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Identification of facial images in peripheral vision

Pia Mäkelä [a,*], Risto Näsänen [b], Jyrki Rovamo [a], Dean Melmoth [a]

[a] *Department of Optometry and Vision Sciences, Cardiff University, Redwood Building, King Edward VII Avenue, Cathays Park, Cardiff CF10 3NB, Wales, UK*

[b] *Brain Work Laboratory, Finnish Institute of Occupational Health, Topeliuksenkatu 41aA, FIN-00250 Helsinki, Finland*

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Abstract

Contrast sensitivity for face identification was measured as a function of image size to find out whether foveal and peripheral performance would become equivalent by magnification. Size scaling was not sufficient for this task, but when the data was scaled both in size and contrast dimensions, there was no significant eccentricity-dependent variation in the data, i.e. for equivalent performance both the size and contrast needed to increase in the periphery. By utilising spatial noise added to the images we found that in periphery information was utilised less efficiently and peripheral inferiority arose completely from lower efficiency, not from increased internal noise. © 2001 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Performance declines towards the visual field periphery in most tasks, when a constant stimulus size is used (e.g. Weymouth, 1958). By using M-scaling, i.e. magnifying the stimulus in inverse proportion to the cortical magnification factor (e.g. Rovamo, Virsu, & Näsänen, 1978), it has often been possible to equate performance for spatially simple tasks involving e.g. detection of stationary, moving, flickering or Gaussian enveloped gratings (Rovamo et al., 1978; Koenderink, Bouman, Bueno de Mesquita, & Slappendel, 1978; Kelly, 1984; Swanson & Wilson, 1985), discrimination of orientation of sine wave gratings (Rovamo & Virsu, 1979), movement detection of random-dot patterns (van de Grind, van Doorn, & Koenderink, 1983), dot-texture discrimination (Saarinen, Rovamo, & Virsu, 1987), referenced movement detection (McKee & Nakayama 1984) and tilt after-effect (Harris & Calvert, 1985). However, there are other tasks where the rate at which peripheral stimuli need to be magnified with increasing eccentricity to keep performance constant varies significantly from one task to another (Levi, Klein, & Aitsebaomo, 1984; Klein & Levi, 1987; Whitaker, Mäkelä, Rovamo, & Latham, 1992a). This means that M-scaling is not applicable to all tasks. In addition, Azzopardi and Cowey (1996) have disputed the M-scaling principle because peripheral scaling is not a general principle of sensory representation in the cortex.

Unlike M-scaling, the spatial or size scaling (S-scaling) method does not depend on pre-determined anatomical or physiological factors. Thus, foveal and peripheral performance can often be equated in a task for which M-scaling has previously failed. The rate by which the stimulus needs to be increased towards periphery to equate visual performance across the visual field can be estimated by measuring performance for a set of stimulus sizes at each eccentricity and plotting performance as a function of size. The needed rate of increase in the stimulus size towards periphery is obtained by determining how much the curves for each eccentricity have to be shifted along the size axis in order to superimpose the curves (Johnston & Wright, 1986; Watson, 1987; Saarinen, Rovamo, & Virsu, 1989; Whitaker et al., 1992a; Whitaker, Rovamo, MacVeigh, & Mäkelä, 1992b).

Spatial scaling has been successful for simple tasks at high and low contrasts. For example, Johnston and Wright (1986) scaled motion detection for slowly drift-

* Corresponding author. Fax: +44-29-20874859.
E-mail address: makela@cf.ac.uk (P. Mäkelä).

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ing sinusoidal gratings and Watson (1987) contrast detection for Gabor stimuli. Spatial scaling has also been successfully applied to various more demanding tasks at high contrasts; vernier acuity, orientation discrimination and spatial interval discrimination can be made equal at high-contrast across the visual field by spatial scaling (Whitaker et al., 1992a,b; Mäkelä, Whitaker, & Rovamo, 1993). Farrell and Desmarais (1990) showed that recognition of blue numerals (of 3.17 cd m^{-2} luminance) on white background could be made equal at the fovea and up to of 8.12° eccentricity. Detecting distortions of a high contrast face image becomes independent of eccentricity within 0–20° by spatial scaling (Rovamo, Mäkelä, Näsänen, & Whitaker, 1997).

Finally, there are certain tasks where spatial scaling alone cannot equate contrast sensitivities. In these tasks foveal performance remains superior despite adequate size increase in the periphery and an additional contrast scaling appears to be required. A phase-encoding deficit in peripheral vision has been suggested to be the reason why performance in certain tasks cannot be compensated for by size increase only (e.g. Hilz, Rentschler, & Brettel, 1981; Harvey, Rentschler, & Weiss, 1985; Rentschler & Treutwein, 1985; Bennett & Banks, 1987; Hess & Watt, 1990; Bennett & Banks, 1991; Hess & Holliday, 1992; Hess & Field, 1993). In these experiments various methods have been used to determine the suitable peripheral image sizes. Bennett and Banks (1987) reported that discrimination of phase shifts in compound gratings could not be equated between the fovea and periphery. The optimal spatial frequency for each eccentricity studied was produced by changing the viewing distance of a constant size target. The contrast of the gratings were set about 1 log unit above detection threshold. At 40° eccentricity the discrimination of phase shift was no longer possible. These results were confirmed for a wider range of stimulus sizes at 10 and 20° eccentricities (Bennett & Banks, 1991). The authors show (p. 1769) that, whereas 0–180 phase shifts at the fovea and 10° eccentricity can be equated by a shift in spatial dimension only, two factors are needed to equate thresholds for 90–270 phase shift, one referred to as *sensitivity* scaling factor and the other *spatial* scaling factor (Bennett & Banks, 1991). The scaling factors are shown for the 10° eccentricity data, but the resulting scaled data is not shown.

Other experiments that have failed in equating foveal and peripheral performance include Bijl, Koenderink, and Kappers (1992), who measured diameter-threshold functions for red filtered Gaussian blobs at temporal and nasal eccentricities up to 42°. The diameter-threshold functions in the temporal visual field were displaced only in size dimension, whereas in the nasal visual field they were displaced both in size and contrast dimensions, as the foveal thresholds were consistently lower than those measured at 12 and 42° eccentricity. The authors concluded (but did not show) that two factors (regarding spatial scale and relative sensitivity) were needed simultaneously to superimpose the horizontal and vertical shifts measured in the nasal visual field. Valeton and Watson (1990) also found that contrast sensitivities for stationary 2-D grating patches and Gaussian blobs cannot be made equal by increasing the size of the stimulus towards the periphery (4 and 16° eccentricity).

Strasburger and Rentschler have shown in several papers that both spatial and contrast scaling is needed for recognition of numerals (Strasburger, Harvey, & Rentschler, 1991; Strasburger, Rentschler, & Harvey, 1994; Strasburger & Rentschler, 1996). Strasburger et al., (1991, 1994) measured recognition of single numerals presented at 2–40% contrast as a function of stimulus size and eccentricity. At low contrasts recognition was not possible peripherally even with optimal numeral sizes. However, recognition of high contrast (40%) characters up to 35° eccentricity can be roughly equated by increasing the peripheral stimulus size according to the values of Rovamo and Virsu (1979). Strasburger et al., (1994) found that M-scaling alone is not adequate, contrast scaling is needed as well, and proceeded to determine the parameters that fully described their data in both spatial and contrast dimensions. The scaling procedure was not extended to show the data after scaling. Strasburger and Rentschler, (1996) compared character recognition with contrast detection and suggested that recognition of form at low contrasts ($<2\%$) is specifically confined to the central visual field, and beyond 6° eccentricity no image enlargement will improve performance to the foveal level for contrasts below 4%. It was found, however, that simple detection tasks could be performed equally well across the visual field provided that the stimulus sizes are appropriate.

Summarising the above, it appears to be possible to equate foveal and peripheral performance by spatial scaling for certain tasks as long as contrast is high. However, when low contrast images are used or contrast thresholds are measured, peripheral pattern recognition is inferior to that at the fovea despite size scaling, which indicates the need of additional contrast scaling.

Face recognition is a complex process that can differ in several aspects from object recognition. It improves in youth (e.g. Carey, Diamond, & Woods, 1980) and is refined during adulthood, although we are keenly tuned into it from birth; humans prefer looking at faces to other objects already as neonates (Goren, Sarty, & Wu, 1975). Faces appear to be processed more efficiently in the right hemisphere of the brain, especially in recognition or matching tasks (see e.g. a review by Rhodes, 1985). Recognition of familiar faces can be selectively affected in brain damage patients, the condition is called prosopagnosia (see e.g. review by Benton, 1990).

Face recognition also suffers disproportionately from image manipulation. In comparison to object or letter recognition, face recognition is degraded far more when the face is inverted (e.g. Yin, 1969 and a review by Valentine, 1988) or band-pass filtered (e.g. Gold, Bennett, & Sekuler, 1999). On this basis, the need and success of double scaling for artificial images, such as Gaussian blobs (Bijl et al., 1992; Valeton & Watson, 1990) and letters (Strasburger et al., 1991; Strasburger & Rentschler, 1996) does not necessarily mean that natural images such as faces also require double scaling. Further, double scaling may not equalise performance across eccentricities, even though artificial images would seem to need contrast increase outside the fovea.

This study had two aims. Firstly, it was designed to find out whether identification sensitivity, expressed as the inverse of the lowest contrast enabling identification between four face images presented randomly one at a time, could be equated at different visual field locations simply by magnifying the peripheral stimulus sizes appropriately, or whether contrast scaling is also needed.

The rate at which magnification must increase with eccentricity to retain visual performance comparable to that of the fovea was determined using the spatial scaling method. The rate of increase can be expressed by E_2 for size, the value denoting the eccentricity at which the foveal image size has to double to retain performance at the foveal level (Levi, Klein, & Aitsebaomo, 1985). In analogy, the E_2 value for contrast was defined in this study to denote the eccentricity at which the foveal image contrast has to double to retain performance at the foveal level, when spatial scaling is simultaneously applied to image size. E_2 is easy to understand, as it is the eccentricity where the stimulus size/contrast must be doubled to obtain equivalent performance with that at the fovea. E_2 does not necessarily, however, relate directly to the physiological or anatomical properties of the visual system, as it is based solely on measured psychophysical data.

The second aim of this study was to find out whether the inferiority of periphery relative to fovea follows from less efficient use of contrast or increase in neural equivalent noise (Pelli, 1990). The question was answered by measuring performance for stimuli embedded in strong two-dimensional spatial noise.

Fig. 1. The face images used in the experiments were photographs transformed to a digital form by means of a scanner. The faces were standardised by magnifying or minifying the original image to produce a constant interpupillary distance at each image size to eliminate marked size cues and cropped so that only facial features were included to avoid any obvious luminance difference cues.

2. Methods

2.1. Apparatus

The stimuli were generated under computer control (166 MHz Pentium) on a 17 in. RGB monitor (Eizo Flexscan F553-M) driven at the frame rate of 60 Hz by a graphics board (Diamond Stealth 64 VRAM PCI) that generated 640 × 480 pixels. The pixel size was 0.47 mm × 0.47 mm on the screen. The average photopic luminance of the screen was measured with a Minolta Luminance Meter LS-110 and set to 50 cd m^{-2}. The non-linear luminance response of the display was linearised by using the inverse function of the luminance response in stimulus image computations. To obtain a monochrome signal of 256 intensity levels (8 bits) from a monochrome palette of 16 384 (14 bits) we combined the red, green, and blue outputs of the graphics board by using a video summation device built according to Pelli and Zhang (1991).

2.2. Stimuli

The stimuli were created and the experiments were run by means of software developed by one of the authors (RN). The software utilised the graphics subroutine library of Professional HALO 2.0 developed by Media Cybernetics.

The original images were colour photographs of faces (three females, one male, taken by RN, see Fig. 1). They were transformed to black and white images in digital form by means of a scanner (Hewlett Packard ScanJet 4C). The four different face images were standardised by magnifying or minifying the images to produce constant interpupillary distance in all four faces. This procedure eliminated any marked size differences of the original images. Further, the face images were cropped to include only facial features between approximately the middle of the forehead and the chin to exclude any significant luminance difference cues caused by variations in hair colour and clothing.

Five face image sizes (magnifications) on the display were used. They were 9.8×11.2, 7.0×8.0, 4.9×5.6, 3.4×3.9 and 2.4×2.8 cm^2 in horizontal (width) and vertical (height) dimensions, respectively. The horizontal and vertical dimensions of the rectangular equiluminous surround were 30.5 and 23.0 cm, respectively. The range of viewing distances was 0.28–6.74 m, producing angular image widths of 0.20–27.5°. A set of images with decreasing contrast was created for each face image. The decrease between each contrast level was 1.26 (0.1 $\log_{10}$ units).

Because of a large number of repetitions the accuracy of staircase algorithm is better than 0.1 log units. A measure of the accuracy is the standard error of the mean (SE) calculated from the results, which, on average, were 7.6%, i.e. 0.03 log units of the mean in the experiments of this study.

The RMS contrasts of the images were calculated as

$$C_{\mathrm{RMS}} = \left[\sum\sum c(x,y)^2/A\right]^{1/2}, \tag{1}$$

where $c(x, y)$ is the contrast signal of the image. It is defined as

$$C(x,y) = (L(x,y) - L_{\mathrm{o}})L_{\mathrm{o}}, \tag{2}$$

where $L(x, y)$ is the luminance image and L_{o} the mean luminance.

Images embedded in spatial noise were 9.8×11.2 cm^2 in horizontal (width) and vertical (height) dimensions, respectively. Noise check size on the screen was the same as the image pixel size. Two-dimensional white noise was created by adding a random number to each noise check. The random numbers were drawn from a Gaussian luminance distribution with zero mean and truncation at ± 2.5 SD units. The RMS contrast (C_n) of noise, i.e. the standard deviation of the Gaussian luminance distribution normalised by the average screen luminance, was 0.3.

The scaled spectral density of noise was calculated (Legge, Kersten, & Burgess, 1987) as

$$N_e = C_n^2 p^2/F^2, \tag{3}$$

where p^2 is the noise check size (deg^2) used in the experiment of Fig. 4A, and F is the scaling factor from Eq. (11).

The scaled contrast energy (ε) of the image at identification threshold was calculated as

$$\varepsilon = S^{-2}A/F^2, \tag{4}$$

where S is contrast sensitivity determined experimentally and A is the image area (deg^2) used in the experiment of Fig. 4A.

In bright light and without added external noise, perception is affected only by internal noise (N_i) in the visual system. The spectral density of internal noise can be expressed in terms of external noise (N_{eq}) equivalent to internal noise (Pelli, 1990). For instance, if N_{eq} is added in the image, then contrast energy at performance threshold is doubled, as half of the noise determining the threshold is of external and half of internal origin. Equivalent noise (N_{eq}) can be regarded as internal noise (N_i) backprojected into the visual field.

Signal-to-noise ratio at threshold for the sole internal noise and internal plus external noise conditions are equal:

$$\varepsilon_0/N_{\mathrm{eq}} = \varepsilon_n/(N_{\mathrm{eq}} + N_e). \tag{5}$$

The scaled N_{eq} can be solved from this as

$$N_{\mathrm{eq}} = \varepsilon_0 N_e/(\varepsilon_n - \varepsilon_0). \tag{6}$$

Human efficiency (η) is computed as

$$\eta = \varepsilon_{\mathrm{ideal}}/\varepsilon_n, \tag{7}$$

where $\varepsilon_{\mathrm{ideal}}$ is the scaled energy threshold for the ideal observer. The ideal observer in this task is a template matching observer. In order to identify the received noisy signal ($s(x, y)$), the ideal observer searches for the shortest Euclidean distance between the signal and a set of internal templates ($m_i\ (x, y)$), which are noiseless copies of the signals to be identified. Euclidean distance (D) is computed as

$$D_i = \left\{\sum\sum [s(x,y) - m_i(x,y)]^2\right\}^{1/2}. \tag{8}$$

The performance of the ideal observer was determined by means of computer simulation using the same threshold estimation algorithm as with human observers.

Five different noisy images of each face were created for each stimulus contrast level to minimise learning of randomly created structures in noise. One of these five was chosen randomly for each presentation. The range of viewing distances was 0.39–2.28 m, producing angular image widths of 2.46–14.2°. Only one scaled stimulus size per eccentricity was used. The appropriate image size was the largest foveal stimulus size of Fig. 2 without magnification at the fovea but magnified at the peripheral locations according to individual E_2 values, which were obtained by double scaling the data collected without noise.

2.3. Procedures

Contrast sensitivity for face identification was measured for a series of stimulus sizes at the fovea and eccentricities of 2.5, 5 and 10°. For the foveal presentation the fixation target was positioned in the middle of the right hand edge of the image to create comparable decline in the retinal sampling density across the image for the foveal and peripheral stimuli. Thus, as both observers used their right eye, the whole image was positioned in the nasal visual field. Our control experiments showed, however, that thresholds remained the same whether fixation was at the centre or at the edge of the image. For the peripheral stimuli the fixation target was placed so that the stimulus was on the horizontal meridian further in the nasal visual field. Eccentricity therefore refers to the angular distance between the nearest (i.e. right) edge of the stimulus and the point of fixation.

The room was dimly illuminated (0.04 cd m^{-2}) so that just enough indirect light was available for the fixation target to be visible. No reflections were visible on the CRT screen and the area surrounding the stimulus was masked by black cardboard.

The lowest contrast for identification was determined by a single-interval 4-stimulus identification procedure with feedback. The subject was viewing the CRT where one of the four face images was shown at a time. Each face was assigned to one of the selected four keys of an ordinary keyboard. If the face was recognised and indicated correctly via a key, the next presentation showed randomly one of the four faces, which had the same or lower contrast, depending on the requirements of the staircase at that point (see below). Each incorrect response increased the contrast by one step. Exposure duration was 500 ms. The delay for the new trial after each response was 250 ms.

Contrast adaptation was minimised by reaching the approximate threshold level as quickly as possible. When starting from clearly visible stimuli at the beginning of the measurement, the threshold was approached by a staircase with one-correct-down, one-wrong-up rule. The second wrong choice initiated another staircase, which was slower, but more accurate, and measured the threshold for the level of 84% correct with four-correct-down, one-wrong-up rule (Wetherill & Levitt, 1965). Each estimate of threshold was calculated as the arithmetic mean of the last eight reversals. Each data point shown in Fig. 2 and Fig. 4 is the mean of five threshold estimates.

2.4. Subjects

Two experienced observers, the authors PM and RN, were fully corrected moderate myopes (-2.25 and -4.25 DS, respectively). Neither observer had any ocular abnormality. Viewing was monocular using the dominant eye, which by coincidence was the right eye for both observers. This study followed the principles of Helsinki Declaration.

3. Results

In the experiments of Fig. 2 contrast sensitivity for face identification within a set of four was measured as a function of image magnification at the fovea and at 2.5, 5 and 10° eccentricities. At all visual field locations sensitivity first increased with stimulus size (indicated by image width) up to a critical size. At larger stimulus sizes the increase of identification sensitivity saturated for both subjects.

According to Rovamo, Luntinen, and Näsänen (1993) the increase of contrast sensitivity with increasing grating area can be described as $S = S_{\max}(1 + A_c/A)^{-0.5}$, where S is contrast sensitivity, $S_{\max}$ is the maximum contrast sensitivity, A_c is the critical grating area and A is the grating area. In analogy, the increase of identification sensitivity with increasing image size (obtained by magnification) was described by

$$S = S_{\max}[1 + (w_0/w)^p]^{-n}, \tag{9}$$

where S is identification sensitivity, $S_{\max}$ is the maximum sensitivity, w_0 is critical image size, and w is the image size. We fitted a least-squares curve to the data of each subject separately at each eccentricity using KaleidaGraph 3.0.1.

The product (pn) of the exponents in Eq. (9) indicates the slope of increase when identification sensitivity is plotted in double-logarithmic co-ordinates. For subjects PM (Fig. 2A) and RN (Fig. 2B) the slope of increase is 2 and 1.2, respectively. Thus, for PM $p = 2/n$ and for RN $p = 1.2/n$. The optimal value for the exponent $-n$ was found to be 0.5 for PM and 0.3 for RN. It gave the highest value for the correlation coefficient R averaged across eccentricities, which was 99% (range 98–100%) for PM and 97% (range 95–99%) for RN. The critical stimulus size marking the saturation of spatial summation increased with eccentricity. For PM the saturation level for foveal identification sensitivities is about 2 times (0.3 log units) higher than the saturation level at the eccentricity of 10°. For RN the foveal saturation level is about 1.5 times (0.2 log units) higher than the peripheral level and the optimal contrast sensitivity appears to remain almost constant between 2.5 and 10° eccentricities.

The shapes of the sensitivity curves measured at different eccentricities are fairly similar. The amount by which the ascending part of each peripheral sensitivity curve is displaced horizontally from the foveal curve reveals the rate by which the image size at sensitivities below 30, i.e. at contrasts above 3%, should be increased with eccentricity in order to keep identification sensitivity constant. As in Mäkelä, Whitaker, and Rovamo (1997) for example, a scaling factor for each eccentricity was estimated by determining visually the amount by which the peripheral data needs to be shifted to the left along the x-axis to bring the periph-

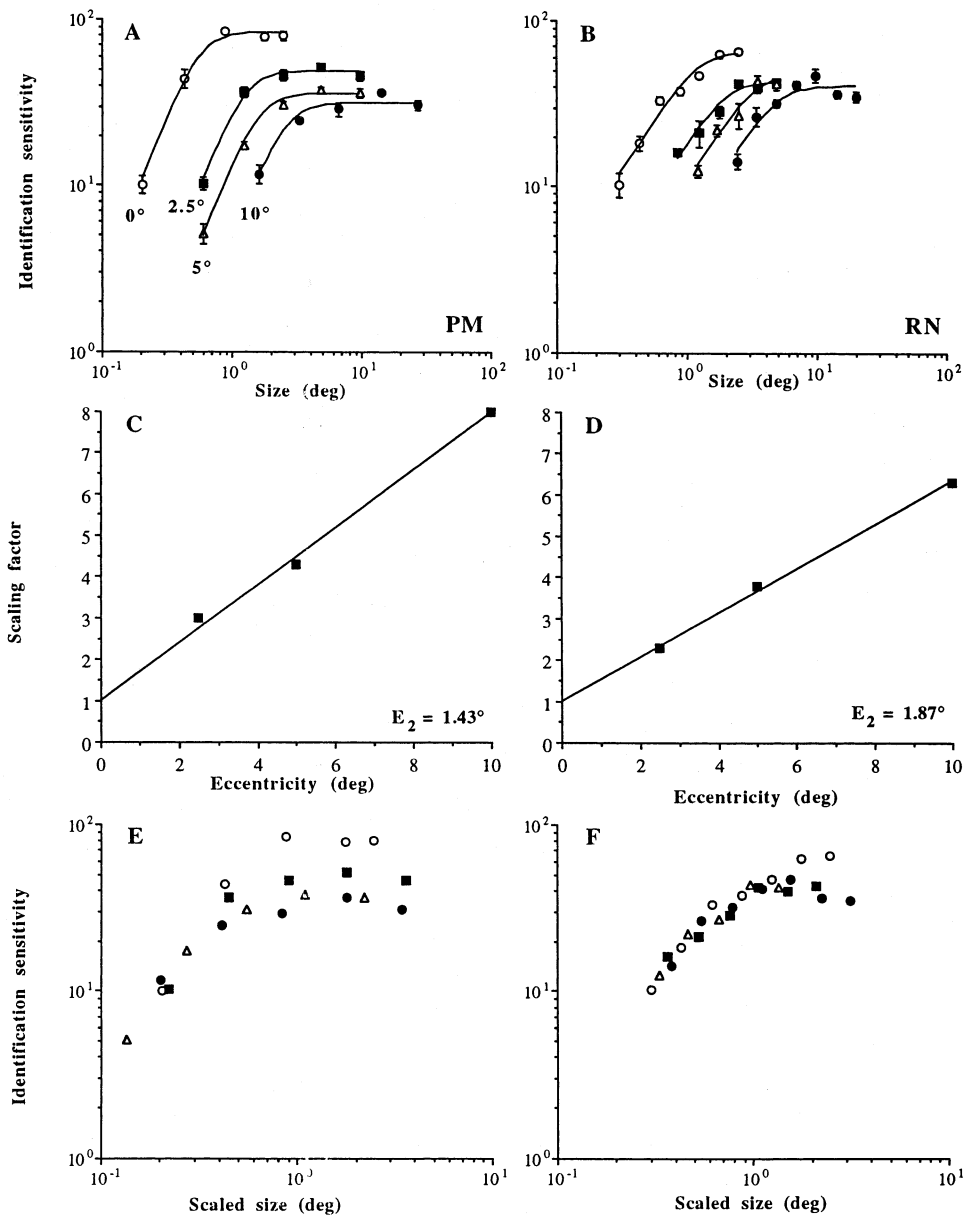

Fig. 2. (A, B) Contrast sensitivity for identification of four different faces plotted against horizontal stimulus size in degrees. Subjects and eccentricities are as indicated. Standard errors are shown when they exceed the symbol size. The least squares curves for each subject were determined separately at each eccentricity by fitting Eq. (9) to the data. (C, D) Spatial scaling factors, obtained at each eccentricity by shifting horizontally the least squares curves to overlap at $S = 20$, are plotted against eccentricity for each subject. (E, F) Contrast sensitivity for identification plotted against scaled stimulus size, i.e. the data is scaled in the horizontal direction. At large scaled sizes identification sensitivity decreases with increasing eccentricity.

eral data points into alignment with the foveal data at the ascending part of the sensitivity curves. The curves were utilised in the present estimation by shifting them horizontally to superimpose at the identification sensitivity value 20 for each subject.

Scaling factors obtained at each eccentricity are shown as a function of eccentricity in Fig. 2C and D. The foveal scaling factor is constrained to be 1, since the foveal data scaled onto itself corresponds to the value of 1. As usual, the scaling factor (F) increases linearly with eccentricity (E). Thus, the dependence of scaling factor on eccentricity can be described by the equation

$$F = 1 + kE, \quad (10)$$

where k is the gradient of the linear regression. The rate of increase is usually expressed in terms of E_2 value, defined as the eccentricity at which the scaling factor doubles (Levi et al., 1985). In other words, E_2 is the eccentricity at which the foveal stimulus size must

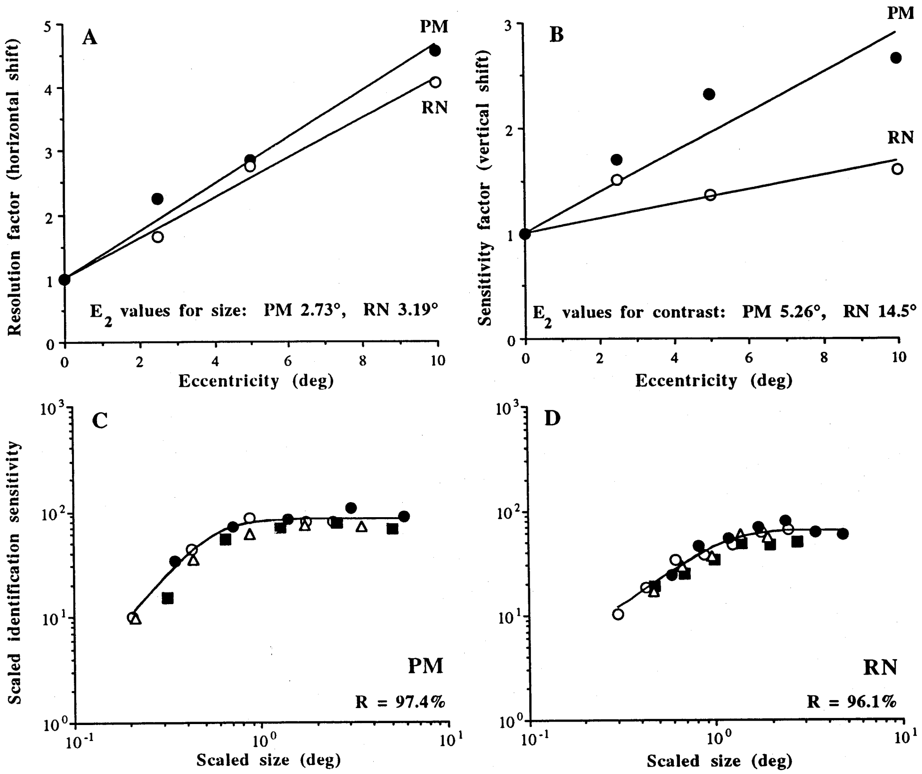

Fig. 3. (A, B) Scaling factors for horizontal size dimension (A) and vertical contrast dimension (B) obtained for each subject are plotted against eccentricity. (C, D) Scaled contrast sensitivity for identification from Fig. 2A and B plotted against scaled stimulus size, i.e. the data is scaled in both the horizontal and vertical direction. Now the foveal and peripheral data collapse together well. Correlation coefficients (R) are as shown.

double in order to maintain performance at the foveal level. According to Whitaker et al. (1992a),

$$E_2 = \frac{1}{k}. \tag{11}$$

Hence,

$$F = 1 + \frac{E}{E_2}, \tag{12}$$

Eq. (12) was fitted to the data of each subject separately by the means of the least squares method using KaleidaGraph 3.0.1. The E_2 value ($\pm$ standard error of the mean) for face identification above 3% contrast was found to be 1.43 ($\pm$0.033)° for PM and 1.87 ($\pm$ 0.024)° for RN.

In Fig. 2E and F the data of Fig. 2A and B are scaled in the horizontal direction, i.e. the stimulus sizes have been divided by scaling factors calculated according to Eq. (12) fitted to the data of Fig. 2C and D. Identification sensitivity is then replotted as a function of scaled stimulus size. It is clear that the curves cannot be completely superimposed simply by shifting them along the horizontal axis relative to one another, i.e. foveal and peripheral performance cannot be equated at sensitivities above 30–40, i.e. at contrasts smaller than 3%, in this task simply by magnifying the stimulus size.

In order to fully equate the data at the fovea and in the periphery it is necessary to scale the data both in contrast and size dimensions by performing a double scaling. This makes it possible to also take into account the low contrast portions of the identification sensitivity curves because the shapes of the sensitivity curves measured at different eccentricities are fairly similar. To determine the scaling factors needed for shifting the peripheral data left and up along the x- and y-axes so that the peripheral data points are brought into alignment with the foveal data, we used the least-squares curve at each eccentricity fitted separately to the data of each subject from Fig. 2A and B.

Individual scaling factors for size and contrast obtained at each eccentricity for each subject are shown separately for horizontal (Fig. 3A) and vertical (Fig. 3B) directions. The horizontal size scaling factors, corresponding to the ratio $w_0(E)/w_0(0)$ of critical sizes obtained by means of least-squares fits, are plotted against eccentricity in Fig. 3A. The vertical contrast scaling factors, corresponding to the ratio $S_{\max}(0)/S_{\max}(E)$ of maximum sensitivities also obtained by means of least squares fits, are plotted against eccentricity in Fig. 3B.

As previously, Eq. (11) was fitted to the data of Fig. 3A and B by means of the least squares method.

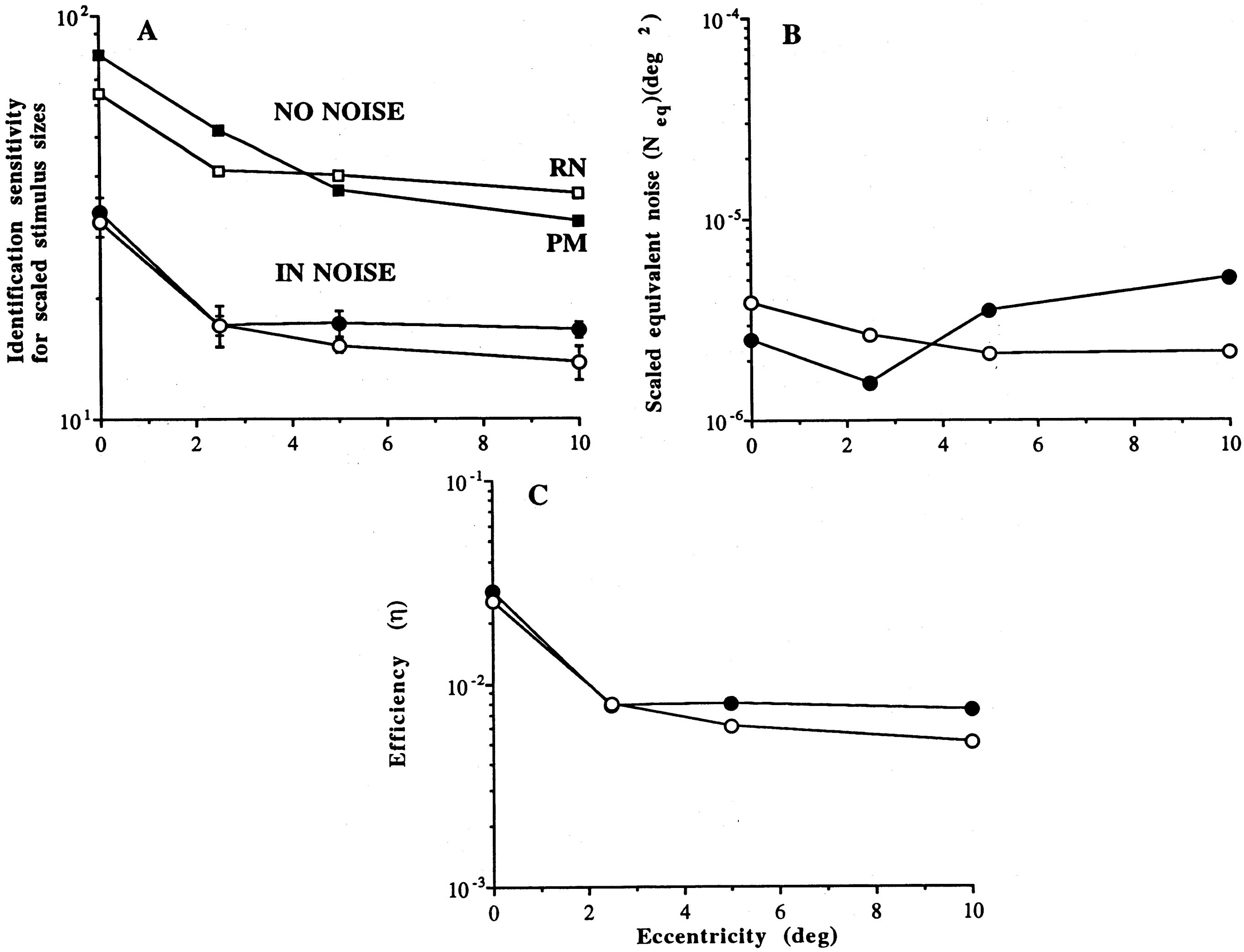

Fig. 4. (A) Contrast sensitivity for identification with and without noise plotted against eccentricity. (B) Equivalent noise (N_{eq}) plotted against eccentricity. (C) Efficiency (η) plotted against eccentricity. Subjects are as indicated.

Horizontal E_2 value ($\pm$ standard error of the mean) for size scaling was found to be 2.73 ($\pm$ 0.13)° for PM and 3.19 ($\pm$ 0.12)° for RN. The correlation coefficient (R) was 99% for both PM and RN. Vertical E_2 value ($\pm$ standard error of the mean) for contrast scaling was found to be 5.25 ($\pm$ 0.70)° for PM and 14.5 ($\pm$ 3.6)° for RN. The correlation coefficient (R) was 92% for PM and 66% for RN. The latter value is due to the odd point at the eccentricity of 2.5°. When removed, $R =$ 99% for RN.

The data shown in Fig. 3C and D is scaled both in horizontal and vertical directions, i.e. stimulus sizes have been divided and identification sensitivities have been multiplied by scaling factors calculated according to Eq. (12) fitted to the data of Fig. 3A and B. Now the foveal and peripheral data collapse together well, as the fit of Eq. (9) to the composite data gives correlation coefficient (R) 97% for PM and 96% for RN.

It is worth noting that by superimposing solely the ascending portions of the curves, size scaling factors are slightly larger and E_2 values correspondingly smaller than when also contrast dimension is taken into account.

Next we wanted to find out why contrast scaling is necessary for identification at threshold in peripheral vision. This cannot be due to optics because increasing stimulus size would eventually compensate for any losses in optical quality. However, it could be that contrast is attenuated in the peripheral retina and subsequent visual pathways or that internal neural noise increases with eccentricity. It could also be that peripheral contrast information is utilised less efficiently. To reveal the reason(s) we conducted an additional experiment.

In Fig. 4A identification sensitivities of both subjects measured for optimal size images embedded in two-dimensional spatial noise have been plotted against eccentricity. At the fovea we used the largest stimulus size of Fig. 2 and in the periphery stimuli were magnified using the individual E_2 values based on the data obtained without noise. The corresponding identification sensitivities without noise (based on interpolation of the data of Fig. 2A and B) are shown for comparison. The results reveal two important points. Firstly, image noise reduced sensitivity at all eccentricities to about one third of the sensitivity without noise. Secondly, peripheral sensitivities for the scaled image sizes with and without scaled noise are approximately half of those at the fovea for both subjects. Thus, the relationship between foveal and peripheral sensitivities is the same with and without noise.

In Fig. 4B the scaled equivalent noise (N_{eq}) calculated according to Eq. (6) is plotted against eccentricity for both subjects. There is no significant difference in equivalent noise across eccentricities, as scaled N_{eq} increases slightly with eccentricity for subject PM and decreases slightly for RN while scaled N_{eq} at the fovea for PM equals N_{eq} at 10° eccentricity for RN, and vice versa. This implies that for scaled stimuli internal neural noise as well as contrast transfer in the retina and subsequent neural visual pathways are independent of eccentricity. Therefore, the differences in this identification task between the foveal and peripheral locations arise completely from inefficiencies in the peripheral vision.

In Fig. 4C, efficiency (η) calculated according to Eq. (7) is plotted against eccentricity for both subjects. Efficiencies at all peripheral locations are practically constant, being about one third of the foveal efficiency i.e. at the cortical level contrast energy in this identification task is utilised more efficiently at the central than in the peripheral vision.

4. Discussion

This study showed that when contrast sensitivity is used as a measure of identifying faces (representing spatially complex images), it was not possible to equate foveal and peripheral identification sensitivity at contrasts below 3% by size scaling alone. An increasing amount of contrast is needed towards visual periphery to keep performance at the foveal level. This resembles to previous finding obtained when using spatial scaling for studying the dependence of flicker sensitivity on stimulus size as a function of eccentricity (Mäkelä, Rovamo, & Whitaker, 1994). At temporal frequencies of 1–10 Hz foveal flicker sensitivity at large stimulus sizes exceeded that of peripheral sensitivity even after appropriate magnification of the peripheral stimuli, i.e. a higher contrast was needed to detect a homogeneous flickering stimulus in the periphery.

Our results agree with the findings of Strasburger et al. (Strasburger et al., 1994; Strasburger & Rentschler, 1996), who showed that for character recognition both size and contrast have to increase in peripheral vision to maintain constant performance. Strasburger et al. found that M-scaling is not adequate for equating contrast sensitivity for character recognition and suggest that character recognition depends on multidimensional pattern representations in higher cortical areas. They further hypothesise (Strasburger & Rentschler, 1996) that the dissociation of visual recognition and detection fields occurs at low pattern contrasts, so that recognition can be performed within a much narrower field, the window of visual intelligence.

The above theory suggests a qualitative difference between foveal and peripheral processing, which our results do not support. Contrary to the expectations based on the window of visual intelligence hypothesis by Strasburger and Rentschler (1996), we were able to equate face identification performance at the eccentricities studied, as long as contrast scaling was implemented. It is worth noting that these studies investigated stimuli with constant contrast. We made performance constant by double scaling, in which case 'the window of visual intelligence' disappeared. According to our results there is no qualitative difference between fovea and periphery in processing this task. Low contrasts are processed less efficiently in the periphery, but our study has not been designed to suggest a physiological reason for this.

It is possible that double scaling in the present form could work for equating foveal and peripheral letter recognition (Strasburger et al., 1991; Strasburger & Rentschler, 1996), diameter-threshold functions of Gaussian blobs (Bijl et al., 1992) or discrimination of phase shifts in compound gratings (Bennett & Banks, 1987, 1991). Both Bennett and Banks and Strasburger et al. have brought up the need for double scaling and determined scaling factors or equations. However, neither determined E_2 values or showed any scaled data as we did in the present study.

Ability to recognise faces declines fast towards periphery for a patient with central scotoma. Relative increase in peripheral contrast can equalise foveal and peripheral face recognition in normal subjects (the present study; Melmoth, Kukkonen, Mäkelä, & Rovamo, 2000). Thus, it is easy to understand why patients with central visual field loss could benefit from enhancing contrast in complex natural images. Foveal loss of visual field cannot be fully compensated for by enlarging the facial images, but the visually impaired patients seem to benefit to some extent from enhancement of image contrast (Peli, Goldstein, Young, Trempe, & Buzney, 1991). Spatial frequency content of an image is significant. For example, Fiorentini, Maffei, and Sandini (1983) found that for normal subjects recognition of faces in foveal viewing was better for images containing only high (above 5 cycles per face width) than only low (below 5 cycles per face width) spatial frequencies. Hübner, Rentschler, and Encke (1985) combined a high pass filtered image of one face and low-pass filtered image of another face and found that the high frequency image dominated the recognition process. They also found that M-scaling was successful in equating foveal and peripheral performance when a face was mixed with a checkerboard pattern, whereas recognition remained poorer in the periphery (at 2° eccentricity) than at the fovea, when two faces were mixed. The authors suggested that the masking effect is stronger in extrafoveal than foveal vision in the presence of spectrally adjacent or overlapping noise energy. However, it is also possible that the increase in the peripheral image size simply was inadequate.

When contrast is taken into account in the present task by double scaling, the size scaling E_2 values shift close to the traditional range (2–3°) of M-scaling estimates (Rovamo & Virsu, 1979)[1]. It may be possible that the large differences in E_2 values for hyperacuities found by, e.g. Whitaker et al. (1992a) would be removed by double scaling if contrast sensitivity were measured instead of spatial resolution.

In the present study, different E_2 values were found for size and contrast scaling. However, the need of two scaling factors is not limited to contrast sensitivity measurements. Two different scaling factors have also been found necessary to describe eccentricity dependence in hyperacuity tasks such as vernier acuity and spatial interval discrimination. For example, Westheimer (1982) noted that for a two-dot vernier acuity task dot separation for optimum thresholds increased relatively slowly with eccentricity in comparison with vernier thresholds. Yap, Levi, and Klein (1989) also used two dots as stimuli in a spatial interval task up to 10° eccentricity. E_2 value for the spatial interval task was 0.6–0.8° but for optimum separation of the dots E_2 was 2.0°.

At suprathreshold levels perceived contrast does not depend on spatial frequency or area when a 2° diameter sine wave grating patch is used to match perceived contrasts up to 40° eccentricity at contrasts up to 0.8% (Cannon, 1985). The results indicated that at high physical contrasts stimuli are perceived as having equal contrasts even when thresholds are different. Thus, at high contrasts perceived contrast shows almost no change with eccentricity, although thresholds increase by at least an order of magnitude, i.e. tenfold. These contrast matching studies seem to provide an explanation of why size scaling aiming to equalise resolution across eccentricities is enough to equalise performance at suprathreshold contrasts for a wide range of high-contrast spatial tasks from movement discrimination to hyperacuities and face discrimination (Whitaker et al., 1992a; Mäkelä et al., 1993; Rovamo et al., 1997). However, the matching studies cannot explain the present results as they are at threshold.

The present results imply that for spatially scaled stimuli internal neural noise as well as contrast transfer in the ocular optics, retina and subsequent neural visual pathways are independent of eccentricity. Therefore, in this identification task the performance differences between the foveal and peripheral locations for spatially scaled stimuli arise completely from the lower efficiency of peripheral vision. Efficiencies at all peripheral locations are about one third of the foveal efficiency, i.e. at the cortical level contrast energy in this identification task is utilised more efficiently at the foveal than in the peripheral vision. This is in agreement with the findings of Näsänen and O'Leary (1998) who used band-pass filtered hand-written numerals to compare foveal and peripheral recognition efficiency. Within the 20° eccentricity studied, peripheral efficiencies were found to be lower than at the fovea at low spatial frequencies (c/object).

Our results are also in agreement with Strasburger et al. (1994), who suggest that detection tasks and recognition of high contrast characters obey the M-scaling principle, whereas recognition of low contrast characters does not. Even after optimal size scaling recognition contrast thresholds increase about tenfold between the fovea and 32° eccentricity. As possible reasons for this the authors consider the contrast sensitivity of ganglion cells, overlap of the receptive fields and positional jitter. All these possibilities are excluded and the authors conclude that the marked reduction in contrast sensitivity in the periphery is a consequence of a combination of several thresholds arising from the primary visual cortex or at a functionally later stage. Our results are fully in agreement with this theory, as the decreased efficiency that we found for peripheral vision is likely to originate at processing stages higher than the retino-cortical pathways.

5. Summary

In order to identify spatially complex images (such as faces), an increase in signal energy, i.e. contrast and image size is needed towards visual periphery to keep performance at the foveal level. When contrast is taken into account in the present task by double scaling, the size scaling E_2 values shift close to the traditional range

[1] In fact, E_2 is about 0.8° for cortical magnification factor (Cowey & Rolls, 1974; Levi et al., 1985; Drasdo, 1991; Grüsser, 1995; Virsu & Hari, 1996), but in practice its slope is shallower corresponding to $E_2 = 2$–3° because visual acuity is limited by cones and ocular optics at the fovea but not in the periphery (e.g. Anderson, Mullen, & Hess, 1991), where the limiting factor is retinal ganglion cells.

(2–3°) of M-scaling estimates (Rovamo & Virsu, 1979), which compensates for retinal sampling differences (cones at $E = 0–10°$ and ganglion cells at $E > 10°$).

Efficiencies at all peripheral locations are about one-third of the foveal efficiency, i.e. contrast energy in this identification task is utilised more efficiently at the foveal than in the peripheral vision. Furthermore, the results indicate that the inferiority of peripheral performance for size scaled stimuli originates entirely from the lower efficiency of peripheral vision, not differences in internal neural noise.

The important message of this study is that despite the peripherally reduced acuity and inefficient use of contrast, double scaling equalises performance across eccentricities. This indicates that the difference in processing this task at the fovea and in the periphery is quantitative in nature.

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