

The Two-Dimensional Shape of Spatial Interaction Zones in the Parafovea

ALEXANDER TOET,* DENNIS M. LEVI†

Received 3 September 1991

NOTICE: This material may be protected
by copyright law (Title 17 U.S. Code)

The spatial analysis of a target may be strongly degraded by the simultaneous presentation of nearby pattern elements. The present study investigated the shape and extent of the region of interaction as a function of retinal location. The stimuli consisted of 3 collinear Ts which were randomly oriented up (T) or down (⊥). The task was to discriminate the orientation of the middle T. The retinal locations studied were at 0, 2.5, 5 and 10°, on the lower vertical meridian and on the nasal halves of both the horizontal and the 45° diagonal visual field meridians. The extent of the interaction region was defined as the separation between the midpoint of two adjacent Ts that resulted in 75% correct discrimination. The shape of the interaction region was determined by using several orientations (horizontal, vertical, left diagonal and right diagonal) for the virtual line joining the 3 Ts. Our results show that the size of the interaction regions varies linearly with eccentricity as does the size of a just resolved individual T. However, the size of the interaction region varies much more rapidly than does the resolution threshold for an individual T. The spatial interaction zones appear to be elongated radially, so that they have an elliptical shape. The size of the major axis is about 2–3 times the size of the minor axis. The major axis is along the meridian through the central visual field (i.e. it is oriented radially) while the minor axis is oriented tangentially (i.e. isoeccentrically).

Acuity Target crowding Spatial interference Periphery Eccentricity scaling Cortical magnification

INTRODUCTION

Letter recognition and visual acuity are profoundly influenced by the presence of nearby contours (Ehlers, 1936; Woodworth, 1938; Flom, Weymouth & Kahneman, 1963b; Bouma, 1970; Jacobs, 1979). In the normal fovea, recognition scores are reduced when simultaneously presented flanking targets are within a visual angle of about 3–5 arc min of the target letter. Spatial interactions of this sort occur under a wide range of conditions and tasks, including Vernier acuity (Westheimer & Hauske, 1975; Levi, Klein & Aitsebaomo, 1985; Williams & Essock, 1986), stereo-acuity (Butler & Westheimer, 1978; Westheimer & Levi, 1987; Westheimer & Truong, 1988), and orientation discrimination (Andriessen & Bouma, 1976; Westheimer, Shinamura & McKee, 1976). These adverse spatial interaction effects are sometimes called “contour interaction” or “crowding” and they appear to be ubiquitous in spatial vision. Thus, a complete description of these interactions is essential to our understanding of spatial analysis.

It has long been known that visual acuity varies with eccentricity. Aubert and Foerster (1987) demonstrated that visual acuity declines in an orderly fashion with

eccentricity. This important observation has often been repeated and has been extended to a multiplicity of tasks over the years (see e.g. Weymouth, 1958; Genter, Kandell & Bedell, 1981; Levi *et al.*, 1985). The importance of the gradients of performance is that they may provide clues as to the structures at various levels of the visual pathways which limit performance. Indeed, one of the reasons Polyak gave for undertaking his classical study of the retina was to obtain a better understanding of the “striking difference between the central and the peripheral acuity” (Polyak, 1941). Weymouth (1958) was perhaps the first to recognize that for a wide range of pattern discrimination tasks (including visual acuity), visual performance varies approximately linearly with eccentricity, as do many of the anatomical and physiological functions thought to constrain performance. The approximately linear variation in structure and function with eccentricity implies that many visual functions may be equated in central and peripheral vision by applying a scale factor F of the form: $F = 1 + E/E_2$, where E is the eccentricity of the stimulus, and E_2 is eccentricity at which the foveal function value is doubled. E_2 is a scale-free factor, which captures the rate at which structure and function vary with eccentricity (Levi *et al.*, 1985; Yap, Levi & Klein, 1987a, b).

The range of spatial interactions also varies with eccentricity (Bouma, 1970; Jacobs, 1979), and one viewpoint is that spatial interactions are more extensive in the periphery than in the fovea. For example, Jacobs (1979) showed that when four flanking bars were placed around

*Institute for Perception TNO, Vision Group, Kampweg 5, 3769 DE Soesterberg, The Netherlands.

†University of Houston, College of Optometry, 4901 Calhoun Boulevard, Houston, TX 77204-6052, U.S.A.

a Landolt C target, visual acuity decreased more rapidly with eccentricity than for unflanked targets (i.e. E_2 changed from about 1.9 to 0.7 deg), and that contour interaction was stronger in the periphery than in the fovea (see also Flom, 1991). Bouma (1970) estimated that the range of spatial interactions for letter recognition in peripheral vision may be as large as half the target letter eccentricity. Recently, Strasburger, Harvey and Rentschler (1991) suggested that for low contrast letters, the fovea and periphery are qualitatively different, since they found strong crowding in the periphery, but no crowding in the fovea.

A different point of view is that contour interaction in the periphery is qualitatively similar in foveal and peripheral vision, differing only by a scale factor. For example, Levi *et al.* (1985) suggested that the extent of spatial interaction in Vernier acuity is approx. $0.1 E/E_2$ at all eccentricities. For Vernier acuity both the unflanked Vernier acuity, and the range of spatial interactions vary with eccentricity at the same rate (doubling at about 0.7 deg). This "scaling" hypothesis also receives support from the work of Flom *et al.* (1963b). They showed that in both normal foveal vision, and in amblyopic eyes, the extent of spatial interaction is proportional to the observers minimal angle of resolution. Is spatial interaction in letter recognition qualitatively similar in the fovea and peripheral vision? One hint that it might differ comes from Bouma (1970), who suggested that the zone of spatial interaction may be elliptical in the periphery. However, to date, we know of no quantitative analysis of the two-dimensional shape of the zone of spatial interactions across the visual field. Thus, the purpose of the present study was to map out, in detail, the shape of the zone of spatial interaction in both central and peripheral vision.

METHODS

Subjects

Four male and two female observers, aged between 24 and 34, participated in the experiments reported below. Subjects AT (one of the authors), JT, MS and YS are highly trained. Subjects AT, JT, JE and YS are myopic, and wore either spectacles or contact lenses with appropriate foveal refractive correction. Subject MS is emmetropic. All subjects practiced the tasks prior to data collection.

Apparatus and stimuli

An Atari 1024 ST microcomputer was used to generate, process and present the stimuli, record the responses and analyze the data.

The stimuli consisted of one or more Ts against a homogeneous background. The orientation of the Ts was randomly chosen and could be either normal (T) or upside-down (\perp).

The stimuli were displayed on an Atari SM124 high resolution monochrome monitor with Paper White phosphor. The display consisted of 400×640 pixels in

a screen size of $20.5 \times 12.7 \text{ cm}^2$. The background luminance was 71 cd/m^2 .

Acuity thresholds were determined by scaling the size of a single T target and measuring the target size required for 75% correct responses. The size of the Ts in all other experiments was 1.5 times this threshold size.

Viewing conditions

The experimental setup was placed in a brightly illuminated room with nonreflecting white walls. The monitor screen was placed behind a circular opening in a large white cardboard screen. The cardboard screen was indirectly illuminated and matched the monitor screen both in illuminance and color. The continuously present fixation point was a black dot that was either on the monitor screen or on the cardboard surround.

Observers were seated with their heads supported by a head rest, adjusted in height and position so that their dominant eye was on the line perpendicular to the fixation dot. Viewing was monocular with the subject's dominant eye. The unused eye was covered with a black eye cap.

The eccentricities studied were 0, 2.5, 5 and 10° . The retinal locations studied were situated on the lower vertical meridian and on the nasal halves of both the horizontal and the 45° diagonal visual field meridians. They were measured from the center of the stimulus configuration.

Procedure

After having adapted to the background luminance level the subject started a run by pressing a digital switch. A warning tone indicated the on- and offset of each stimulus presentation, which lasted 0.15 sec. After completion of a presentation the subject had to report (forced choice) his/her decision for the task at hand to the computer by pressing the appropriate one of two response buttons. Auditory feedback was given after each trial (a high tone for a correct response, and a low tone for an incorrect response). The observers' response initiated a new presentation, following a 0.25 sec delay. By withholding the answer for a while the observer was able to take a short rest.

Because both target orientation (up or down) were equiprobable, the proportion of correct discriminations was 50% when the observer performed at a chance level. At each retinal location studied we measured the percentage of correct responses as a function of the size of the T target. The results were plotted and the pattern size required for 75% correct responses was estimated graphically by interpolation or by Probit analysis (Finney, 1971). Each datum is based on at least 600 trials. The error bars indicated by Probit analysis are typically 10% or less.

T-acuity

The T stimulus we used was constructed from two bars ($| + -$) of equal length. In the T-acuity experiments we adopted the length of these bars as the characteristic

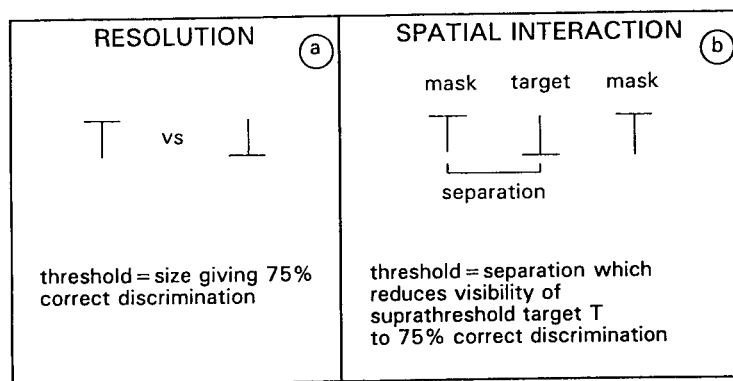


FIGURE 1. (a) Stimulus used to test single T-acuity. (b) Stimulus used to test 3T-interaction.

spatial parameter, i.e. as the size of the T target see Fig. 1(a)].

3T-interaction

For the spatial interaction experiments the target was a T whose size was approx. 1.5 times the resolution threshold in isolation (determined for each subject individually and giving approx. 90% correct identification). The interacting targets were a pair of Ts (of the same size as the target) which flanked the target [see Fig. 1(b)]. The distance between the target and flanks was varied, and the percentage of correct responses were plotted. The target-to-flank distance for 75% correct responses was estimated graphically, or by Probit analysis. Thus, the zone of spatial interaction represents the distance between the midpoints of the vertical bars of two adjacent Ts which reduces the visibility of the target to 75% correct discrimination.

RESULTS

Experiment 1: spatial resolution thresholds as a function of eccentricity

The lefthand panels in Figs 2, 3 and 4 shows the T-acuity thresholds (i.e. the size required for a single T to obtain 75% correct answers) for an exposure duration of 0.15 sec as a function of retinal eccentricity along the lower vertical meridian. Figures 2 and 3 are the data of AT and JT, and were obtained in Soesterberg and Houston respectively. For each observer, the resolution thresholds show the usual increase with eccentricity that is commonly found for spatial acuity tasks (Wertheim, 1894; Weymouth, 1958; Jacobs, 1979). The lines shown in Figs 2 and 3 represent the best fitting non-linear regression lines of the form:

$$T = T_0(1 + E/E_2) \quad (1)$$

where T_0 is the foveal threshold, E is the target eccentricity and E_2 is the eccentricity at which the threshold reaches twice the foveal value (see Table 1). The E_2 values vary from 1.1 (for JT) to 2.4 (for MS), with a mean of approx. 2 deg, consistent with both the mean and the range of E_2 values found previously for resolution tasks (e.g. Weymouth, 1958; Genter *et al.*, 1981; Rovamo & Virsu, 1979; Levi *et al.*, 1985). Increasing the exposure duration to 0.5 sec resulted in slightly better

resolution at all eccentricities. However, the rate of fall-off remained essentially unchanged. These findings are in agreement with the results from previous studies (Saarinen, 1988). The left panel in Fig. 4 shows the resolution thresholds of each of the 6 observers, and the lines show the computer fits to three of the 6 data sets (i.e. the data sets with the highest and lowest E_2 values).

Experiment 2: spatial interaction regions as a function of eccentricity

The righthand panels of Figs 2 and 3 show how the zone of spatial interaction (i.e. the separation required between three collinear Ts to obtain 75% correct answers) varies as a function of retinal eccentricity along the lower vertical meridian for observers AT and JT. The zone of spatial interaction was estimated for both horizontal (solid circles) and vertical (solid squares) alignment of the 3 individual Ts. Pilot measurements showed no interaction effects for 2T configurations. This is contrary to Bouma's (1970) observation. However, the absence of interaction effects has also been found for orientation discrimination (Westheimer *et al.*, 1976) and for Vernier acuity (Badcock & Westheimer, 1985).

It is important to note the difference in scales of the left and righthand panels in Figs 2 and 3. While resolution thresholds are <0.25 deg at an eccentricity of 10 deg, the zone of spatial interaction may be 25 times larger. To emphasize this point, the resolution data from the left panels of Figs 2 and 3 are replotted (open circles) in the righthand panels. These figures show the following three main points:

(1) The zone of spatial interaction shows a much steeper increase with eccentricity than the T-acuity thresholds. The lines in Fig. 1 represent the best fitting

TABLE 1. E_2 values (deg)

Observer	Resolution	Horizontal zone	Vertical zone
AT	2.37 ± 0.28	0.41 ± 0.03	0.17 ± 0.01
JE	2.06 ± 0.28	0.35 ± 0.04	0.13 ± 0.01
JT	1.18 ± 0.09	0.25 ± 0.06	0.11 ± 0.01
JW	2.17 ± 0.41	0.39 ± 0.06	0.17 ± 0.02
MS	2.42 ± 0.26	0.43 ± 0.05	0.16 ± 0.02
PB	2.06 ± 0.22	0.23 ± 0.03	0.32 ± 0.02
Mean	2.04 ± 0.19	0.34 ± 0.04	0.18 ± 0.03

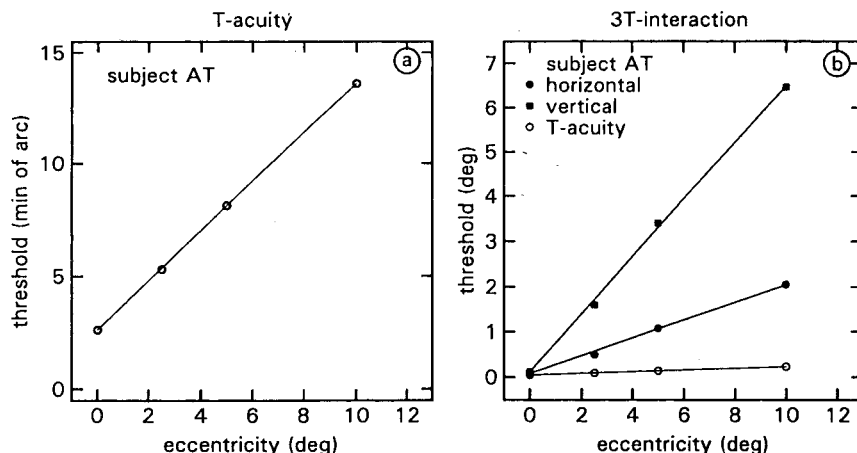


FIGURE 2. (a) The single T-acuity thresholds (i.e. the size required for a single T to obtain 75% correct answers) as a function of retinal eccentricity along the lower vertical meridian. (b) The 3T-interaction thresholds (i.e. the separation required between 3 collinear Ts to obtain 75% correct answers) as a function of retinal eccentricity along the lower vertical meridian and for 2 different orientations (horizontal and vertical) of the virtual line joining the centers of the 3 individual Ts. The resolution data from (a) are replotted here to show the difference in scale between the interaction and resolution thresholds. The results are shown for an exposure duration of 0.15 sec and for subject AT. The lines represent the best fitting non-linear regression lines of the form $T = T_0(1 + E/E_2)$ (see text).

lines using equation (1). As can be seen in Table 1, the E_2 values for the horizontal and vertical interaction zones are very much smaller than the corresponding values for resolution, indicating that the interaction regions grow much more rapidly with eccentricity than the acuity threshold size.

(2) Any simple notion of resolution scaling seems implausible; for example, while the size of the zone of spatial interference is approximately twice the resolution threshold in the fovea, it is about 10 times the resolution threshold at 10 deg when the flanks are oriented horizontally, and about 30 times, when the flanks are oriented vertically. The righthand panel of Fig. 4, and Table 1 shows that these effects, while varying quantitatively between individuals, are quite general.

(3) There is a strong anisotropy in the size of the zone of spatial interaction in the periphery. In the lower visual field the zones are considerably larger when the flanking Ts are above and below the test T (i.e. vertical alignment) than when the flanking Ts were on either side of

the test T (i.e. horizontal alignment). Since there is little anisotropy in the fovea, the zone of interaction increases with eccentricity at about twice the rate for vertical compared to horizontal alignment of the 3 Ts target. This can be clearly seen in Table 1, where the E_2 value is approx. 0.4 deg for the horizontal dimension of the zone of interaction, compared with 0.2 deg for the vertical dimension.

Thus, in contrast with the approximately circular foveal interaction regions (see Fig. 5), we find a strong anisotropy in the size of the interaction region in the lower visual field. The 3T-interaction extent thresholds for vertically aligned Ts are always about 2 times larger than the thresholds obtained for horizontally aligned Ts. This effect is reminiscent of Yap *et al.*'s (1987b) finding that isoeccentric bisection is better than radial bisection and Koenderink and van de Grind's (personal communication) result that isoeccentric motion detection thresholds are lower than radial thresholds.

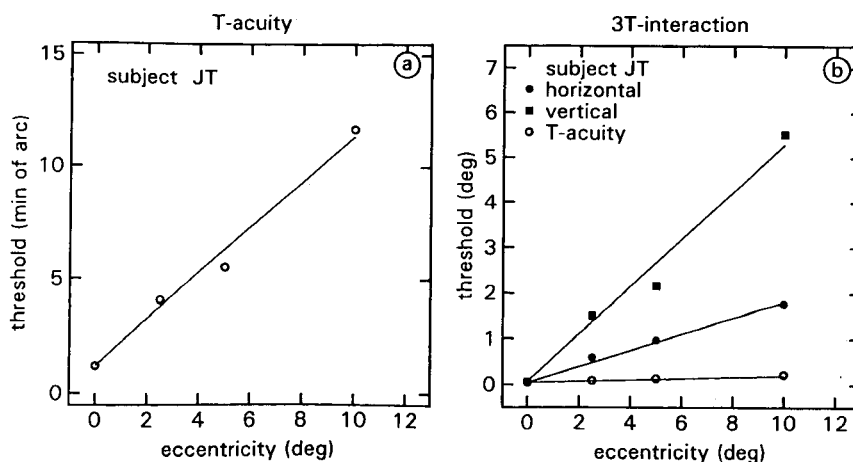


FIGURE 3. As Fig. 2 for the subject JT.

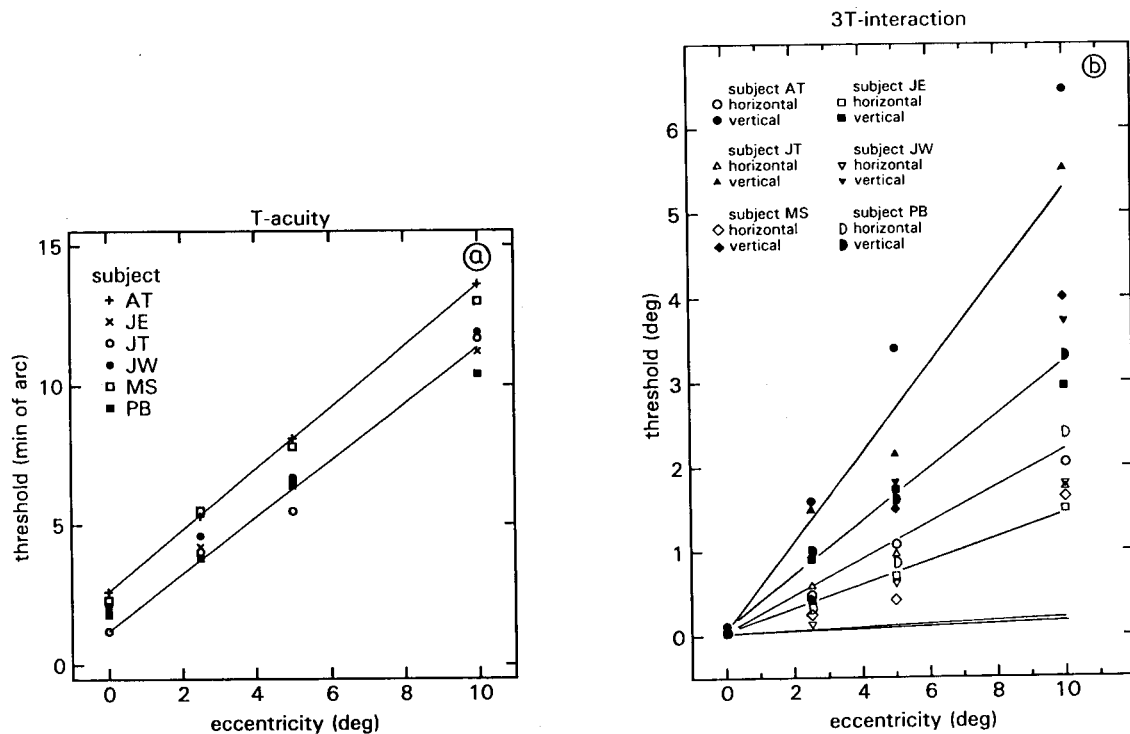


FIGURE 4. As Fig. 2 for all 6 subjects. The lines represent the best fitting nonlinear regression lines with extremal E_2 values, in (a) and from top to bottom for respectively the minimal and maximal E_2 values for the resolution data, and in (b) and from top to bottom for respectively the minimal and maximal E_2 values for the vertical interaction data, the minimal and maximal E_2 values for the horizontal interaction data, and the minimal and maximal E_2 values for the resolution data from (a).

Experiment 3: the shape of spatial interaction regions as a function of retinal location

The results of Experiment 2 suggest an elliptical form for the 3T-interference regions, as already hinted at by Bouma (1970). To test this assumption we performed an experiment to determine the shape of the 3T-interaction regions as a function of eccentricity and retinal location. In this experiment we measured the size of the zone of spatial interactions in the direction of the horizontal, vertical, left diagonal and right diagonal. The retinal

locations studied were at 0, 2.5, 5 and 10° on the lower vertical meridian and on the nasal halves of both the horizontal and the 45° diagonal visual field meridians.

Figure 5 shows the two-dimensional region of interaction in the fovea of each of our 6 subjects. Note that the foveal interaction region is approximately circular and has a radius of about 0.06 deg (3.6 min arc).

Figure 6 shows the spatial interaction zones superimposed on the visual field and for each of the 6 observers. This figure shows that there is considerable individual variation in the exact size and shapes of the interaction zones. However, two points are clear: (i) the zone of interaction increases dramatically in size with increasing eccentricity; and (ii) it appears that the interaction regions have an elongated shape in the peripheral field of vision.

Table 2 lists the ratio of the length of the major (meridional) axis to the length of the minor (isoeccentric) axis of the spatial interaction regions for all 6 observers

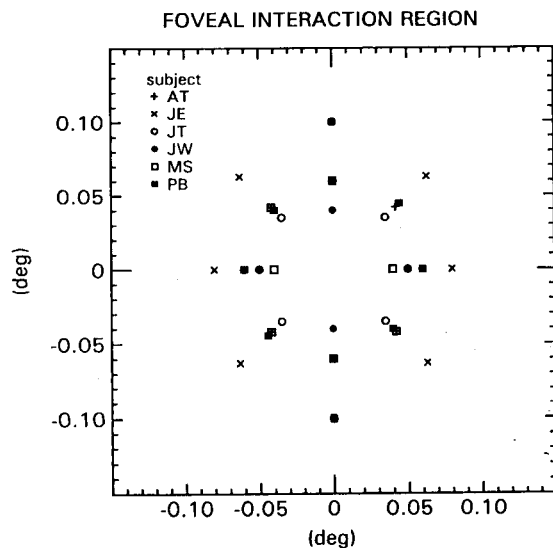


FIGURE 5. The foveal 3T-interaction thresholds for 4 different orientations (i.e. -45, 0, 45 and 90 deg) of the virtual line joining the centers of the 3 individual Ts and for all 6 subjects.

TABLE 2. The asymmetry of the spatial interaction region

Observer	Mean ratio of major and minor axis along		
	Horizontal	Oblique	Vertical
AT	3.02 ± 0.20	1.86 ± 0.26	3.19 ± 0.05
JE	1.84 ± 0.48	3.37 ± 1.45	2.20 ± 0.27
JT	3.17 ± 0.18	1.72 ± 0.45	2.63 ± 0.46
JW	1.80 ± 0.38	1.27 ± 0.17	2.62 ± 0.49
MS	2.80 ± 1.27	1.88 ± 0.15	2.68 ± 0.75
PB	1.75 ± 0.51	1.75 ± 0.37	1.95 ± 0.67
Mean	2.40 ± 0.67	1.98 ± 0.72	2.55 ± 0.43

and along the 3 meridians that were tested in this study. Since the data show no appreciable variation with eccentricity the listed values represent the mean of the

thresholds that were determined at 0, 2.5, 5 and 10° along the corresponding meridian. This Table shows that the size of the major axis is, on average, a factor of

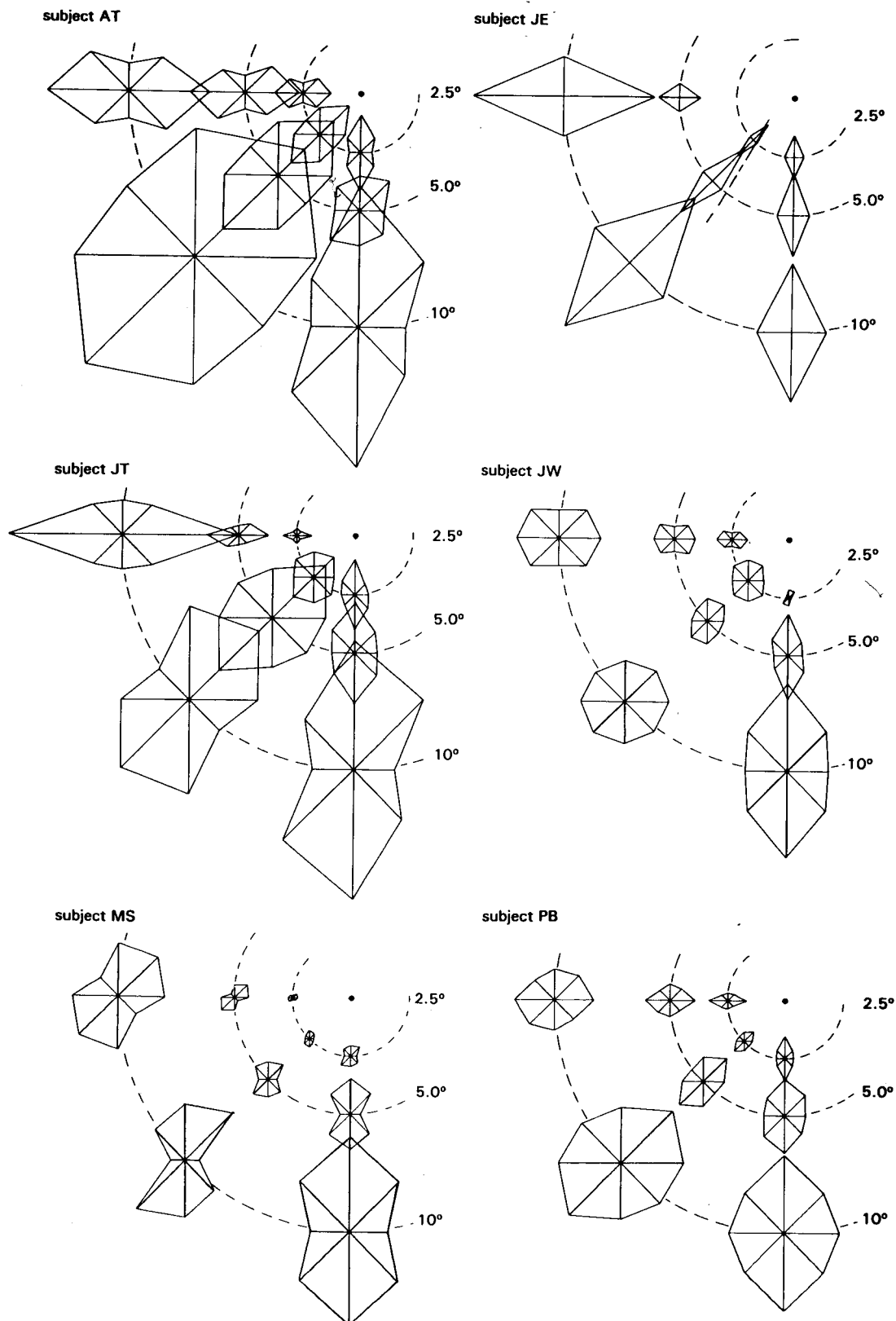


FIGURE 6. The 3T-interaction thresholds at 3 different eccentricities (0, 2.5 and 10 deg) and along 3 different meridians (horizontal, vertical and 45° oblique) for 4 different stimulus orientations (−45, 0, 45 and 90 deg). The thresholds are plotted on the retinal field as line segments with the same orientation as the test stimulus, centered on the test locations, and with a length proportional to twice their value. The endpoints of these line segments were joined to delineate the contours of the two-dimensional 3T-interaction regions.

about 2 times the size of the minor axis. The lowest ratios are generally found along the oblique meridian. The major axis is along the meridian through the central visual field. The minor axis is tangent to the isoecentric arc through the retinal locus of observation.

DISCUSSION

We have measured visual acuity and the two-dimensional shape of the zone of spatial interaction at various locations in the peripheral visual field. Our main results are: (i) while both visual acuity (i.e. the minimum angle of resolution) and the zone of spatial interaction grow approximately linearly with eccentricity they grow at quite different rates; and (ii) the zone of spatial interaction appears to be more or less elliptical in shape in the peripheral visual field, with the long axis along a radial line connecting the fovea to the peripheral location of the test target.

It is interesting to note that our T-acuity task varies with eccentricity in a very similar manner to more standard acuity tasks, so that E_2 is approx. 2 deg, consistent with many previous studies of visual acuity with eccentricity in which the foveal minimum angle of resolution doubles at about 1.5–2.5 deg (Wertheim, 1984; Weymouth, 1958; Virsu & Rovamo, 1979; Jacobs, 1979; Genter *et al.*, 1981; Levi *et al.*, 1985). In contrast, the zone of interaction increases with eccentricity much more rapidly, the foveal size doubling at about 0.4 deg in the tangential direction, and at about 0.2 deg in the radial direction. Our study is consistent with the work of Jacobs (1979), who showed that when four flanking bars were placed around a Landolt C target, visual acuity decreased more rapidly with eccentricity than for unflanked targets, and suggests that the simple acuity "scaling" hypothesis (Flom *et al.*, 1963b) does not account for spatial interactions in the periphery. In the fovea, we find that the zone of spatial interaction extends approximately twice the minimum angle of resolution, while at 10 deg the zone of spatial interaction may extend almost 15 times the minimum angle of resolution. Moreover, the change in shape, from a more or less circular zone, to an ellipse is a clear violation of any simple notion of scaling.

Our present findings are also largely in agreement with Bouma's (1970) results that suggest extensive spatial interactions in peripheral vision. Bouma suggested that the extent of spatial interactions may be as large as half the target eccentricity. Our results suggest that there is considerable individual variation in the size, shape and degree of overlap of the spatial interaction zones. At 10 deg, the extent of spatial interactions for our task ranges from about $0.1 \times$ eccentricity in the tangential direction up to as much as $0.5 \times$ eccentricity in the radial direction, which happens to be the direction of Bouma's measurements.

The present results may also serve to clarify the recent findings of Strasburger *et al.* (1991). In their study, Strasburger *et al.* presented low contrast digits along the horizontal meridian, with flanking digits on either side.

Thus, their peripheral stimuli were oriented radially, where we find spatial interference to be most extensive. On the other hand, we found that the zone of spatial interaction in the fovea was tiny (i.e. smaller than 4 arc min). Strasburger *et al.* were unable to test such small separations because of their low contrast stimuli, so they were unable to reveal the spatial interactions which exist in the fovea.

Spatial interactions are ubiquitous, occurring for a wide variety of tasks involving both acuity and hyperacuity (e.g. Westheimer & Hauske, 1975; Levi *et al.*, 1985; Yap, Levi & Klein, 1987a). Spatial interference with acuity occurs when the interfering targets are bars (Flom *et al.*, 1963b) or letters (Bouma, 1970; present study). These effects also occur under dichoptic conditions (i.e. the target letter presented to one eye and the interfering flanks of the other) (Flom, Heath & Tahashi, 1963a), suggesting the need for cortical interactions. The extent of foveal spatial interactions appears to be similar for both acuity and hyperacuity, and both hyperacuity thresholds and the extent of spatial interactions appear to vary more rapidly in the periphery than does visual resolution. For example, Yap *et al.* (1987a) found that for a 3-dot bisection task, both the optimal bisection threshold and the extent of crowding have E_2 values of 0.5–0.6 deg. Although Yap *et al.* did not investigate the extent of spatial interactions for different orientations, consistent with the present study, they did show that bisection thresholds are anisotropic in the periphery, with thresholds being lowest when the direction of offset was isoecentric, and highest when the direction of offset was radial.

Anisotropies in peripheral vision

Our hypothesis is that resolution is limited by retinal factors (i.e. the eye's optics, cone and ganglion cell spacing) while spatial interference is limited cortically. If this hypothesis is correct, it predicts that while both resolution and spatial interference are likely to show a radial organization, the details may differ for the two tasks. While other explanations (e.g. attention) have been suggested to account for spatial interference (Wolford & Chambers, 1983); it is difficult to see how the strong anisotropies evident in our study could be explained in this way.

It appears that orientational anisotropies in performance are widespread in the peripheral field of vision. For example, in peripheral vision, grating resolution and grating visibility are best for gratings oriented radially with respect to the fovea (Rovamo, Virsu, Laurinen & Hyvärinen, 1982; Temme, Marcus & Noell, 1985). Similarly, there are orientational effects for bisection (Yap *et al.*, 1987), curvature detection (Fahle, 1986), motion detection (Koenderink & van der Grind, personal communication; Scobey & van Kan, 1991) and phase discrimination (Bennett & Banks, 1991). All of these psychophysical findings point to a radial organization of the peripheral visual field, although it is not clear that performance on each of these tasks is constrained by the same underlying mechanisms. For example, previous

studies suggest that resolution only shows strong radial organization (threshold ratios of 2:1) beyond about 20 deg (Rovamo *et al.*, 1982), while both hyperacuity, and the extent of spatial interference (present study) show a strong radial organization at eccentricities as small as 2.5 deg (Yap *et al.*, 1987b). In this regard, it is also of interest to note that at the level of the LGN, in primate, cells in the parvocellular layer show a preference for radial orientations, and this orientation bias is strongest for eccentricities greater than 12 deg (Smith, Chino, Ridder, Kitagawa & Langston, 1990).

There is also a good deal of evidence for a radial organization of both the anatomy and physiology of the retino-cortico pathways. In the periphery, ganglion cell (Leventhal & Schall, 1983; Levick & Thibos, 1980, 1982; Rodieck, Binmoeller & Dineen, 1985; Schall, Perry & Leventhal, 1986), LGN (Smith *et al.*, 1990) and cortical cell receptive fields (Bauer & Dow, 1989; Leventhal, 1983) are elongated and have a radial orientation bias. Cortical ocular dominance columns lie along approximately iso-eccentric contours with respect to the visual field (LeVay *et al.*, 1985).

Hubel and Wiesel (1977) suggested that the cortical magnification factor may be locally anisotropic in order to compensate for the double representation (i.e. right plus left eye) perpendicular to the ocular dominance strips. Specifically, they suggested that the magnification was halved perpendicular to the long axis of the strips. However, Tootell, Switkes, Silverman and Hamilton (1988) found little evidence to support such an anisotropy in magnification. This means that the overall cortical representation is approximately doubled perpendicular to the ocular dominance strips (Tootell *et al.*, 1988). If indeed spatial interference is related to the organization of cortical receptive fields or cortical modules, than the iso-eccentric organization of ocular dominance columns leads to the prediction that spatial interference effects would be radially organized, with interference extending over longer distances along radial lines (i.e. the zones would be elliptical).

Relationship to phase discrimination

Discrimination of the spatial phase of mirror image stimuli is extremely difficult in the periphery when the stimuli are repetitive gratings (Rentschler & Treutwein, 1985; Bennett & Banks, 1987, 1991). For example, Bennett and Banks (1987) reported that discrimination of 180 deg phase shifts in compound gratings consisting of a first and second harmonic was extremely difficult in the periphery, when the harmonics were in sine phase (mirror symmetric), compared to cosine phase (or any other phase for that matter). Interestingly, Bennett and Banks (1991) have noted large anisotropies in the ability to make mirror image phase discriminations in the periphery. When stimuli are oriented radially with respect to the fovea, discrimination is very much easier than for other orientations. In the tangential direction, mirror image phase discrimination is much worse than can be predicted on the basis of the peripheral contrast sensitivity. In contrast, Morrone, Burr and Spinelli

(1989) found that mirror image phase discrimination in the periphery was identical to that of the fovea when the stimuli were scaled in order to equate contrast sensitivity. Morrone *et al.* used a unique, nonrepetitive stimulus composed of 256 harmonics. They suggested that the poorer phase discrimination of Bennett and Banks could be a consequence of spatial interference because of the repetitive nature of their two-harmonic stimuli. Although the stimuli used in the present study were much simpler than those of either Bennett and Banks (1987, 1991), or Morrone *et al.* (1989), the task is in some ways very similar, because the observer must make a mirror image discrimination of the orientation of the T-target. Therefore, we believe that our results are closely related to those of Bennett and Banks. Our stimuli (3 Ts) are repetitive like those of Bennett and Banks. The mirror image discrimination is much more difficult in the periphery, so long as the distance between the 3 Ts is not too large (i.e. as long as there is spatial interaction). Moreover, for a given eccentricity, the critical spacing depends on the orientation of the stimuli (i.e. the spatial interaction is anisotropic). Consider the repetitive targets of Bennett and Banks (1987). At 10 deg in the periphery, they found that mirror image phase discrimination was impaired for stimuli of 0.5 c/deg but not for stimuli of 0.092 c/deg. Thus, one hypothesis is that at the higher spatial frequency, spatial interference occurred between adjacent harmonic components when the gratings were oriented tangentially (the direction in which we find large spatial interference regions), but not radially (because the extent of spatial interference is about a factor of two or three smaller).

Implications for extrafoveal reading

Our results may also have implications for persons with low vision who must read extrafoveally. While the standard prescription for low vision is to uniformly magnify the stimuli, the present results suggest that letter spacing and letter size may need to be increased differentially, i.e. we suggest anisotropic stretching of text in addition to magnification. The exact nature of the anisometric stretching would depend critically upon the retinal location preferred for the reading task.

REFERENCES

- Andriessen, J. J. & Bouma, H. (1976). Eccentric vision: Adverse interactions between line segments. *Vision Research*, 16, 71-78.
- Aubert, H. & Foerster, R. (1857). Beiträge zur Kenntnisse des indirekten Sehens. *Gräfers Archiv für Ophthalmologie*, 3, 1-37.
- Badcock, D. R. & Westheimer, G. (1985). Spatial location and hyperacuity: The centre/surround localization contribution has two substrates. *Vision Research*, 25, 1259-1267.
- Bauer, R. & Dow, B. M. (1989). Complementary global maps for orientation coding in upper and lower layers of the monkey's foveal striate cortex. *Experimental Brain Research*, 76, 503-509.
- Bennett, P. J. & Banks, M. S. (1987). Sensitivity loss in odd-symmetric mechanisms and phase anomalies in peripheral vision. *Nature*, 326, 873-876.
- Bennett, P. J. & Banks, M. S. (1991). The effect of contrast, spatial scale, and orientation on foveal and peripheral phase discrimination. *Vision Research*, 31, 1759-1786.

- Bouma, H. (1970). Interaction effects in parafoveal letter recognition. *Nature*, 226, 177-178.
- Butler, T. W. & Westheimer, G. (1978). Interference with stereoscopic acuity: Spatial, temporal and disparity tuning. *Vision Research*, 18, 1387-1392.
- Ehlers, H. (1936). The movements of eyes during reading. *Archives of Ophthalmology*, 14, 56-63.
- Fahle, M. (1986). Curvature detection in the visual field and a possible physiological correlate. *Experimental Brain Research*, 63, 113-124.
- Finney, D. J. (1971). *Probit analysis* (3rd edn.). Cambridge: Cambridge University Press.
- Flom, M. C. (1991). Contour interaction and the crowding effect. In Rutstein, R. P. (Ed.), *Problems in optometry 3* (pp. 237-257). Philadelphia, Pa: Lippincott.
- Flom, M. C., Heath, G. G. & Takahashi, E. (1963a). Contour interaction and visual resolution: Contralateral effects. *Science*, 142, 979-980.
- Flom, M. C., Weymouth, F. W. & Kahnemann, D. (1963b). Visual resolution and contour interaction. *Journal of the Optical Society of America*, 53, 1026-1032.
- Genter, C. R., Kandell, G. L. & Bedell, H. E. (1981). The minimum angle of resolution vs angle of regard function as measured with different targets. *Ophthalmology and Physiological Optics*, 1, 3-13.
- Hubel, D. H. & Wiesel, T. N. (1977). Functional architecture of macaque monkey visual cortex. *Proceedings of the Royal Society of London B*, 198, 1-59.
- Jacobs, R. J. (1979). Visual resolution and contour interaction in the fovea and periphery. *Vision Research*, 19, 1187-1195.
- LeVay, S., Conally, M., Houde, J. & Van Essen, D. C. (1985). The complete patterns of ocular dominance stripes in the striate cortex and visual field of the macaque monkey. *Journal of Neuroscience*, 5, 486-501.
- Leventhal, A. G. (1983). Relationship between preferred orientation and receptive field position of neurons in cat striate cortex. *Journal of Comparative Neurology*, 220, 476-483.
- Leventhal, A. G. & Schall, J. D. (1983). Structural basis of orientation sensitivity of cat retinal ganglion cells. *Journal of Comparative Neurology*, 220, 465-475.
- Levi, D. M., Klein, S. A. & Aitsebaomo, A. P. (1985). Vernier acuity, crowding and cortical magnification. *Vision Research*, 25, 963-977.
- Levick, W. R. & Thibos, L. N. (1980). Orientation bias of cat retinal ganglion cells. *Nature*, 286, 389-390.
- Levick, W. R. & Thibos, L. N. (1982). Analysis of orientation bias in cat retina. *Journal of Physiology*, 329, 243-261.
- Morrone, M. C., Burr, D. C. & Spinelli, D. (1989). Discrimination of spatial phase in central and peripheral vision. *Vision Research*, 29, 433-445.
- Polyak, S. L. (1941). *The retina*. Chicago Ill.: University of Chicago Press.
- Rentschler, I. & Treutwein, B. (1985). Loss of spatial phase relationships in extrafoveal vision. *Nature*, 313, 308-310.
- Rodieck, R. W., Binmoeller, K. F. & Dineen, J. (1985). Parasol and midget ganglion cells of the human retina. *Journal of Comparative Neurology*, 223, 115-132.
- Rovamo, J., Virsu, V., Laurinen, P. & Hyvärinen, L. (1982). Resolution of gratings oriented along and across meridians in peripheral vision. *Investigative Ophthalmology and Visual Science*, 23, 666-670.
- Saarinen, J. (1988). The effect of exposure duration on the analysis of spatial structure in eccentric vision. *Spatial Vision*, 3, 1-7.
- Schall, J. F., Perry, V. H. & Leventhal, A. G. (1986). Retinal ganglion cell dendritic fields in Old-World monkeys are oriented radially. *Brain Research*, 368, 18-23.
- Scobey, R. P. & van Kan, P. L. E. (1991). A horizontal stripe of displacement sensitivity in the human visual field. *Vision Research*, 31, 99-109.
- Smith, E. L., Chino, Y., Ridder, W. H., Kitagawa, K. & Langston, A. (1990). Orientation bias of neurons in the lateral geniculate nucleus of macaque monkeys. *Visual Neuroscience*, 5, 525-545.
- Strasburger, H., Harvey, L. O. & Rentschler, I. (1991). Contrast thresholds for identification of numeric characters in direct and eccentric view. *Perception and Psychophysics*, 49, 495-508.
- Temme, L. A., Marcus, L. & Noell, W. K. (1985). Peripheral visual field is radially organized. *American Journal of Optometry and Physiological Optics*, 62, 545-554.
- Tootell, R. B., Switkes, E., Silverman, M. S. & Hamilton, S. L. (1988). Functional anatomy of macaque striate cortex. II. Retinotopic organization. *Journal of Neuroscience*, 8, 1531-1568.
- Virsu, V. & Rovamo, J. (1979). Visual resolution, contrast sensitivity, and the cortical magnification factor. *Experimental Brain Research*, 37, 475-494.
- Wertheim, T. (1894). Über die indirekte Sehschärfe. *Zeitschrift für Psychologie und Physiologie der Sinnesorgane*, 7, 172-189.
- Westheimer, G. & Hauske, G. (1975). Temporal and spatial interference with Vernier acuity. *Vision Research*, 15, 1137-1141.
- Westheimer, G. & Levi, D. M. (1987). Depth attraction and repulsion of disparate foveal stimuli. *Vision Research*, 27, 1361-1368.
- Westheimer, G. & Truong, T. T. (1988). Target crowding in foveal and peripheral stereoacuity. *American Journal of Optometry and Physiological Optics*, 65, 395-399.
- Westheimer, G., Shimamura, K. & McKee, S. P. (1976). Interference with line-orientation sensitivity. *Journal of the Optical Society of America*, 66, 332-338.
- Weymouth, F. W. (1958). Visual sensory units and the minimal angle of resolution. *American Journal of Ophthalmology*, 46, 102-113.
- Williams, R. A. & Essock, E. A. (1986). Areas of spatial interaction for a hyperacuity stimulus. *Vision Research*, 26, 349-360.
- Wolford, G. & Chambers, L. (1983). Lateral masking as a function of spacing. *Perception and Psychophysics*, 33, 129-138.
- Woodworth, R. S. (1930). *Experimental psychology*. New York: Holt.
- Yap, Y. L., Levi, D. M. & Klein, S. A. (1987a). Peripheral hyperacuity: 3-dot spatial interval scales to a single factor from 0 to 10 deg. *Journal of the Optical Society of America A*, 4, 1554-1561.
- Yap, Y. L., Levi, D. M. & Klein, S. A. (1987b). Peripheral hyperacuity: Isoeccentric bisection is better than radial bisection. *Journal of Optical Society of America A*, 4, 1562-1567.

Acknowledgements—Supported in part by the Netherlands Organization for Scientific Research, Artivisual Intelligence Research (AIR) Inc., NATO Grant CRG 890970 and grant RO1 EY01728 from the National Eye Institute, Bethesda, Md.