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Detection and Identification of Mirror-image Letter Pairs in Central and Peripheral Vision

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Reading performance is poorer in the peripheral than in the central visual field, even after size-scaling to compensate for differences in visual acuity at the different eccentricities. Since several studies have indicated that the peripheral retina is deficient with respect to spatial phase discrimination, we compared the psychometric functions for detection (D) and identification (I) of size-scaled, mirror-symmetric letters (i.e. letters differing in the phase spectra of their odd symmetric components) at three inferior field eccentricities (0, 4, and 7.5 deg) using a two-alternative, temporal, forced-choice procedure and retinal image stabilization to control retinal locus. Each subject's data were fit with Weibull functions and tested for goodness-of-fit under several hypotheses. This analysis revealed that while the psychometric functions were of constant shape across eccentricity for the respective tasks, they showed statistically significant variations in the D/I threshold ratios. However, these variations were so small that poorer reading outside the fovea is unlikely to be due to reduced letter discriminability that might occur secondary to a loss of peripheral field phase sensitivity.

Reading Peripheral vision Detection Identification Phase

INTRODUCTION

Reading involves two initial activities, one motor and one sensory. The motor activity consists of a series of eye movements (saccades), the direction and magnitude of which are influenced by visual information from the text (McConkie & Rayner, 1975; Rayner & McConkie, 1975; O'Regan, 1990; Vitu, 1991). Between saccades, when the eyes are relatively motionless, the normally-sighted reader must acquire the necessary visual information for detecting and recognizing the word(s) fixated (i.e. 'foveated').

Numerous everyday activities depend upon our ability to perform this task which, from a visual perspective, should be quite effortless. Legge, Pelli, Rubin and Schleske (1985a) have shown that the visual requirements for normal reading are quite modest. When, however, the central visual field is compromised as a consequence of ocular disorder, this simple, everyday activity can become an inefficient and frustrating task for the individual (e.g., Faye, 1984; Legge, Rubin, Pelli & Schleske, 1985b; Cummings, Whittaker, Watson & Budd, 1985). Teaching a person with central field loss to read using peripheral vision often requires numerous hours of training and practice (Goodrich, Mehr, Quillman, Shaw & Wiley, 1977; Watson & Berg, 1983) and, even with the use of magnification to compensate for the poorer peripheral acuity, such training rarely results in restoring reading performance to the level achievable with a normal central visual field.

Two broad types of hypotheses, each corresponding to one of the initial component activities of reading, have been offered to explain the deficient performance associated with using peripheral vision. The oculomotor hypothesis attributes the problem to inadequate eye movement control (e.g. Whittaker, Budd & Cummings, 1988; Rubin & Turano, 1994). In oversimplified terms, an individual with a central field loss might persist in attempting to use saccadic eye movements to foveate words, even though this would result in the word being imaged within the non-seeing scotoma. However, measurements of reading using rapid serial visual presentation (RSVP) to eliminate the need for saccadic eye movements indicate that oculomotor factors cannot explain the entire deficit, either in patients with central field loss or in patients having other types of visual loss (Rubin & Turano, 1994).

The sensory hypothesis, in contrast, attributes the deficit to an inability of peripheral vision to perform complex pattern recognition (e.g. Rubin & Turano, 1994). In the case of patients having some type of ocular disorder, for example, peripheral retina reading rates might arguably be limited by subclinical field losses. However, it is unlikely that this version of the hypothesis would, by itself, suffice; reading performance was found to be deficient in the periphery of otherwise normal subjects (Turano & Rubin, 1988; Rubin & Turano, 1994).

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Another variant of the sensory hypothesis might attribute the problem to a difference in the resolution of central vs peripheral vision. For example, declines in letter acuity, grating acuity, and contrast sensitivity with increased eccentricity are well documented (e.g. Westheimer, 1982). However, such declines are clearly not sufficient to explain peripheral reading deficits as Rubin and Turano (1994), for example, found that reading rate declined with eccentricity even though text was size-scaled to normalize peripheral and and central field spatial contrast sensitivity values.

It is possible that the Rubin and Turano approach was, in principle, appropriate, but that their spatial scaling factor was inappropriate. While many peripheral visual thresholds can be normalized to foveal levels by spatial scaling (e.g. Virsu & Rovamo, 1979), there is, in fact, no scale factor that will normalize all peripheral thresholds to central field values (e.g. Westheimer, 1987). For this reason Levi, Klein and Yap (1987) have suggested that different types of visual tasks may be limited by different factors, with for example, conventional acuities being limited by retinal factors and positional acuities (e.g. vernier) being limited by cortical factors. Accordingly, reading might be better related to visual phenomena that decline faster with eccentricity than do conventional letter acuity or contrast sensitivity.

The 'crowding' effect offers one possibility. It is well known that visual acuity is better when the letters of the chart are presented in isolation than when presented with nearby contours (e.g. Stuart & Burian, 1962; Flom, Weymouth & Kahneman, 1963). There is evidence that the magnitude of the crowding effect may be greater in peripheral vision (e.g. Loomis, 1978; Jacobs, 1979). If true, it might imply that optimal spacing differs for central and peripheral vision. However, while there is some evidence that letter spacing may affect word recognition (Whittaker *et al.*, 1989; Arditi, Cagenello & Jacobs, 1995) and reading rate (Arditi, Knoblauch & Grunwald, 1990), there is not complete agreement on the importance of this factor (Legge *et al.*, 1985b).

Another potentially important variant of this hypothesis is that reading with peripheral retina may be constrained or limited by a loss of positional information. Evidence from several studies suggests that human observers are less certain about the spatial location of targets presented in the peripheral than central field (e.g. Pelli, 1981; Cohn & Wardlaw, 1985). Levi *et al.* (1987), for example, found a greater reduction in bisection acuity than grating acuity in the normal periphery and, also, in the central field of strabismic amblyopes. Their findings were consistent with a model that invokes cortical undersampling of stimuli as a means of producing positional uncertainty in these two visual systems. In general, the hyperacuities (e.g. vernier) decline 3–4 times faster than grating or Snellen acuities (e.g. Westheimer, 1982). Thus, the deficit observed by Rubin and Turano (1994) finds a closer parallel with the decline in position acuity than with that of resolution acuity.

The concept of position is frequently linked with the concept of phase in the Fourier domain. Moreover, several studies indicate that peripheral vision shows deficits in spatial phase discrimination relative to central vision (Braddick, 1981; Rentschler & Treutwein, 1985; Harvey, Rentschler & Weiss, 1985; Bennett & Banks, 1987). Further, sensitivity to spatial phase declines with eccentricity more rapidly than contrast sensitivity, i.e. at a rate similar to that of the positional acuities (e.g. Rentschler & Treutwein, 1985; Bennett & Banks, 1987). However, none of these studies examined the possible implications of phase anomalies for the generally slower reading rates characteristic of patients with central field loss (e.g. Legge *et al.*, 1985b) or for normal subjects using peripheral retina (Rubin & Turano, 1994). Phase deficits could, however, interfere with word recognition by interfering with (i) the processing of letter position information, as already noted, and/or (ii) the identification of individual letters of words.

How phase deficits would affect letter discrimination would, of course, depend on how the Fourier components of individual letters contribute to their discriminability. Gervais, Harvey and Roberts (1984), for example, found that among several models for predicting the confusability of uppercase letters, a spatial frequency model based on letter amplitude spectra weighted by the normal contrast sensitivity function accounted well for the data. Moreover, a model including phase as well as filtered amplitude information was superior to a model based on only amplitude information alone. Phase information could, for example, contribute to the discrimination of letters like 'M' and 'W', 'p' and 'q', or 'b' and 'd'. Members of such letter pairs have identical magnitude spectra and differ primarily in terms of the phase spectra of their odd symmetric components (horizontal components for the first pair of letters and vertical components for the latter two pairs).

We have attempted to evaluate the similarity of the mechanisms mediating detection and identification of alphabetic characters in the central and peripheral fields by using size-scaled mirror symmetric, lower case letters. Stimuli were scaled according to the procedure previously used by Rubin and Turano (1988, 1994). Specifically, this scale factor failed to normalize peripheral reading and, consequently, our objective was, in part, to determine whether this scale factor would also fail to normalize peripheral field detection/identification performance for mirror symmetric letters, i.e. differing in phase. By analyzing the psychometric functions for these tasks, we were able to distinguish between possible changes in precision, as reflected in the steepness of the psychometric function, and changes in the relative sensitivity of the processes mediating contrast detection (D) and identification (I), as reflected in the D/I threshold ratio.

METHODS

Subjects

The subjects were three normal observers, ranging in age from 26 to 50 yr; two were authors and the third was naive to the purpose of this experiment. All subjects had 20/20 or better visual acuity and normal visual fields.

Viewing conditions

Each subject was tested monocularly (right eye only) while viewing the stimulus field through the optics of a stimulus deflector unit (Crane & Clark, 1978). The latter contains two orthogonally-rotating mirrors which were driven by the horizontal and vertical eye movement signals from a Double Purkinje-image Eyetracker. These mirrors were used to produce the optical displacement of the stimulus field necessary to compensate for the subject's eye movements (Crane & Steele, 1978). To preclude accommodative fluctuations from influencing test results, each subject was administered a cycloplegic (1% cyclopentolate). Since this procedure also produced mydriasis, a 3 mm artificial pupil was used. Each subject was tested foveally and at two inferior field eccentricities, 4.0 and 7.5 deg. Head position was maintained by the use of a bite bar and forehead rest.

Stimulus generation and psychophysical procedure

A two-alternative temporal forced-choice procedure was used to measure detection and identification of the letters 'b' and 'd' at each of several contrast levels (e.g. Thomas, 1987). The subject indicated in which of two successive 50 msec time intervals a letter was presented and, in addition, identified which letter was presented.

Stimuli were presented on a Commodore Amiga 1084 RGB monitor and appeared as dark letters against a white background. The luminance of the white background of the stimulus field was 5 cd/m^2 after passing through the optics of the stimulus deflector unit. Stimulus letter height was 13 min arc for the foveal test distance (183 cm). Stimulus contrast values were selected to produce levels of correct detection and identification of from 50% (chance) to about 95–98% and so that identification judgments were nearly asymptotic. Stimulus size was scaled for the 4.0 and 7.5 deg eccentricities by decreasing the test distance to 81 and 54.7 cm respectively, i.e. by an amount that Virsu and Rovamo (1979) showed was necessary to normalize peripheral spatial contrast sensitivity to foveal values (see also Rubin & Turano, 1994).

Subjects were dark-adapted for 10–12 min prior to each session. Each subject was aligned in the eyetracker, allowed to light adapt for 2–3 min, and then required to make 100 judgments using a fixed contrast and eccentricity. Subsequent to a short rest, testing proceeded in similar fashion for each contrast level. Between six and nine contrast values were tested at each eccentricity, depending on the subject, with the procedure repeated two or three times for each subject and for each eccentricity. Thus each of the plotted points in figures 1–3 was based on a minimum of 200 judgments.

In summary, for each of three eccentricities, a pair of frequency-of-seeing functions was generated for each subject. One member of each pair represented performance on the detection task as a function of contrast. The other member represented performance on the identification task over the same range of contrasts.

RESULTS

Figure 1 shows the proportion correct detection (○) and identification (●) for one subject at one eccentricity. Chance performance (50%) is shown by the dashed, horizontal line. The identification data showed a shallower psychometric function relative to that for detection, a result similar to that reported by Knoblauch (1995) for the detection and identification of color. The higher threshold for identification was also a regular feature in our data and probably indicates that additional processing is required to make identification judgments.

The critical question to be answered in the subsequent analysis is whether similar differences in slope and threshold are obtained at two additional eccentricities tested for each subject and using the size-scaled stimuli. The frequency-of-seeing data for each subject at the three eccentricities were fit with Weibull functions and then tested for goodness-of-fit under three hypotheses described below. These fits were carried out using a maximum likelihood procedure described previously by Watson (1979) and a minimization routine (Chandler, 1965). The solid lines in Fig. 1 represent one such fit. Since this was a two-alternative forced-choice procedure, a function of the following general form was used:

$$f(\alpha) = 0.5 + 0.5*\exp[-(\alpha/\alpha_o)^\beta]*(1-\delta),$$

where α is the contrast; α_o is the contrast at which f is approximately $(1-\delta) \times 0.81$, i.e. threshold for detection or identification respectively; β is a steepness parameter related to the slope; δ is an 'attentional' factor.

We define the D/I threshold ratio as α_d/α_i. The attentional factor was introduced to account for the fact

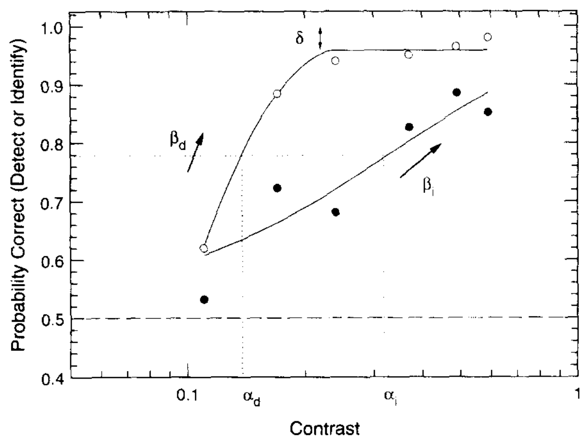

FIGURE 1. Probability correct detection (○) and identification (●) as a function of contrast for one subject under foveal viewing conditions. The solid curves represent Weibull functions to which the respective sets of data were fit. The "attentional" parameter is indicated by δ and the "steepness" parameter by β. The respective threshold contrasts for detection and identification are designated along the abscissa by α_d and α_i and represent the log contrast values (vertical dashed lines) required to produce a criterion response level after correction for the attentional factor, δ.

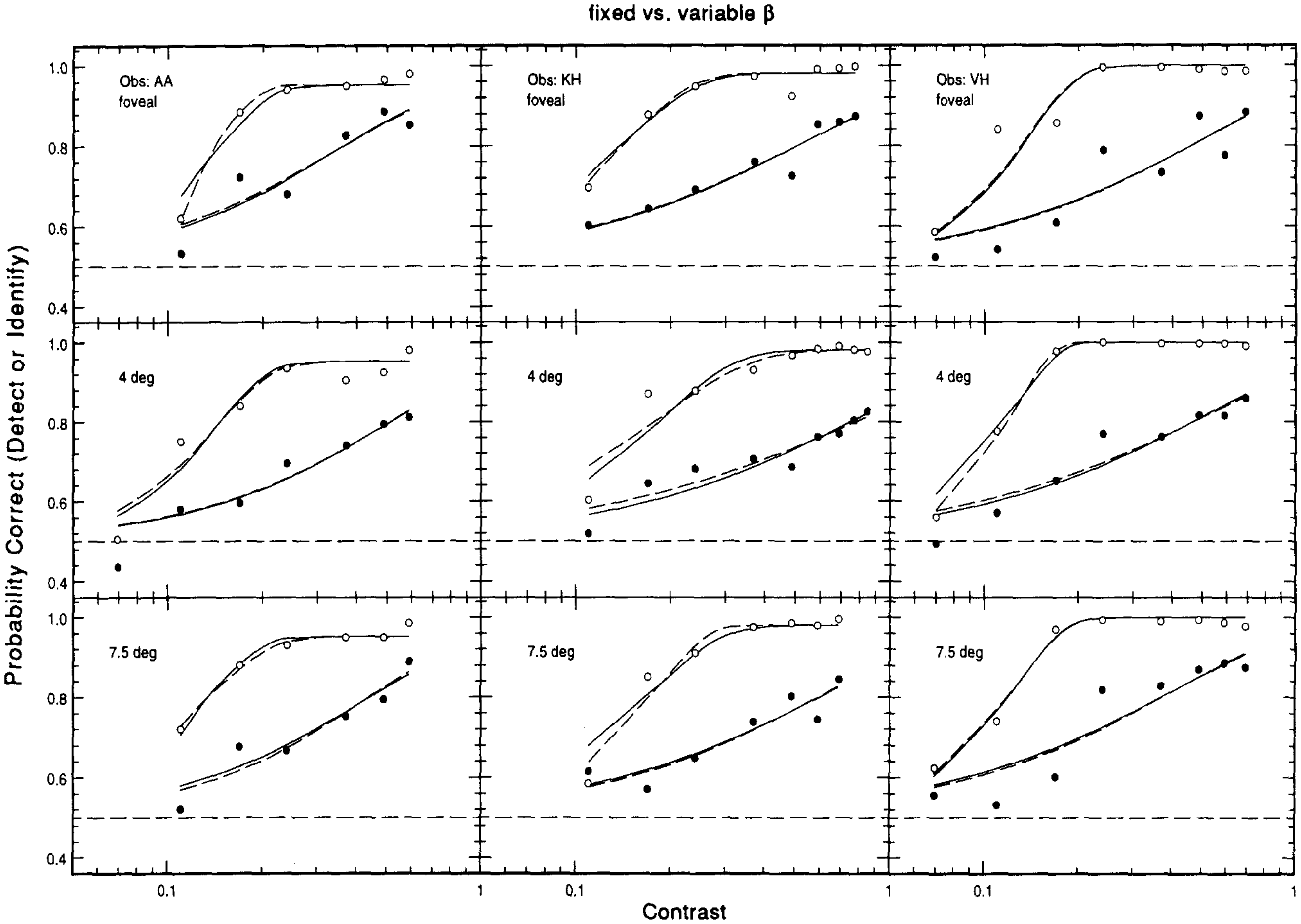

FIGURE 2. Comparison of fits to Weibull function across eccentricities under Hypothesis 1 (βs and αs free to vary across eccentricities and tasks) vs Hypothesis 2 (β constant within task and across eccentricities) for each of the three subjects, with each column representing a different subject. Here, as in Figs 1 and 3, ○ represent detection results and ● represent identification results. The dashed curve represents the fit under Hypothesis 1 and the solid curve represents the fit under Hypothesis 2. Values of the attentional and steepness parameters δ and β, obtained from the fit provided by Hypothesis 2 for each subject are given in Table 2. See Table 1 for a summary of results of statistical comparison of goodness-of-fit illustrated in this figure as well as in Fig. 3.

that the psychometric functions did not reach 100% at the highest contrast levels used. There were a number of reasons for this. Occasionally, for example, a subject would indicate 'interval 1' (or 'b') when (s)he meant to indicate 'interval 2' (or 'd'), or vice versa. For each subject, however, the value of δ was held constant across tasks and eccentricities. Holding δ constant produced satisfactory fits with values of δ that were always less than 10% (see Table 2). Since δ was held constant across eccentricity and task for a given subject, the primary interest in this analysis concerns possible changes across eccentricity in the two parameters that are free to vary, i.e. the βs and the αs for detection and identification.

Figure 2 shows the results of fitting the data at the three eccentricities for each of the three subjects under two hypotheses. Columns represent subjects and rows represent eccentricities. Under Hypothesis 1 (dashed curves), all of the parameters of the psychometric function were free to vary across tasks and eccentricity, except for the attentional parameter, δ. Under Hypothesis 2 (solid curves), the slopes of the psychometric functions were constrained to be constant within tasks (D or I), while the D/I threshold ratio was allowed to vary. Although visual inspection of Fig. 2 appears to show slight differences between the fits provided by the two hypotheses, Table 1 indicates no significant differences in the goodness-of-fit for any of the three subjects. These results are thus consistent with the view that the precision of judgments

TABLE 1. Results of statistical comparison of hypotheses by subject

	Subject		
	VH	AA	KH
Hypothesis 2 vs Hypothesis 1			
χ^2	5.62	6.72	7.045
d.f.*	4	4	4
$P =$	0.23	0.15	0.134
Hypothesis 3 vs Hypothesis 2			
χ^2	10.302	9.02	14.3
d.f.*	2	2	2
$P =$	0.006	0.00078	0.01

*The indicated d.f. correspond to the difference in d.f. (in number of free parameters) under the two hypotheses being tested. For Hypothesis 1, 13 values are free to vary (6 αs, 6 βs, and 1 δ for each subject). For Hypothesis 2, only 9 of these values are free to vary as there are only 2 βs under this hypothesis. This corresponds to a difference of 4 d.f., as indicated above. For Hypothesis 3, 7 parameters are free to vary (3 αs, 2 βs, 1 δ, and 1 D/I threshold ratio).

TABLE 2. Weibull parameters, β and δ, from fit using Hypothesis 2

Parameter	Subject		
	VH	AA	KH
$\beta_{detection}$	2.58	2.54	1.78
$\beta_{identification}$	0.99	1.25	0.98
δ*100%	1.7%	9.5%	4.0%

was constant across the range of eccentricities tested for these size-scaled stimuli. Table 2 gives values β of and δ for each subject, as derived from the fit carried out under Hypothesis 2.

Figure 3 compares the fit under Hypothesis 2 with that of a third hypothesis having the added constraint that the threshold ratio, α_d/α_i, was constant across eccentricity. As in Fig. 2, the fits provided by Hypothesis 2 (constant βs) are illustrated by the solid curves. The fits provided by Hypothesis 3 (constant βs and constant α_d/α_i) are shown by the dashed curves. We compared the goodness-of-fit under Hypothesis 3 with that under Hypothesis 2; Hypothesis 3 was rejected for all three subjects (see Table 1). Thus, while the slopes of the functions for the respective tasks were constant across eccentricity, the D/I threshold ratios varied significantly.

Figure 4 shows the magnitude of the variation in the D/I threshold ratio across eccentricities for each of the three subjects. These ratios were computed for each subject from the fit provided by Hypothesis 2. It is important to note that while the data do not fall on perfect horizontal lines, as would have been predicted by Hypothesis 3, there did not appear to be any systematic trends across subjects. It should also be noted that the largest magnitude of within-subject change in the D/I ratio was, in absolute terms, small.

DISCUSSION AND CONCLUSION

These results are generally consistent with an accumulating body of evidence indicating that many of the differences between peripheral and central visual thresholds can be resolved by the application of an appropriate spatial scaling factor (e.g. Virsu & Rovamo, 1979; Thomas, 1987; Farrell & Desmarais, 1990; Saarinen, Rovamo & Virsu, 1989). In the present study, we used a scaling factor that previous researchers had shown was sufficient to normalize peripheral contrast sensitivity to central field values. This same scale factor was sufficient, on average, to normalize peripheral field detection and identification of mirror-symmetric, lowercase letters to central field performance levels.

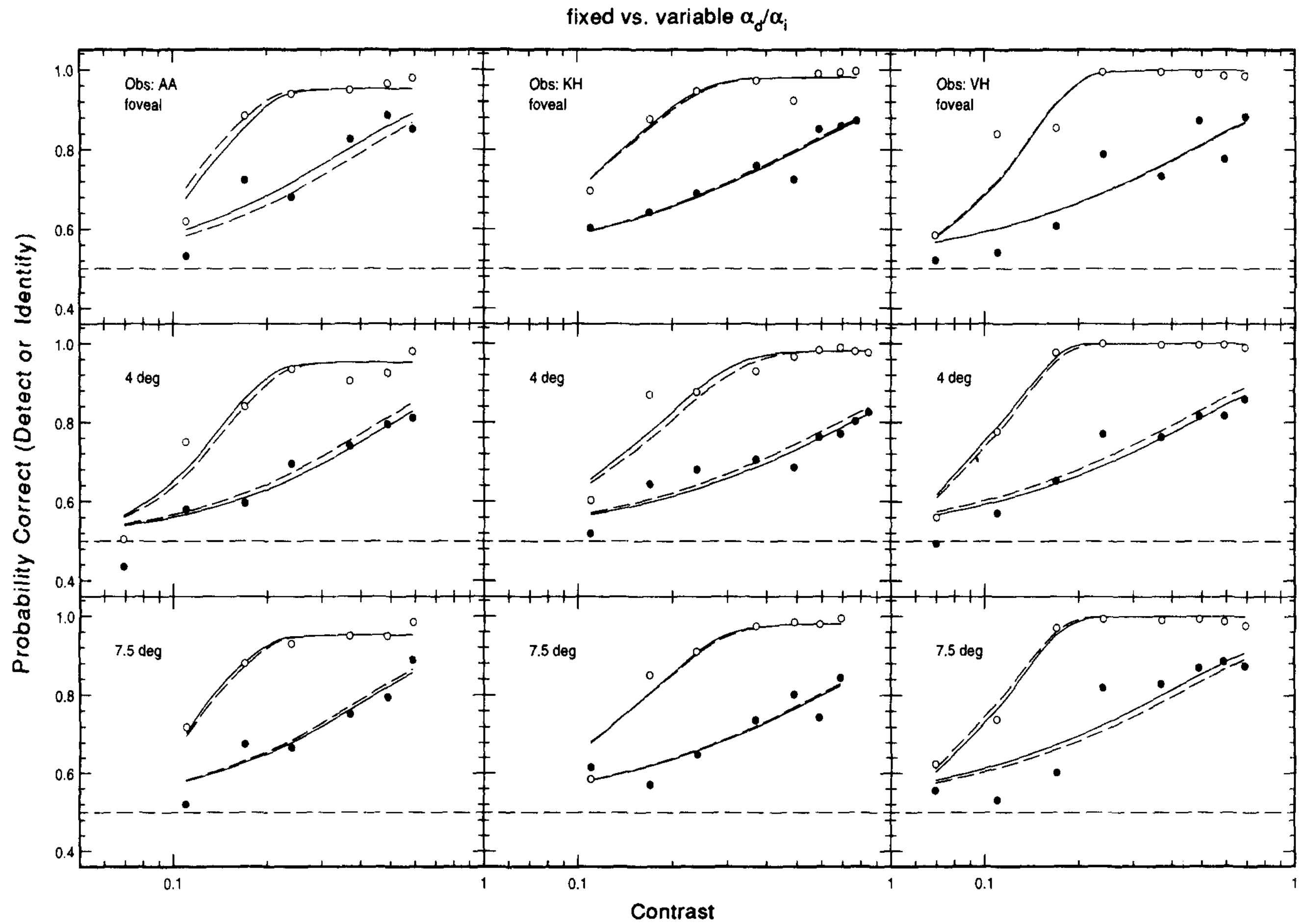

FIGURE 3. Comparison of fits to Weibull function across eccentricities under Hypothesis 2 (β constant within task) vs Hypothesis 3 (β constant within task and across eccentricity and, in addition, D/I threshold ratio constant across eccentricity). As in Fig. 2, the solid curve represents the fit under Hypothesis 2; the dashed, smooth curve represents the fit under Hypothesis 3. See Table 1 for summary of statistical results.

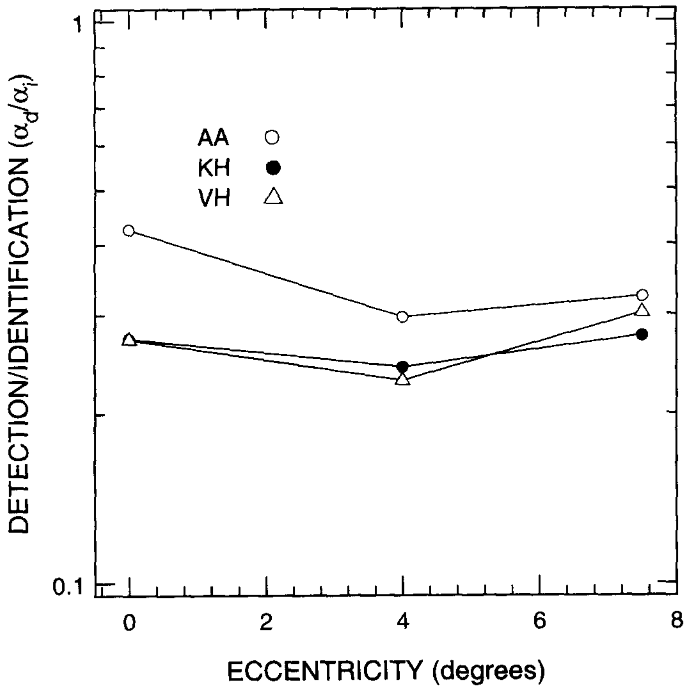

FIGURE 4. Change in D/I threshold ratio across eccentricity. The D/I threshold ratio was calculated for each subject from the fit provided by Hypothesis 2. The magnitude of the ratio for each subject and eccentricity corresponds to the lateral separation of the respective solid curves in Figs 2 and 3.

In a previous investigation of spatial frequency and orientation discrimination across eccentricity, Thomas (1987) reported trends analogous to those described here. Thus, while he obtained results that were, on average, consistent with the view that the major change from central to peripheral vision was a change in spatial scale, he also found that results for individual subjects showed statistically reliable, but unsystematic, changes with eccentricity. This latter result finds a ready parallel in the rejection of Hypothesis 3 which was predicated on constancy of the D/I ratio as well as constancy of the slope factor, β. However, it should also be noted that the magnitude of within-subject variation in the D/I ratios was small in absolute terms, with the largest magnitude in Fig. 4 corresponding to the smallest magnitude of within-subject variation observed by Thomas (1987, Fig. 3). Whether the observed departures from strict constancy of the D/I ratio we observed were due to the use of a single 'average' spatial scaling factor for all subjects is not known. More importantly, there was no consistent trend in the D/I threshold ratio that would offer a viable quantitative parallel for the marked decline (approaching 1 log unit) in peripheral retina RSVP reading rate in normal subjects over the same range of eccentricities (cf. Rubin & Turano, 1994, Fig. 8).

These results might seem at odds with previous studies such as that of Bennett and Banks (1987). The latter, for example, reported a selective loss in the discriminability of mirror-symmetric compound gratings (i.e. compound gratings differing by 90–270 deg of relative phase), a finding that they concluded was consistent with a selective loss in sensitivity of odd-symmetric mechanisms with increasing eccentricity. More recently, however, Morrone, Burr and Spinelli (1989) used stimuli which, while one-dimensional, were more complex and found no evidence of a selective decline in phase sensitivity. Their stimuli consisted of the sum of 256 vertically-oriented cosine harmonics. The harmonics were added in different phases to produce pairs of contrast-reversed patterns having 'edge-like' (90 and 270 deg) or 'line-like' (0 and 180 deg) features (Burr, Morrone & Spinelli, 1989). Morrone *et al.* (1989) found that the discriminability of the pairs was as good in the periphery as it was in the fovea. Thus, the use of a spatial scaling factor that was sufficient to equate peripheral contrast sensitivity and grating acuity to central-field values was also sufficient to equate peripheral and central phase sensitivity for these more complex stimuli.

Bennett (1992) has also suggested a possible means of resolving the discrepancy between results of studies using the narrow-band vs broad-band stimuli, with only the former suggesting a selective loss in phase sensitivity with eccentricity. Specifically, Bennett argued that both types of stimuli can be thought of as an array of spatial features such as lines and edges. In the case of gratings, the size and separation of the features capable of mediating discrimination are correlated such that the features typically abut spatially. Thus, it is possible that closer proximity of features capable of mediating the 90–270 deg phase shift discrimination may have rendered it selectively more vulnerable to the deleterious effects of lateral masking or crowding. This would not necessarily be the case for the Morrone *et al.* type of stimulus pattern where the feature size and separation can be independently varied. Using the latter type of stimuli, Bennett (1992) found that peripheral thresholds for the 90–270 and 0–180 deg stimuli rose at the same rate as feature separation was decreased.

The stimuli used in the present study are more similar to those of Morrone *et al.* than to those in studies using compound gratings. Mirror-symmetric letters of the same contrast polarity contain an identical and broad spatial frequency representation where the phase of only the vertical odd components differ by 180deg (e.g. Bracewell, 1986). Moreover, for these stimuli, like those of Morrone *et al.*, the use of a spatial scale factor sufficient to equate central and peripheral contrast and phase sensitivity was sufficient to produce generally similar detection/identification performance at the different eccentricities for mirror, symmetric letters.

In conclusion, these results argue against the hypothesis that poorer reading performance outside the fovea is due to reduced letter discriminability secondary to peripheral-field phase sensitivity loss. Instead they suggest that other factors are more likely responsible for the decline in peripheral retina reading rate described by Rubin and Turano (1994). The crowding phenomenon may represent a more important source of confusion in letter discriminability in the periphery. Rubin and Turano have shown that reading rate appears to decline at a faster rate with eccentricity than does conventional acuity and, as noted in the Introduction, there is evidence to suggest that the magnitude of the crowding phenomenon may be disproportionately greater in peripheral vision. However, the significance of the crowding phenomenon to the deficient reading performance characteristic of peripheral retina is, as yet, unknown.

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