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NUMEROSITY JUDGMENTS IN PERIPHERAL VISION: LIMITATIONS OF THE CORTICAL MAGNIFICATION HYPOTHESIS

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We studied visual numerosity judgments for linear dot arrays with regular spacing under central and off-axis observation conditions. Results indicate that an appropriate increase in stimulus size, as determined by the human cortical magnification factor, may compensate for the retinal inhomogeneity of numerosity judgments. Such a compensation, however, is no longer possible if in the numerosity judgments observers are deprived of the cue of overall dot-array length. Thus, there are aspects of the relative insensitivity of peripheral visual function that are not captured by purely geometrical considerations of the retino-cortical projection.

INTRODUCTION

Many aspects of visual performance decrease as the retinal eccentricity of the image increases. This result has been known for more than a century for spatial resolution (see ref. 6) as well as for photopic luminance increment sensitivity[7]. The data obtained by Hilz and Cavonius[9] from measuring the visibility of sinusoidal gratings fit in with these findings.

Recently, however, the concept of cortical magnification has been developed, a hypothesis that the relative insensitivity of peripheral vision may be compensated for by scaling the stimulus size according to the cortical magnification factor. The numerical value of this factor is a function of retinal image eccentricity and it reflects the reduction in scale due to the retino-cortical projection. Indeed, an increase in stimulus size as determined by the cortical magnification factor may compensate for the retinal inhomogeneity of visual acuity[4] and of contrast sensitivity[18]. What is not yet clear is how far this applies to a wider class of visual functions.

In this study, therefore, we considered a visual numerosity judgment task; a test of the observer's ability to correctly report the number of items presented in a brief exposure.

Since in 1871 Jevons[11] gave one of the earliest reports on a related experiment, the subject of numerosity judgment has found considerable attention in the psychological literature[13,14,17]. The problem with these studies is that nearly all of them have employed two-dimensional dot-arrays. That is, it is rather difficult to interprete their results in terms of current concepts of visual pattern processing which are mostly concerned with one-dimensional stimulus patterns[5]. This led Atkinson et al.[1] to study numerosity judgments by using simple patterns of linear dot-arrays. They chose regular (i.e. periodical) spacing of the dots in order to avoid perceptual grouping. Atkinson

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and her coworkers found it suitable to characterize such displays in terms of the fundamental spatial frequency determined by the one-dimensional pattern periodicity. This is why their experimental paradigm can readily be used to study such issues related to retinal inhomogeneity.

METHOD

We used the experimental paradigm of Atkinson et al.[1] who studied numerosity judgments for central fixation of the stimuli. Besides this condition 3 stimulus locations in the temporal visual field (4°, 8° and 20°) were used. The stimulus patterns consisted of linear dot-arrays with equal dot diameter and separation (see Fig. 1).

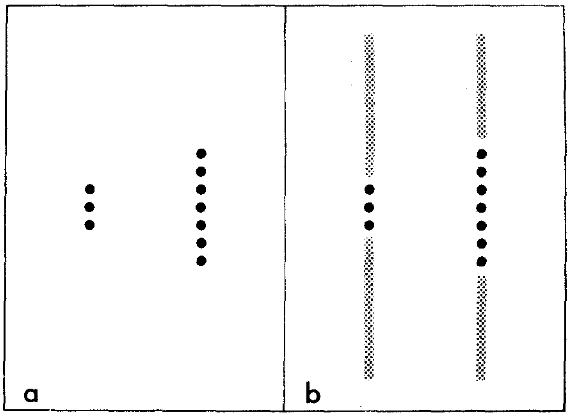

Fig. 1. Stimuli used for numerosity judgments. a: linear dot-arrays, b: constant length patterns, namely dot-arrays within two bars with checker-board texture to match average luminance.

TABLE I

The cortical magnification factor M_T for the temporal visual field and stimulus size at various eccentricities (see ref. 12). Size is specified by dot diameter being equal to dot separation. Values in brackets indicate corresponding spatial frequency.

Eccentricity (deg of arc)	M_T	*Stimulus size min of arc (cpd)*		
0	1	10 (3)	5 (6)	2.5 (12)
4	2.16	21.6	10.8	5.4
8	3.33	33.3	16.7	8.4
20	6.89	68.9	34.5	17.3

Throughout the experiments these stimuli were vertically oriented and had a contrast of 98%. Two sets of stimulus sizes were used, namely such with unscaled size and such increased in size according to the cortical magnification factor

$$M_T = M_o\ (1 + 0.29E + 0.000012E^3)^{-1},$$

as proposed by Rovamo et al.[16]. Here M_T is the magnification factor for the temporal visual field and E denotes retinal eccentricity in degrees of visual angle. The unscaled patterns had a dot size of 10, 5, and 2.5 min of arc in diameter corresponding to spatial frequencies of 3, 6, and 12 cycles per degree (cpd), respectively. The actual dot sizes of the scaled patterns are given in Table I. The number of dots varied from one to twelve. The stimuli were projected onto a screen by a slide-projector. Exposure durations, controlled by an electronic shutter, were 20, 50, 100 or 250 ms. That is, the shorter durations were less than the latency of the first saccadic eye-movement that may have occurred[15]. The monocularly observing subject sat in a moderately illuminated room. Viewing distance was 220 cm. The observer was instructed to fixate a red light-emitting diode (15 min of arc diameter), and the experimenter monitored the subject's eye movements using an electro-oculogram to assure proper fixation. The experimenter announced the onset of each stimulus presentation. Immediately after seeing the target either centered on the fixation point or in his temporal visual field, the subject reported the number of dots perceived. His response was recorded without feedback on whether he was correct or not. A randomized sequence of 48 slides was used at every condition of presentation time and eccentricity. Thus, each pattern occurred 4 times per sequence. Results were analyzed in terms of percent errors, that is, percent trials the subject gave incorrect number judgments. Eight female and 8 male observers ranging in age from 21 to 40 years took part in the experiments. Some of the subjects participated in more than one of the experimental conditions.

EXPERIMENT I: THE EFFECT OF RESCALING STIMULUS SIZE

Results: stimulus eccentricity and pattern size

Fig. 2 plots percent errors as a function of the number of dots presented in the target. Presentation time was 100 ms and, therefore, most eye movements, except tremor, were impossible. The parameter varied within each set of data was stimulus eccentricity as specified in the inset. In the left panels of Fig. 2 are presented the results for stimuli that were *not* rescaled using the cortical magnification factor. Here, stimulus size is briefly specified as spatial frequency, while the actual size of the dot components of the patterns is given in Table I. The percentage of incorrect judgments increases approximately monotonically with eccentricity for a given spatial frequency. Moreover, as would be predicted, for a given stimulus eccentricity the error rate increases with increasing spatial frequency.

The right panels of Fig. 2 show the results obtained with targets rescaled in size. Here, the stimulus spatial frequency is divided by M_T, the value of the cortical magnification factor at each particular retinal eccentricity (see Table 1 for the actual dot sizes). By comparing the left and right

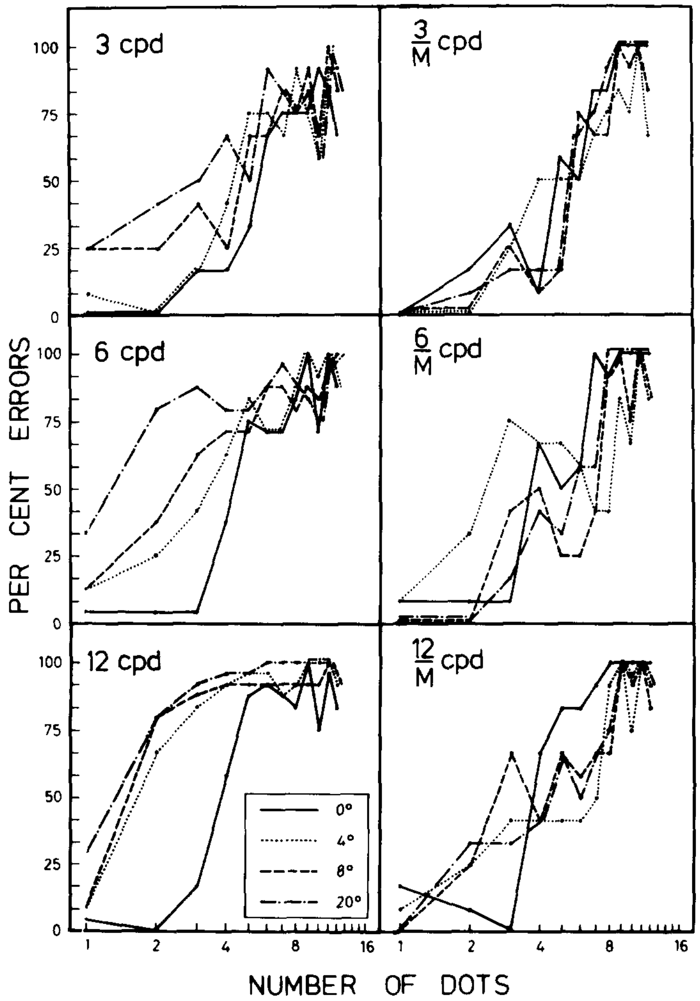

Fig. 2. Error rate in numerosity judgments of dot-arrays as shown in Fig. 1a. Three stimulus sizes (characterized as spatial frequencies) and 3 retinal eccentricities were used. Stimulus duration was 100 ms. The temporal visual field was used for off-axis observation. Data points represent mean values of 12 decisions obtained from 3 monocularly observing subjects. In the right panels, stimulus size is rescaled by dividing by the cortical magnification factor.

panels of Fig. 2 it would seem that rescaling the target size removes all systematic variation of numerosity with eccentricity. The scaling effect as such is most obvious in the low number region.

Results: Stimulus eccentricity and presentation time

Parts of the peripheral retina may surpass the fovea in the capability of processing temporal information. This is true, for example, for critical flicker frequency[8]. Thus, it might be that the retinal homogeneity in numerosity judgments of rescaled targets (Fig. 2, right panel) is due to a temporal advantage of peripheral vision which compensates for a lack in spatial performance. We decided to systematically vary the stimulus presentation time in order to eliminate such a possibility.

Fig. 3 plots results which were obtained at 4 presentation times, namely 20, 50, 100 and 250 ms. Stimulus size was $6/M_T$ cpd, that is cortical magnification was taken into consideration. The data in the 4 panels on the left show the effects of different stimulus eccentricities for a given temporal duration and the same data are replotted in the right panels to show the effects of different temporal durations for a given retinal eccentricity.

Two conclusions can be drawn from these data: first, as can be seen from the right panel in Fig. 3, the dependence of visual numerosity judgments on presentation time does not vary systematically with retinal eccentricity. The hypothesis, that an advantage in temporal processing properties may compensate for a lack of spatial sensitivity in peripheral vision, can therefore be discarded. Second, the data shown in the left panel of Fig. 3 suggest that at all presentation times used, visual numerosity judgments are almost independent of retinal eccentricity.

Moreover, it should be noted that the rescaled stimulus size of $6/M_T$ cpd, as given in the central graph of the right panel of Fig. 2, has been used in all experiments with varying exposure duration. The homogeneity of the data shown in Fig. 3, therefore, strongly supports the conclusion that numerosity judgments for patterns rescaled in size do not depend upon retinal eccentricity.

EXPERIMENT II: SUPPRESSING THE CUE OF DOT-ARRAY-LENGTH

The finding, that one aspect of the relative insensitivity of peripheral vision could be compensated for by taking into account the retino-cortical magnification factor in stimulus size, was a surprise. We, therefore, decided to investigate which cues allow the observer to assess the dot number. Reports by some of the subjects suggested that their decision depended strongly on the cue of overall dot-array-length. Thus, an additional experiment was run in which the subjects were deprived of this cue. This was achieved by presenting the variable length dot-arrays within a gap centered in bars, also of variable length (see Fig. 1b), making the overall length of the patterns a constant across stimuli. These bars had a black-white checker-board texture in order to match the average luminance across the dot-arrays. Otherwise, all experimental conditions and methodologies were identical to those used in Experiment I. Fig. 4 shows the results of suppressing the cue of dot-array-length. Except for the presence of the bars, stimulus conditions and data formats are the same as those used in Fig. 3. In particular, the stimuli were rescaled for cortical magnification. The data obtained for the corresponding dot-arrays without bars are represented in Fig. 4 for comparison by shaded areas. The left panels of this figure show a clear increase in error rate with increasing stimulus eccentricity, the effect being most pronounced for small numbers of dots and between eccentricities of 4° and 8°. This reduction in performance is more severe for shorter presentation times. Moreover, the absence of systematic variation of the error rate with presentation time was confirmed for a given retinal eccentricity (Fig. 4, right panel). In summary, if the array-length cues are removed from the patterns, numerosity judgments for peripherally presented stimuli are worse than those for foveally presented stimuli, even with rescaling the stimulus size for cortical magnification.

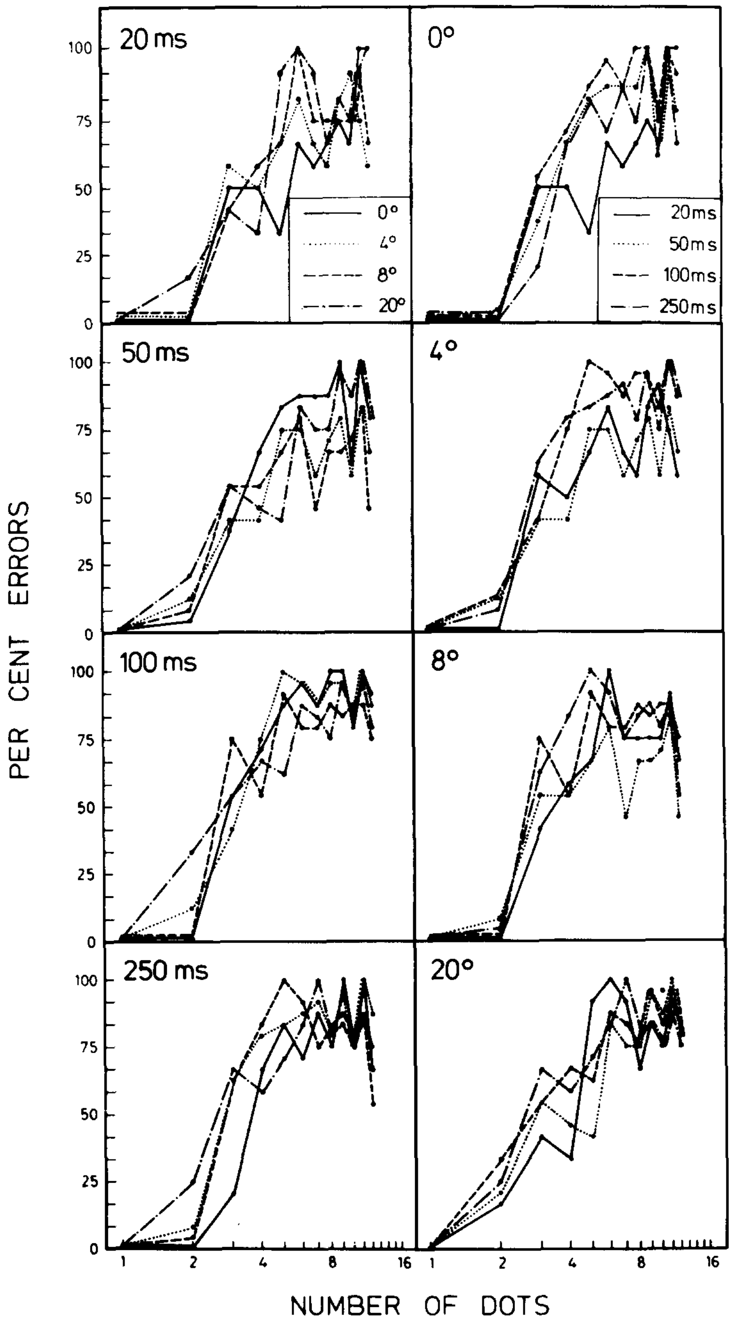

Fig. 3. Stimulus duration and error rate in numerosity judgments of dot-arrays as shown in Fig. 1a. A cortical magnification rescaled stimulus size of $6/M_T$ cpd was used. Data points represent mean values of 24 decisions obtained from 6 observers. Left panel: various eccentricities at a given stimulus duration. The same data replotted in the right panel: various stimulus durations at a given eccentricity.

DISCUSSION

Our study provides additional evidence for the cortical magnification hypothesis of peripheral vision, but also reveals the limitations of this concept. We have shown that an appropriate increase in stimulus size, as determined by the cortical magnification factor, may compensate for the retinal inhomogeneity of visual numerosity judgments with linear dot-arrays. Yet we have

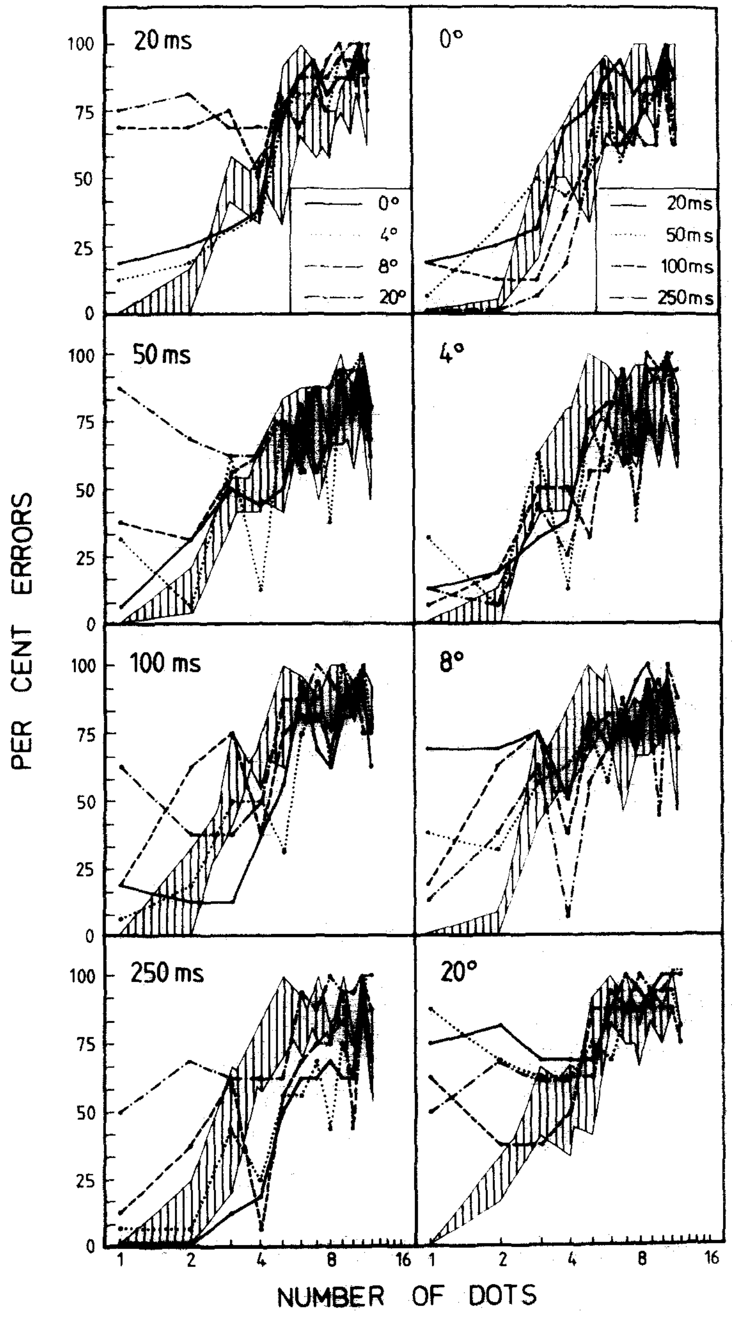

Fig. 4. Error rate in numerosity judgments for constant length patterns as shown in Fig. 1b. Stimulus size and data format as in Fig. 3. For comparison, the corresponding data ranges from Fig. 3 are represented by the shaded areas.

also found a class of stimuli for which rescaling the pattern size does *not* explain most of the error variance in numerosity judgments. These stimuli are modified linear dot-arrays and characterized by the absence of cues for stimulus length.

Atkinson et al.[1], from their study with foveally presented stimuli, have reported a limit in the accuracy of numerosity judgments at 4 for regularly spaced dot elements. This limit depended on the spacing of the elements and held for spatial frequencies below 10 cpd. From our results it would seem that at all spatial frequencies and retinal eccentricities tested (including foveal presentation) accurate counting above two is not possible, even if the stimuli are rescaled for cortical magnification to ensure safe visual resolution of the dots. At present, we see no explanation for this discrepancy.

As suggested by Atkinson and coworkers the ability to discriminate the target patterns on the basis of the number of dots might be seen in relationship to the concept of harmonic frequency analysis in spatial vision (see ref. 5). That is, these authors have proposed that the visual system makes use of the (fundamental) spatial frequency of a dot-array for specifying the number of dots. If this were true, the effects of stimulus size rescaling could be readily related to the findings of Virsu and Rovamo[18] concerning the contrast sensitivity for sinusoidal gratings in the peripheral visual field.

Yet the spatial frequency explanation of numerosity judgments meets a difficulty. Such responses are both accurate and fast only at lower numbers of dots (i.e. below 4–7). But this is just the region where many spatial frequency components are contained even in a one-dimensional spectral representation of the patterns or, in other words, where the spatial frequency bandwidth of the stimuli is very broad. It seems, therefore, that an explanation of the pattern recognition processses involved in terms of a single frequency component would be inappropriate.

The same consideration applies to an alternative proposal made by Atkinson and coworkers, namely that 'numerosity channels' may be the same as those used in detecting spatial phase relationships or, in other words, for capturing the *location* of related spatial frequency components[2,3]. Indeed, recent psychophysical studies concerning texture discrimination [12] and visual sensitivities to temporally modulated gratings[10] have revealed that peripheral vision is relatively insensitive to spatial phase. Thus it is tempting to speculate that, particularly in the case of constant-length patterns, phase values constitute the relevant information for dot-numerosity judgments. However, given the fact that even one-dimensional linear dot-arrays cannot adequately be represented by single spatial frequencies, we are unable to decide about such a hypothesis without enacting a quantitative analysis of the full, that is two-dimensional amplitude- and phase-spectra of the target patterns (see ref. 3). Such issues are the concern of a subsequent paper. To this stage we are left with the simple conclusion that there are aspects of peripheral visual function that are not captured by purely geometrical considerations of the retino-cortical projection.

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