RECOGNITION OF NUMERIC CHARACTERS IN FOVEAL AND ECCENTRIC VIEW.

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Aubert and Foerster (1857) are frequently cited for having shown that the lower visual acuity of peripheral vision can be compensated for by increasing the stimulus size. This result is seemingly consistent with the concept of cortical magnification, and has been confirmed by many subsequent authors. Yet it is rarely noted that Aubert and Foerster also observed a loss of the "quality of form" that re-scaling does not eliminate. We have studied the recognition of numeric characters in foveal and eccentric vision by determining the contrast required for 55% correct identification. Performance regarding threshold recognition contrast for optimally visible sizes decreased towards the periphery, in disagreement with the *cortical magnification concept. Peripheral threshold target sizes at fixed high contrast, however, were* consistent with predictions of the cortical magnification concept up to eccentricities of 6°; performance was relatively lower at higher eccentricities. We have further investigated recognition performance in the presence of neighboring characters (crowding phenomenon). We find that target character size, distance of flanking characters, and precision of focussing of attention are critical parameters. The influence of these parameters is different in the fovea and the periphery. Our findings confirm Aubert and Foerster's original observation of a qualitative difference between foveal and peripheral vision.

Supported by Fraunhofer Ges., grant InSan I-1088-V-6386 to I. R.
and by the Deutsche Forschungsgemeinschaft, grant PO 121/13, part 5 to I.R.

Method

The ten digits, 0 through 9, in various retinal sizes, served as stimuli. They were displayed under computer control on a black and white CRT monitor using a digital image processing system. Contrast was variable in steps of 1/4 dB over a range of 40 dB using a custom made digitally controlled video attenuator. Stimuli were presented for 100 ms as white patterns on a uniform grey background of constant 62 cd/m^2 luminance. The highest attainable contrast was 46%. All contrast specifications are Michelson's contrast. Stimuli were viewed binocularly and were presented foveally or in the left visual field at eccentricities up to 16°. In the crowding conditions, target digits were presented together with a flanking digit left and right. The targets were presented, one at a time, and the task was correct identification. The contrast threshold was obtained using the maximum likelihood adaptive procedure ML-Test (Harvey 1986).

Introduction

Since Aubert & Foerster's (1857) and Wertheim's (1894) pioneering work in the previous century, numerous studies have described the characteristics of peripheral vision under photopic conditions. There are two approaches to specifying visual performance: To specify critical stimulus parameters (size, luminance..), or to specify a performance level (like %-correct). Threshold measurements, like in the present report, are of the first kind. Of the three basic physical variables size, luminance, and contrast which — apart from the pattern — describe a stimulus, surprisingly the influence of contrast has not been studied systematically, except for very simple targets. Many studies using alphanumeric characters have defined performance in terms of the smallest identifiable character. But using size as criterion produces an interaction with the spatial inhomogeneity of the visual system which has a non-linear mapping to the visual cortex (Daniel & Whitteridge 1961). It is desirable, therefore, to be able to specify performance holding the size of a stimulus constant.
In the present study we used recognition threshold contrast, i.e. the contrast required for correct identification, to specify performance. Our results allow us to draw conclusions about the validity of the cortical magnification concept. Further, the technique allowed us to examine the crowding phenomenon, i.e. the degradation of target visibility in the presence of neighboring patterns.

Cortical Magnification

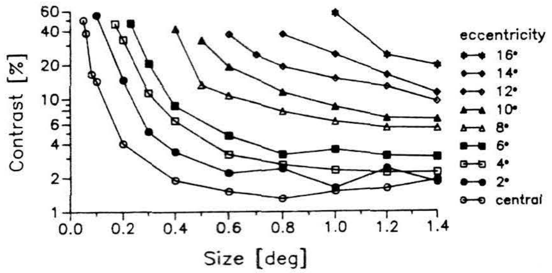
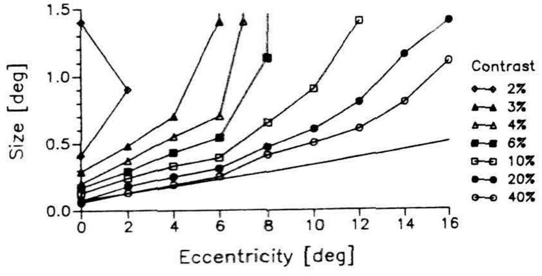


Fig. 1 shows contrast thresholds for recognition of the ten digits as a function of target angular size (mean of two subjects). The digits were presented foveally and in the left visual field at various eccentricities. For foveal view, digits are seen best at a size of 0.8° and slightly less well at larger sizes (!) For smaller sizes, threshold rises steeply until at the lowest discernible size of 0.06°, recognition is limited by the maximum attainable contrast. Extrapolation to 100% contrast, not shown in the figure, corresponds to an acuity measure.
For peripheral vision, identification performance is lower, the curves being shifted to the right and upwards. The shift to the right shows that larger sizes are required peripherally. This complies with the concept of cortical magnification (M-concept), according to which the poorer resolving power of the periphery can be compensated for by using appropriately scaled stimuli. The curves' shift upwards, however, shows that, additionally, the periphery has higher recognition contrast thresholds. Since size and contrast are not fully correlated, this cannot be compensated for by stimulus enlargement.



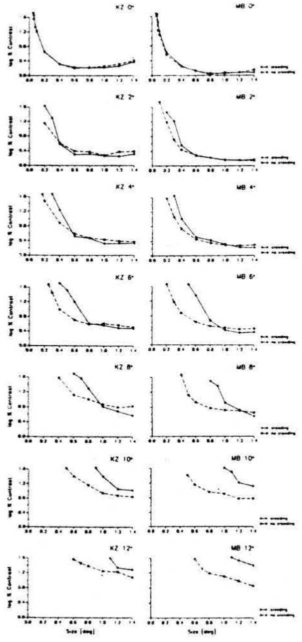
The point is further illustrated in **Fig.** 2, which shows the data from Fig. 1 replotted as a function of eccentricity. Additionally, the size, as predicted by the cortical magnification concept, is shown for the case of 40% contrast. The function $M^{-1} = S(1 + 0.33E + 0.0007E^3)$ from Rovamo & Virsu (1979) is used for this.
There is a good fit of the 40% curve up to 6° eccentricity. For larger eccentricities, size is underesti*mated. More seriously, however, the curves at lower contrast are much more curved, the slope going* to infinity below 6% contrast. Obviously, this cannot be compensated for by any size scaling.

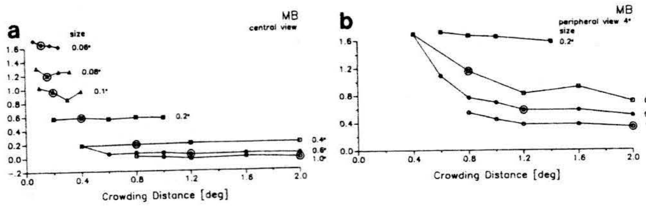
In a formal language, contrast and size are dimensions in the feature space in which peripheral perfor*mance can be described. Since contrast and size are not fully correlated they are linearly independent,* and the space thus has a dimensionality of at least two. Any explanatory concept on a neural level must therefore also involve, at least, two linearly independent variables. In the M-concept only one variable, like cell density, is considered. A possible second variable that could be incorporated is, for example, cell contrast sensitivity.

Crowding

We have further looked at the influence which the presence of neighboring digits has on the visibility of the target digit. Ehlers (1936) has first described the reduced visibility of a character amidst others; Stuart & Burian (1962) later named this the "crowding effect", other authors call it "lateral masking". The effect is most pronounced in peripheral and amblyopic vision and occurs, to a small extent, also in normal foveal vision.

For the data in **Fig.** 3, the target was surrounded by a digit both left and right, with a blank space of one letter size in between. The figure shows, for two subjects, the target's recognition threshold contrast as a function of size. For comparison, the data from Fig. 1 are included. In the foveal condition (top), the curves for crowding and no-crowding coincide, i.e. there is no crowding effect. Already at 2° eccentricity, however, and for all larger eccentricities, there is a strong crowding effect. It shows itself predominantly at small stimulus sizes and, up to 6° eccentricity, disappears for sufficiently large sizes.





In the preceding figure, the flanking distance was scaled to the target size such that the distance was larger for the larger targets. To find out whether target size or flanking distance plays the critical role, the two variables have been varied independently. The result for a representative subject is shown in **Fig.** 4, for foveal view (a) and 4° eccentricity (b). For foveal view, threshold is independent of flanking distance, i.e. there is no crowding, except for a small effect at low sizes and low distances. According to Flom et al. (1963), contours have to be closer than 0.05° for a crowding effect to occur; this condition is fulfilled for only the two leftmost data points in our figure.
At 4° eccentricity, the crowding effect is present below ca. 1.2° crowding distance. Of relevance is, thus, not the relative distance of characters, specified in units of character size, but the absolute spacing in degrees. As a practical consequence, in sidelong seen text the influence of crowding will depend on the distance under which the print is viewed.

Two possible explanations for the crowding effect are considered here. One explanation is that contrast sensitivity is reduced in the presence of contours nearby. The second explanation is that it is difficult to focus attention away from the fixation point. Wolford & Chambers (1983) were able to separate the two causes, quantifying the influence relative to a given level of crowding effect. However, they could not quantify the absolute contribution of each cause. With the present paradigm there is a way of quantifying the contribution of focusing of attention. For this, the error responses in classifying a target were analysed in terms of whether, inadvertently, a flanking digit was reported, and it was assumed that such a report was due to an inadvertent shift of the locus of attention.

	overall errors	Correspondence left	right	l+r
Foveal	400	11%	8%	19%
4° per.	498	21%	21%	42%

The results are shown in the table. Since there are ten digits, chance performance is 10%+10% correspondence between reported response and a flanking digit. In foveal view, the actual performance did not differ from chance. At 4° eccentricity, however, performance exceeded chance level by 22% showing that every fifth classification error was due to an inadvertent, and unnoticed, shift of locus of attention.

Conclusion

Contrast thresholds for the identification of single digits show a steep performance degradation towards the periphery beyond 6° eccentricity. This behavior is not accounted for by the concept of cortical magnification. The feature space for describing peripheral performance has, at least, a dimensionality of two. Recognition of a digit in the presence of neighboring digits is degraded in peripheral vision. This crowding effect occurs below a critical angular distance of flanking characters which, at 4° eccentricity, is around 1.2°. The crowding effect is partly due to inadvertent and unnoticed shifts of the subject's locus of attention.

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