Resolution of gratings oriented along and across meridians in peripheral vision

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Grating resolution was measured at various locations of the visual field for four grating orientations. As an instance of the oblique effect, vertical and horizontal gratings produced the highest resolution values in the central area. At eccentricities larger than about 20 deg, the oblique effect was replaced by a meridional resolution effect, in which resolution was systematically best for meridionally oriented grating bars and worst for grating bars perpendicular to the visual-field meridians. The origin of the effect seems to be neural because it was not caused by peripheral refractive errors or optical distortion of the peripheral retinal image. (INVEST OPHTHALMOL VIS SCI *23:666-670, 1982.*)

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In central vision, acuity and resolution are better for horizontal and vertical than oblique orientations (see ref. 1 for a review). The origin of this "oblique effect" is not yet known. It is probably caused by neural factors because the effect can be demonstrated with interference fringes formed directly onto the retina[2] and because a corresponding effect occurs in cortical-evoked potentials but not in electroretinograms.[3] In eccentric vision, the oblique effect seems to disappear at eccentricities of 8 to 18 deg.[4] We found that at eccentricities larger than these, the oblique effect was replaced by a meridional resolution effect, in which the visual resolution limit was systematically best for meridionally oriented grating bars and worst for grating bars perpendicular to the visual-field meridians. An abstract of this work has already been published.[5]

Methods

Resolution thresholds were measured at various visual-field locations for stationary sinusoidal gratings with a contrast of 0.30. The gratings were generated under computer control[6] on a white (phosphor P4) cathode-ray screen (HP 1300A). The average luminance of the gratings and of the nonmodulated raster was continually 10 cd/m^2. The gratings were viewed with the natural pupil (diameter 6 to 7 mm) at a distance of 228 cm in a dark room. The circular grating field subtended 3 deg. Binocular fixation to a white spot of light was used with eccentric gratings. Eccentricity was measured as the angular distance between the fixation point and the center of the grating field. A bite-board was used to immobilize the observer's head. The orientation of the gratings was varied by rotating the display mounted on an X-ray stand.

The gratings were flashed on for 0.5 sec at each threshold trial. The moment of exposure was controlled by the observer and was indicated by a sound signal. After each exposure the observer reported to the computer whether or not he saw the grating. Starting from an unresolvable bar density, spatial frequency was decreased in small steps

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until the observer reported that he saw a grating. The spatial frequency of the first visible grating was recorded as a resolution threshold. Each experiment, which comprised a series of orientations and visual-field locations, was carried out twice. The two threshold estimates recorded for each condition were the same or very similar, and they were averaged. A two-alternative forced-choice detection method[6] was used in some experiments and produced results similar to those reported in this article.

Three emmetropic observers (J. R., P. L., and V. V.) participated in the experiments and their results were qualitatively similar in all features. The central visual acuity of the observers, measured with the Snellen E chart, was 1.6 or better. The peripheral refractive errors of the emmetropic subjects were determined by means of sciascopy. At an eccentricity of 25 deg the spherical error, averaged over three subjects and the eight half-meridians studied in the experiments, was −0.6 diopters (S.D., 0.6 D) and the average astigmatic error was +1.5 D (S.D., 1.2 D), with axes perpendicular to the corresponding visual-field meridians, in agreement with the typical results of Ferree et al.[7] and Rempt et al.[8] Corrective lenses suggested by sciascopy had no effect on subjective visual acuity tested with single, projected Snellen E-letters, and trial lenses were used only in control experiments.

Results

Fig. 1 shows monocular grating resolution as a function of eccentricity and orientation for one observer along the nasal half-meridian of the visual field. At zero eccentricity, the classic oblique effect occurred; vertical and horizontal gratings could be resolved at higher spatial frequencies than oblique gratings. When eccentricity increased, resolution became first similar for all orientations, in agreement with the previous results.[4] At eccentricities of 25 to 30 deg, however, the resolution limit became about two times higher for horizontal than for vertical and oblique gratings.

Fig. 2 shows monocular grating resolution as a function of orientation and meridional angle for one observer at the eccentricity of 25 deg. The best resolution values were obtained with meridionally oriented grating bars. The poorest resolutions were recorded with grating bars perpendicular to the visual-

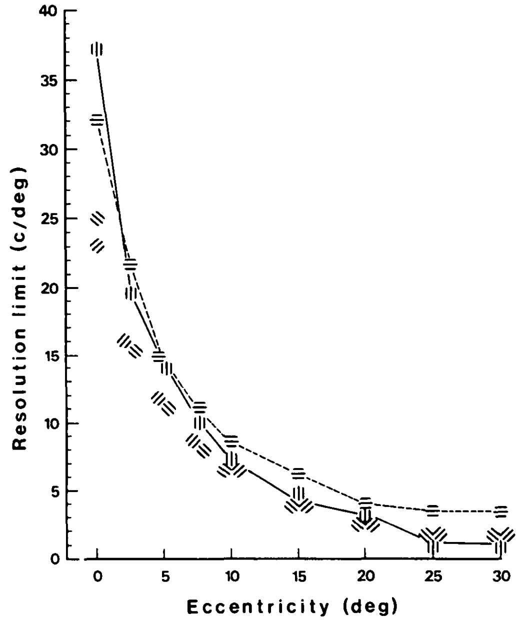

Fig. 1. Grating resolution limits as a function of eccentricity on the nasal half-meridian of the left visual field of subject V. V. The different grating orientations tested were as indicated by the symbols.

field meridians. The resolutions for gratings whose orientation deviated from the meridians by ∓45 deg were intermediate. Since the dependence of resolution on grating orientation in visual periphery was related to meridians, we called it the meridional resolution effect.

When we replicated the experiment of Fig. 2 in binocular vision, the results were similar to those of monocular vision, except for a smaller difference in resolution between meridional and perpendicular grating orientations. In monocular viewing, resolution for meridional gratings averaged over different meridians (n = 8) was 1.48 times better than the corresponding resolution limit for perpendicular gratings, whereas in binocular vision the corresponding ratio was 1.25. When monocular and binocular resolutions for the same grating orientations were compared on the vertical meridian, resolution limits were on the average 1.23 times higher in binocular than monocular vision; other locations were discarded because of the nasotemporal reso-

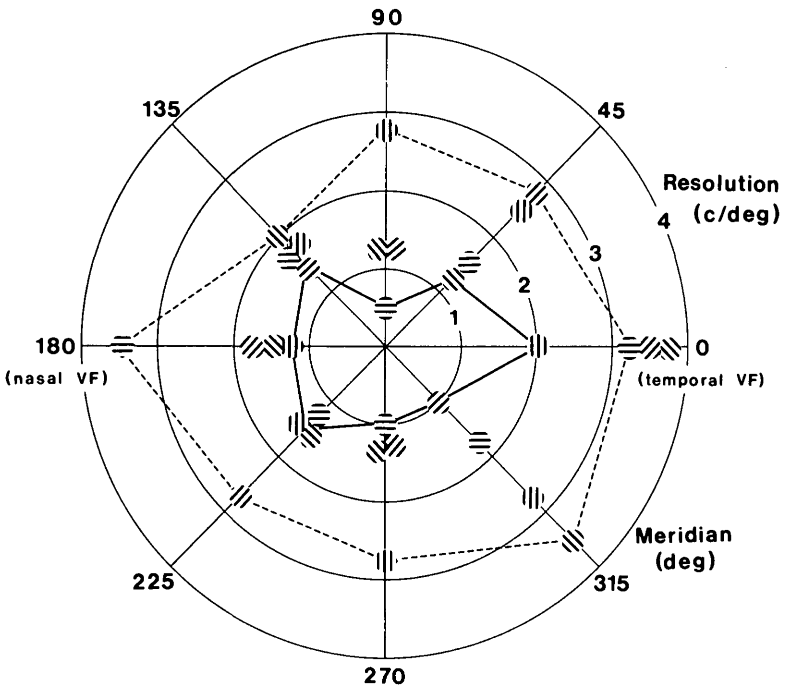

Fig. 2. Resolution limits for different grating orientations on different meridians of the visual field of the right eye of subject P. L. The radii of the graph refer to the different meridians, and the distance from the origo, as indicated by the concentric circles, depicts the resolution limits in cycles per degree. Eccentricity was a constant 25 deg. The values for meridional grating orientations have been connected with dashed lines and the values for perpendicular orientations with continuous lines.

lution asymmetry. Thus binocular summation was incomplete for similar grating orientations on the vertical meridian.

The experiments above were done without correcting peripheral refractive errors because we were mainly interested in normal visual performance. However, the meridional resolution effect illustrated in Fig. 2 might result from astigmatism caused by oblique incidence of light into the eye from peripherally presented stimuli[9, 10] or by individual peripheral refractive errors.

The image plane determined by objective techniques, such as sciascopy, may not correspond closely to the psychophysically appropriate image plane.[11] Therefore, in the control experiments we investigated systematically the effects of optical corrections in our experimental situation with grating stimuli, although occasional attempts to improve the resolution for perpendicular gratings with trial lenses had failed during the main experiments. In the control experiments we measured the resolution for meridionally and perpendicularly oriented gratings with various cylindrical lenses with meridional or perpendicular axis orientation. Cylindrical lenses can simulate combined cylindrical and spherical correction because for gratings there is only one relevant orientation of refraction that is perpendicular to the orientation of grating bars. When properly oriented, cylindrical lenses affect the focus of one grating orientation maximally and leave the focus of the perpendicular orientation unchanged; if the lens axis is vertical, then only the resolution for vertical gratings is affected, as can be readily demonstrated in central vision.

The results of the control experiments were qualitatively similar for all subjects tested at several visual-field locations of Fig. 2. One of the experiments, done in the nasal visual field, is illustrated in Fig. 3, where horizontal refers to meridional direction and vertical re-

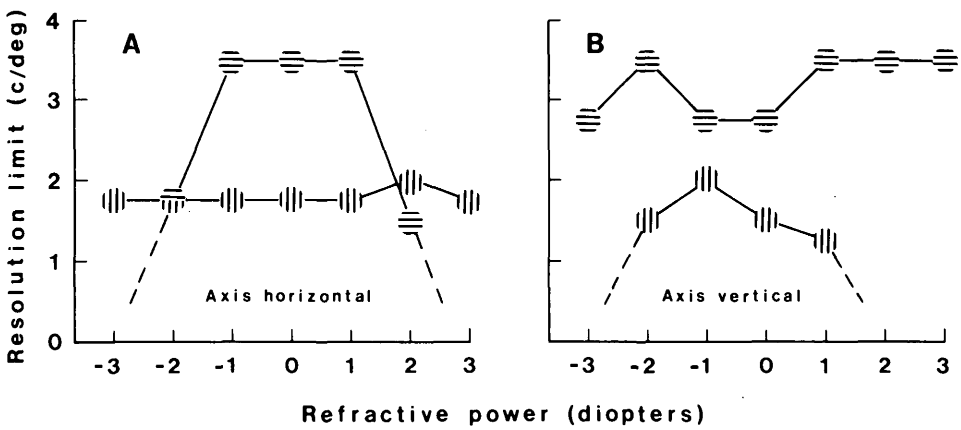

Fig. 3. Resolution limits for two grating orientations (horizontal and vertical) at a nasal eccentricity of 25 deg as a function of the power and axis orientation (horizontal in **A** and vertical in **B**) of a cylinder lens used in front of the right eye of subject P. L.

fers to perpendicular direction. Irrespective of the refractive power of the cylindrical lenses, with vertical axis (Fig. 3, *B*) resolution was lower for vertical gratings than horizontal gratings, and all cylindrical lenses with horizontal axis (Fig. 3, *A*) made resolution for horizontal gratings only worse. Hence correction of peripheral refractive errors does not obliterate the meridional resolution effect. This agrees with previous results, which indicate that refractive errors do not limit static acuity and resolution in normal peripheral vision.[12, 13] Only when the refractive error, produced with astigmatic lenses (c.f. Fig. 3, *A* and *B*), exceeded about ∓ 1.5 D in the direction to be resolved, resolution decreased significantly.

Discussion

The meridional resolution effect described in this article is not caused by peripheral refractive errors. The optical distortion of retinal image size and shape cannot produce the effect either, since up to the eccentricity of 70 deg, the radial and tangential shrinkages are very similar; the difference is less than 5%.[14] Hence the meridional resolution effect appears to have a neural origin like the oblique effect of central vision.

One possible neural explanation for the meridional resolution effect is suggested by the orientation bias found in the cat retinal ganglion cells by Levick and Thibos.[15] Their findings show that the resolution of cat retinal ganglion cells is highest for meridional grating orientations. However, this bias occurs even at small eccentricities, whereas in man the effect was found only at relatively large eccentricities.

Another possibility is that the meridional resolution effect is related to the columnar organization of the visual cortex. The projection of the ocular dominance columns of the rhesus monkey striate cortex into the visual field, as reconstructed by Hubel and Freeman,[16] indicates regularities that correlate well with our observations. At eccentricities larger than about 20 deg, the columns run predominantly in orientations perpendicular to the visual-field meridians. Therefore a peripherally presented grating oriented meridionally runs across the ocular dominance columns and a grating perpendicular to the meridians is parallel to the columns.

Previous results[6, 17, 18] indicate that visual acuity and grating resolution are directly proportional to the cortical magnification factor. On the other hand, the cortical magnification factor is twice as large along a column as across a column. As Hubel and Wiesel[19] express this: "in crossing column after column each eye is heard from only half the time, and if the fields are to keep up with the movement of the receptive fields in the other layers the movement must occur at twice the overall rate. Across a given column magnification (mm cortex/degree visual field) must be half that along the length."

There is evidence[20] that man has ocular dominance columns. Assuming that the columnar organization in man is similar to that of the rhesus monkey, the meridional resolution effect can be regarded as a corollary of the proportionality between visual resolution limit and cortical magnification. With this accepted, the resolution limit for meridional gratings seems to be determined by the retinal density of ganglion cells,[18] whereas the limit for perpendicular gratings seems to be determined by the organization of ocular dominance columns in the cortical input layer.

The monocular resolution for meridional gratings should be two times better than for perpendicular gratings following from the difference in magnification along and across columns. However, this maximal difference was not found, probably because columns are not completely regular. Since binocular summation for resolution was incomplete, the meridional resolution effect cannot disappear completely in binocular vision although the magnifications then are nominally similar for different orientations.[19]

Accepting the explanation above, the oblique effect of central vision may also reflect the organization of the ocular dominance columns, because the foveal columns of the rhesus monkey run predominantly in oblique orientations.[16]

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