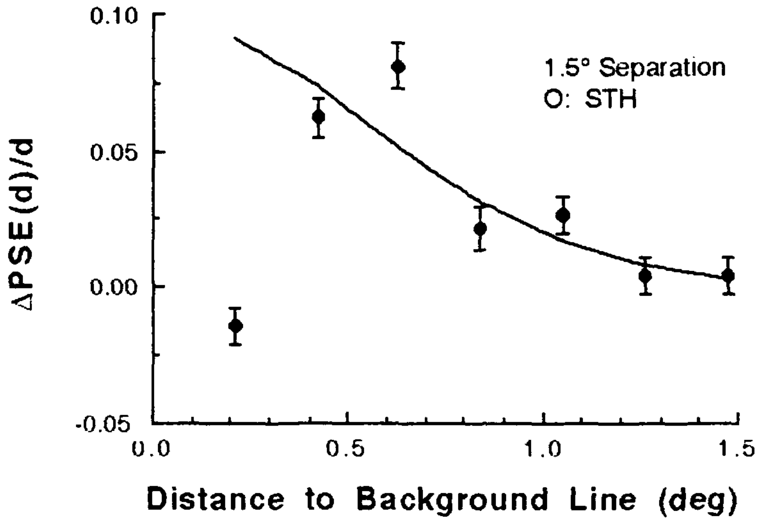
7c



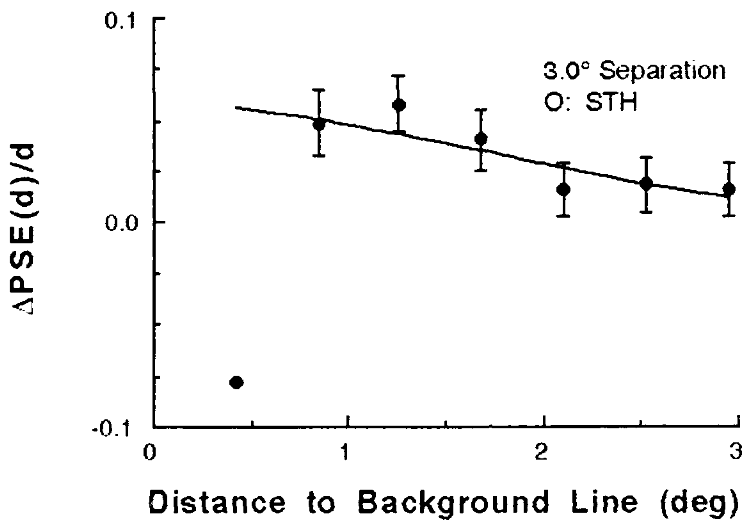
0.4
0.3
0.2
0.1
0.0
0
1
2
3
3.0° Separation
O: VLS
ΔPSE(d)/d
Distance to Background Line (deg)

7d

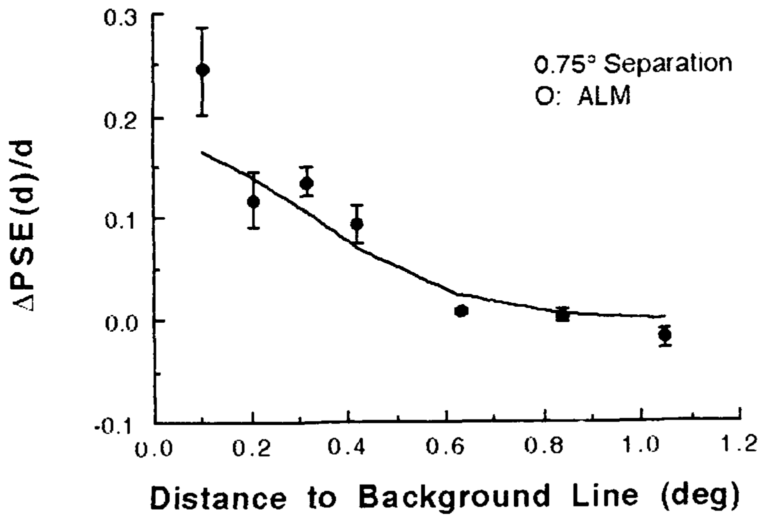

0.75° Separation
O: STH
ΔPSE(d)/d
0.2
0.1
0.0
0.0
0.2
0.4
0.6
0.8
1.0
Distance to Background Line (deg)

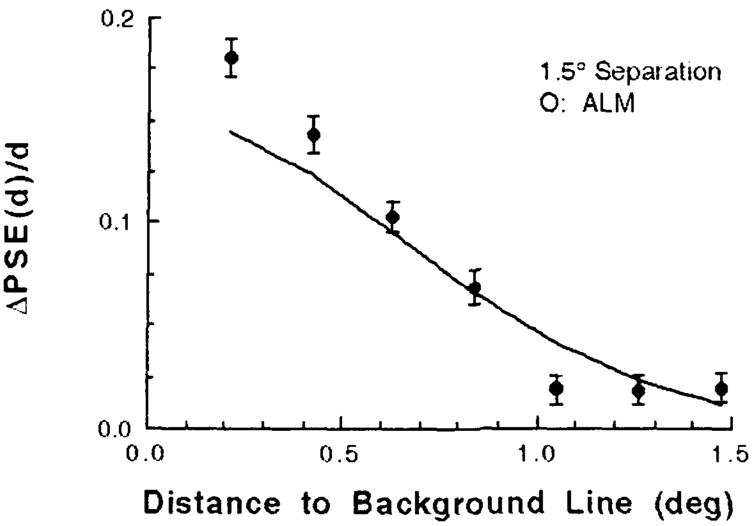


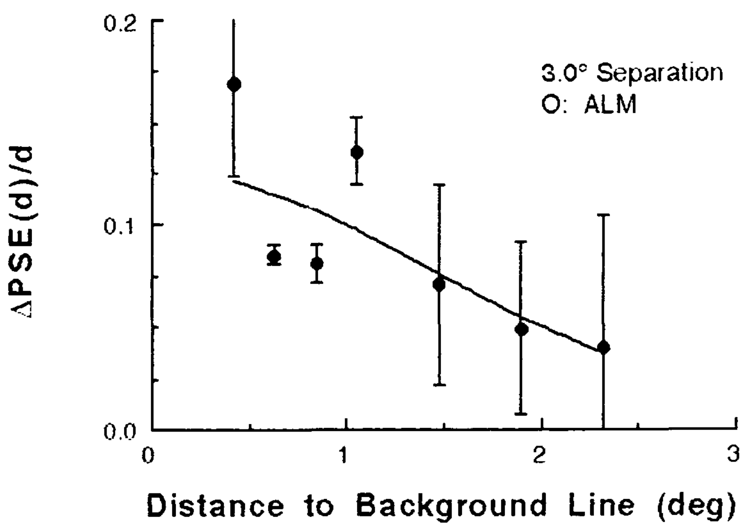
0.10
0.05
0.00
-0.05
ΔPSE(d)/d
1.5° Separation
O: STH
0.0
0.5
1.0
1.5
Distance to Background Line (deg)


0.1
0.0
-0.1
ΔPSE(d)/d
3.0° Separation
O: STH
0
1
2
3
Distance to Background Line (deg)

7g

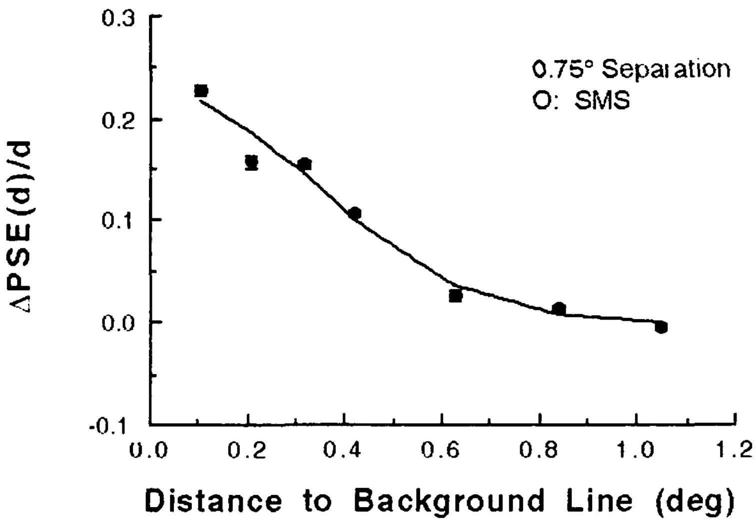

0.75° Separation
O: ALM
ΔPSE(d)/d
0.3
0.2
0.1
0.0
-0.1
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Distance to Background Line (deg)


0.2
0.1
0.0
ΔPSE(d)/d
1.5° Separation
O: ALM
0.0
0.5
1.0
1.5
Distance to Background Line (deg)



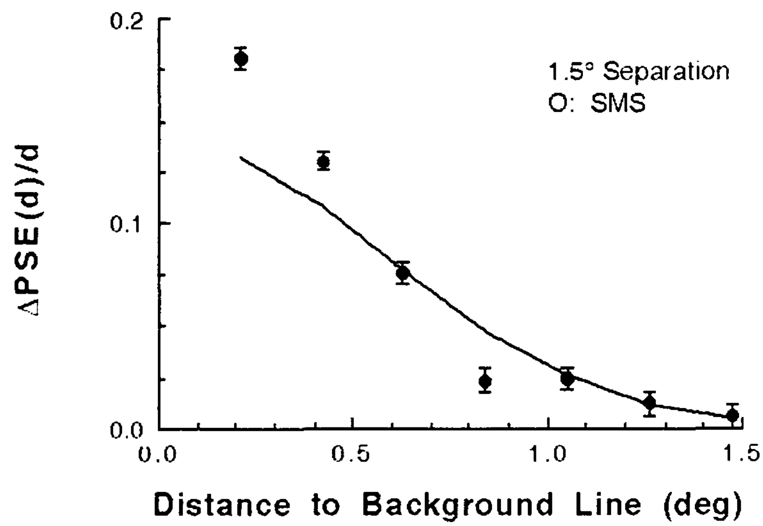
0.2
0.1
0.0
0
1
2
3
3.0° Separation
O: ALM
ΔPSE(d)/d
Distance to Background Line (deg)

7j

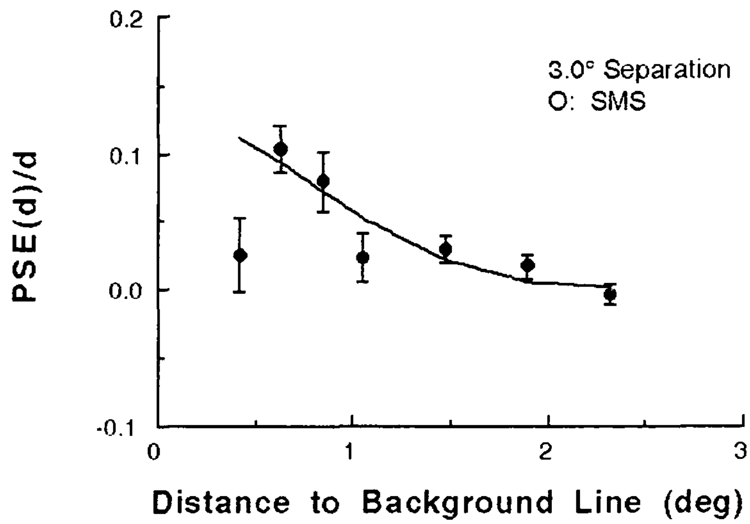


0.75° Separation
O: SMS
ΔPSE(d)/d
0.3
0.2
0.1
0.0
-0.1
0.0
0.2
0.4
0.6
0.8
1.0
1.2
Distance to Background Line (deg)

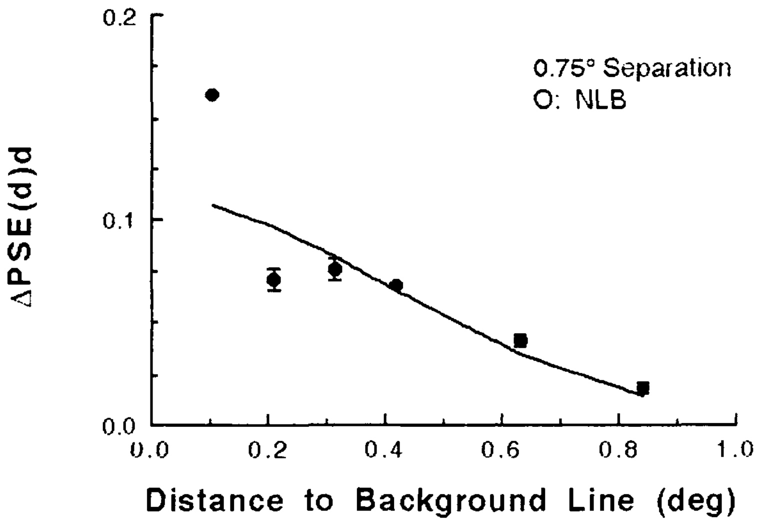
7k



1.5° Separation
O: SMS
ΔPSE(d)/d
0.2
0.1
0.0
0.0
0.5
1.0
1.5
Distance to Background Line (deg)

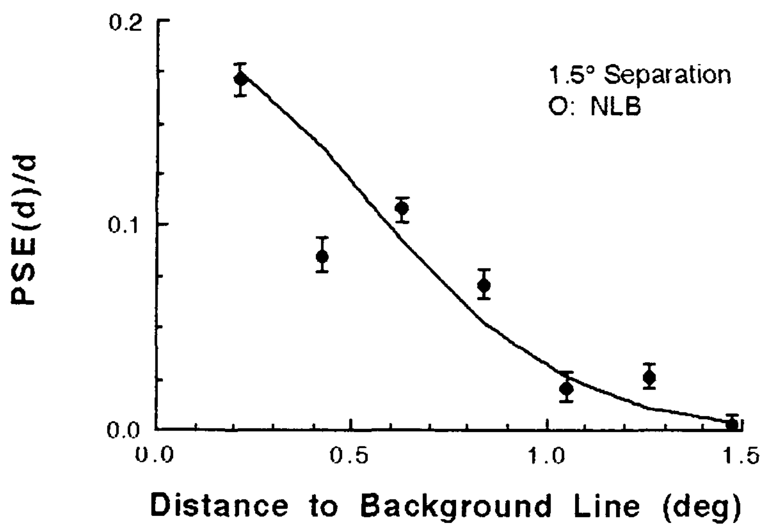

0.2
0.1
0.0
-0.1
PSE(d)/d
3.0° Separation
O: SMS
0
1
2
3
Distance to Background Line (deg)

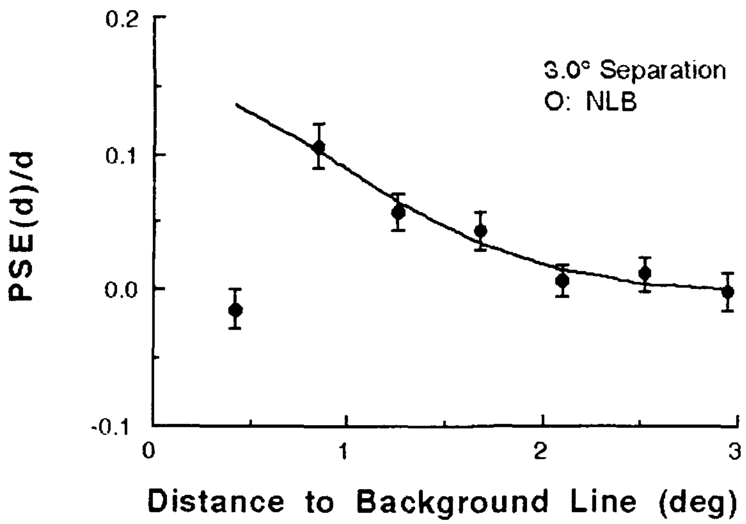
7 m



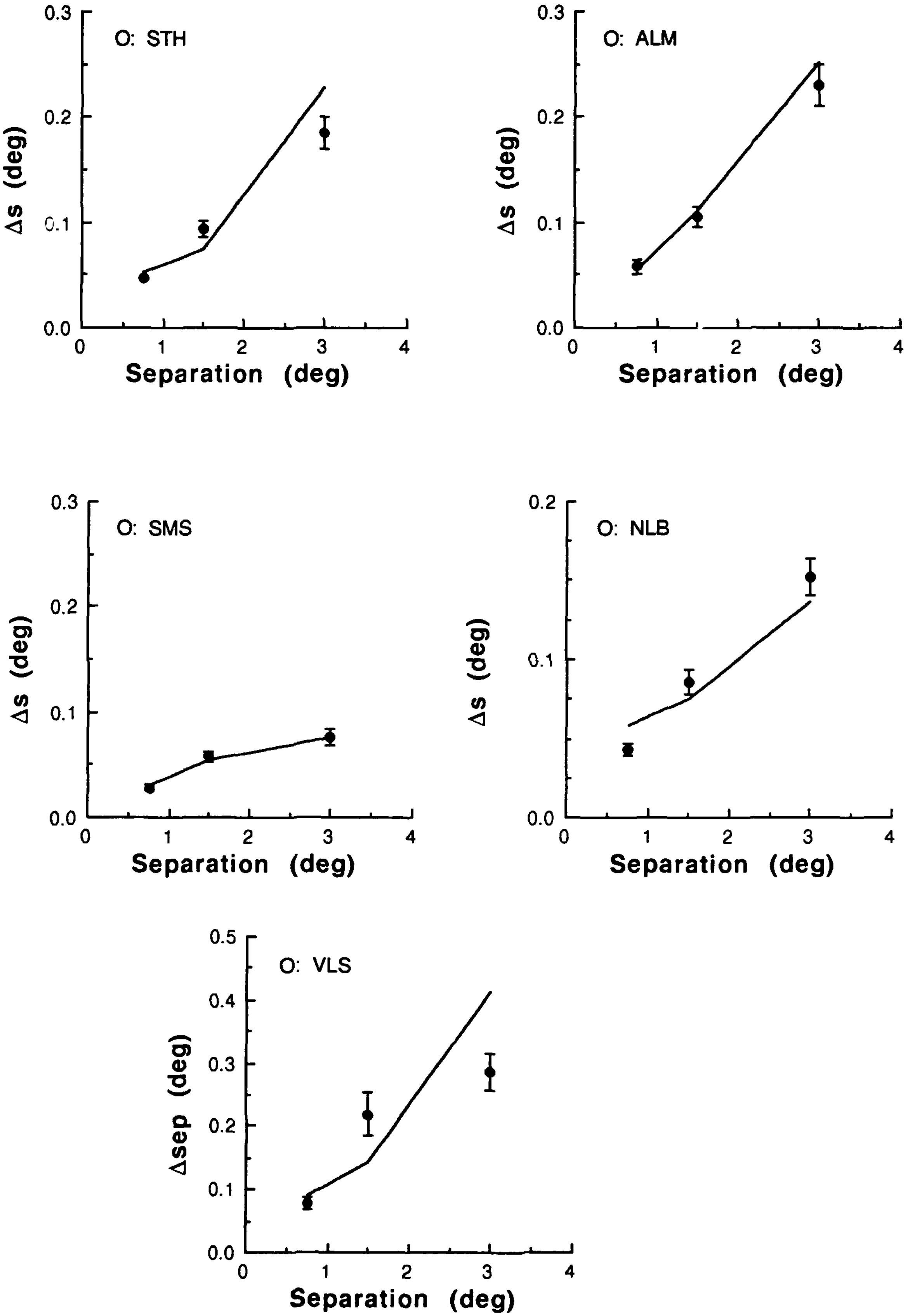
0.2
0.1
0.0
ΔPSE(d)d
0.75° Separation
O: NLB
0.0
0.2
0.4
0.6
0.8
1.0
Distance to Background Line (deg)

7n

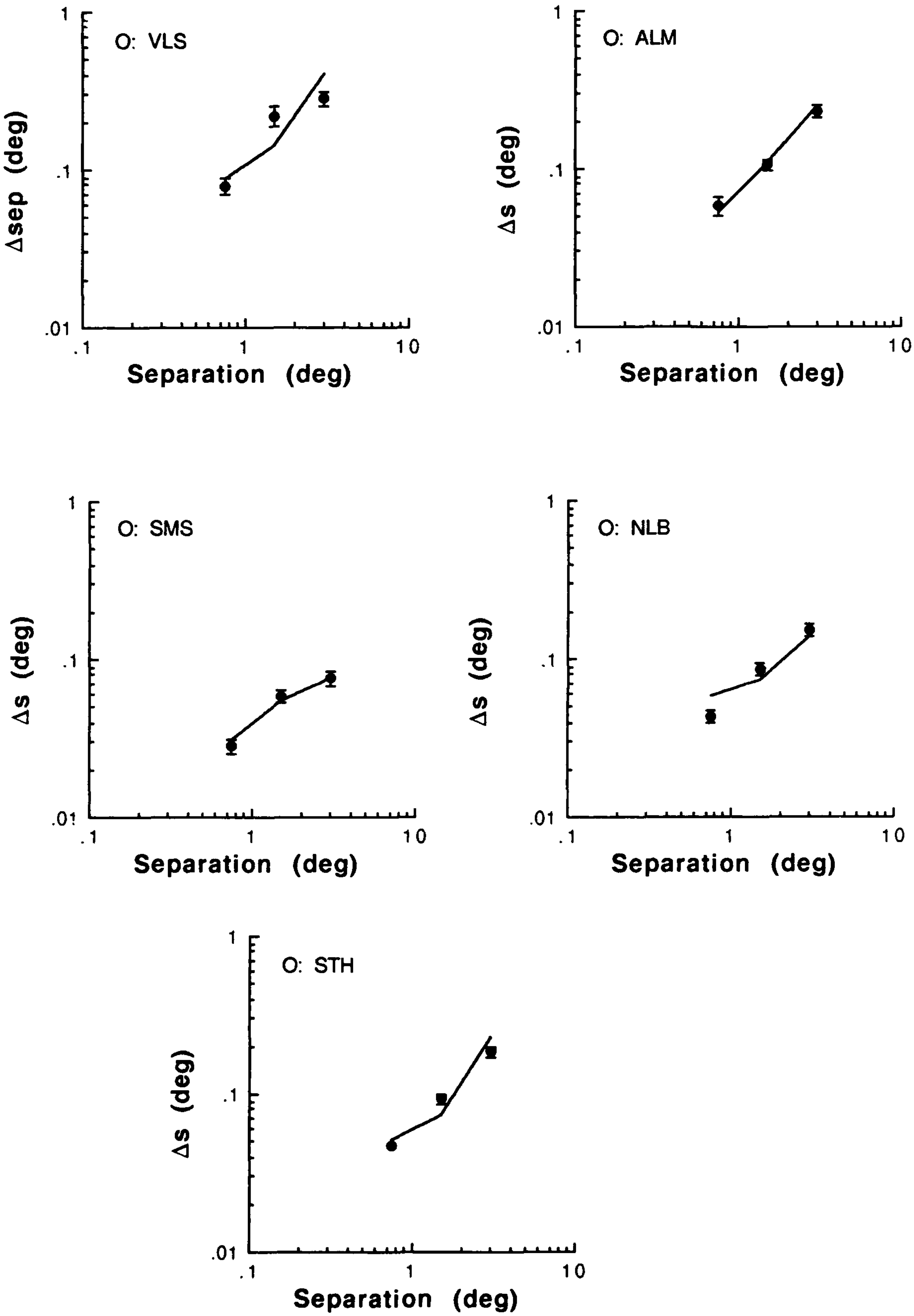

0.2
0.1
0.0
PSE(d)/d
1.5° Separation
O: NLB
0.0
0.5
1.0
1.5
Distance to Background Line (deg)


3.0° Separation
O: NLB
PSE(d)/d
0.2
0.1
0.0
-0.1
0
1
2
3
Distance to Background Line (deg)

8



O: STH
Δs (deg)
Separation (deg)
O: ALM
Δs (deg)
Separation (deg)
O: SMS
Δs (deg)
Separation (deg)
O: NLB
Δs (deg)
Separation (deg)
O: VLS
Δsep (deg)
Separation (deg)



O: VLS
Δsep (deg)
Separation (deg)
O: ALM
Δs (deg)
Separation (deg)
O: SMS
Δs (deg)
Separation (deg)
O: NLB
Δs (deg)
Separation (deg)
O: STH
Δs (deg)
Separation (deg)
1
.1
.01
.1
1
10

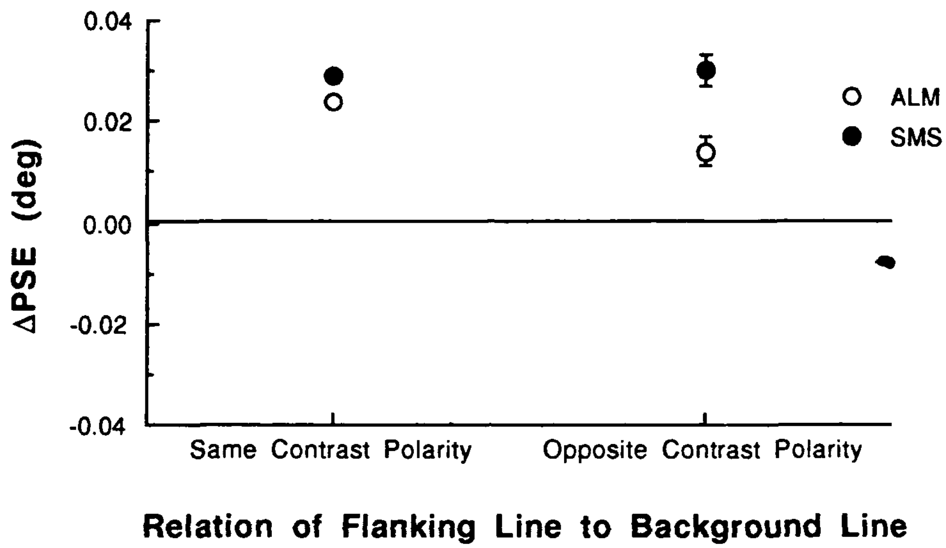

0.04
0.02
0.00
-0.02
-0.04
ΔPSE (deg)
ALM
SMS
Same Contrast Polarity
Opposite Contrast Polarity
Relation of Flanking Line to Background Line

Table 1. Gaussian Model Constants and Regression Coefficients (100 ms Data).

Observer	Separation	Sigma	Amplitude	R^2
ALM	0.75	0.63	.174	.944
	1.50	1.30	.153	.838
	3.00	2.94	.126	.742
NLB	0.75	0.82	.111	.894
	1.50	1.05	.189	.884
	3.0	1.92	.150	.899
SMS	0.75	0.65	.230	.978
	1.50	1.14	.142	.930
	3.00	1.59	.129	.870
STH	0 .75	0.78	.159	.968
	1.50	1.11	.098	.868
	3.00	3.33	.058	.759
VLS	0.75	0.52	.233	.979
	1.50	0.82	.411	.992
	3.00	2.38	.186	.791