Optical and neural resolution in peripheral vision

Lars Frisén and Anders Glansholm

Visual acuity along the horizontal meridian in the peripheral field of vision was determined at a photopic level in two normal subjects. Two types of sinusoidally modulated, monochromatic test patterns of high contrast were used. One was produced directly on the retina by an interferometric technique. The other type was imaged on the retina by the dioptric apparatus of the eye; the resulting image suffered ordinary optical image degradation. The results from the interferometric acuity determinations represent maximal neural discrimination across the visual field. Acuity decreases monotonically toward the periphery, from about 45 cycles per degree in the fovea, to about 0.8 at 80 degrees of eccentricity in the temporal field. The decline is well described by a second-degree polynomial. Acuity for test patterns imaged by the optics of the eye was consistently lower than interferometric acuity. The difference increases toward the periphery. It is attributable to effects of optical aberrations. The discrepancy between optical and neural resolving power on oblique incidence needs to be taken into account whenever results obtained with external, extra-axial stimuli are to be analyzed in terms of retinal architecture.

Key words: peripheral vision, visual fields, visual acuity, interferometry, ametropia.

It has been well established that the optical capacity of the normal human eye matches retinal resolving power for paraxial imagery, but little is known about the role for peripheral vision of the optical faults known to be present with oblique incidence. Even the (axially) well-focused emmetropic eye exhibits substantial spherical and cylindrical ametropia as well as coma outside the optical axis. Magnitudes and types of peripheral aberrations vary widely among normal subjects. This may in part explain the divergent results obtained in earlier investigations of peripheral visual acuity and may require consideration in studies of many other aspects of visual physiology.

Measurement and correction of peripheral optical aberrations of various orders across the whole pupillary aperture is an exceedingly difficult task. The effects on peripheral vision of a less than complete correction is of limited interest. A comparison of unaided visual acuities for gratings and interference fringes should in a more practicable way provide a meaningful indication of the role of optical errors with oblique incidence. The interference technique is considered to bypass the optical faults.

From the Department of Ophthalmology, University of Göteborg, Göteborg, Sweden.

Submitted for publication Oct. 9, 1974.

Reprint requests: Dr. L. Frisén, Ögonklinikken, Sahlgrenska Sjukhuset, S-413 45, Göteborg, Sweden.
We have measured visual acuities at various eccentricities along the horizontal meridian of two emmetropic subjects, alternatingly using monochromatic sinusoidal gratings (imaged on the retina by the optics of the eye) and monochromatic sinusoidal interference fringes formed directly on the retina. Stimuli were alternated with a blank field to prevent their disappearance from view (Troxler effect). Luminances were held in the low photopic range. Target contrast was close to 100 per cent. Frequency-of-seeing curves were obtained at every tenth degree for both types of targets by varying their spatial frequency. Resolution thresholds were defined by probit analysis.

**Methods**

*Interference fringes* of various spatial frequencies were obtained by means of a helium-neon laser, a slit, and a movable Wollaston prism (Fig. 1). The laser (Spectra-Physics Model 155, 0.5 mW, TEM$_{00}$) provided coherent light of 632.8 nm wavelength. The Wollaston prism was mounted on a carriage provided with a device locking into predetermined positions along an optical bench. The distance between the vertical, 0.05 mm wide slit S and the prism W could thus be altered rapidly and reproducibly.

The Wollaston prism splits the laser beam into two horizontally divergent beams, polarized in mutually perpendicular planes. These beams interact constructively and destructively to form an interference pattern with vertical fringes. The spatial separation of the fringes is linearly related to the distance between the slit and the prism. The polarizers P$_1$ and P$_2$, oriented 45° relative to the doubling plane of the prism, serve to improve the definition of the pattern. Still, particularly at low spatial frequencies, fringe definition within the relatively large stimulus aperture used here was not satisfactory (Fig. 2). Lens L$_1$, a negative cylinder lens, axis horizontal, was therefore oscillated vertically at a rate of 50 Hz., sweeping the laser beam along the slit. Because the selected frequency exceeds the critical flicker frequency of the eye, the fringe pattern will now appear more uniform (Fig. 3, time exposure).

**Observation system.** The observation lens L$_2$, a 12 cm focal length camera objective, was located to the opposite end of the optical bench (Fig. 1). A translucent, annular background, B, was placed on the observer's side of L$_2$. It was diffusely transilluminated to provide a constant luminance of 11 cd. per square meter. Gelatin filters, F$_i$, provided color match with the interference pattern seen in the 4° aperture of the background. The test pattern was alternated with a blank field by rotating, at 0.6 Hz., a semicircular...
Fig. 2. Photograph of interference fringes. Note the several types of inhomogeneities in luminance distribution.

Fig. 3. Photograph of interference fringes produced by vertically oscillating laser beam. Note enhanced uniformity.

disk, $R$, behind the background aperture. A separate illumination system (not shown) made the disk match the background surround. A 3 mm. artificial pupil, $AP$, limited the angular subtense of the background to about 15° at the eye, with some vignetting of its periphery. The distance between the artificial pupil and the observer’s pupil plane was 23 mm.

The observer was provided with a well-fitting bite bar permitting rotation of his head around a vertical axis through the center of the pupil of the eye under test. This axis coincided with the posterior focal point of lens $L_1$. A faintly luminous cross-hair, $C$, optically imaged at infinity by lens $L_3$, could be rotated around the same axis, and served as fixation mark. Its direction relative to the optic axis of the apparatus could be read on a protractor. All angular values pertain to the center of the pupil.

**Presentation of gratings.** A slide magazine projector equipped with a diffusing screen, $D$, neutral and interference filters $F_2$, an objective $L_1$, and a front-surface mirror $M$, produced a real image of a transparent grating $G$ in plane $G'$ (Fig. 1). $G'$ coincided with the anterior focal plane of $L_3$, so that $L_3$ imaged $G$ at infinity with appropriate magnification. Thus, with mirror $M$ in place on the optical bench the observer saw an infinitely distant, sinusoidal grating filling the background aperture; with the mirror $M$ removed he saw the same field (in Maxwellian view) filled with interference fringes. An iris diaphragm in plane $G'$ limited the field of view to $4^\circ$ of angle subtended at the observer’s pupil.

**Calibrations.** Interference patterns were produced in 0.05 log steps within the range 0.6 to 60 cycles per degree of visual angle. The corresponding positions of the Wollaston prism $W$ relative to the slit $S$ were determined by calculation and verified from the measured separation in air of the two slit images produced by $L_2$. $L_2$ was then replaced by a 35 mm. camera back (less lens) to obtain, on one and the same photographic film, an equivalent series of sinusoidal gratings.

The transparent gratings were checked in a scanning microdensitometer to ascertain equivalence of transmission to the theoretical sine-square light distribution across the laser-generated interference fringes. Contrast $(I_{\max} - I_{\min})/(I_{\max} + I_{\min})$ was 0.92 for the gratings (in the wavelength interval used here) and (theoretically) unity for the interference pattern. The difference was considered negligible.

The gratings, $G$, were projected through an interference filter $F_3$ (peak transmission at 628 nm, spectral halfwidth 8 nm.) (Fig. 1), making them closely similar in appearance to the laser-generated fringes. The two types of stimuli could not be told apart when presented above threshold in the peripheral field of vision.

The space-average luminance of high-frequency sinusoidal gratings was adjusted to the same value as the background (11 cd. per square meter, Haagner Universal Photometer, Model S 1), by adjusting the voltage of the projector lamp. The interference filter $F_2$ prevented a change in grating color. The luminous power within the test field was also measured by means of a United Detector Technology 21 A Power Meter. A 15 mm. focal length condensing lens (diameter 6 mm.) replaced the pupil of the eye; the detector was located to its focal plane. The sensitivity curve of the detector is flat within the visible range. A power reading of 0.5 pW. was obtained. The luminance of the interference pattern was then adjusted to produce the same power reading by minute adjustments of the slit $S$. The space-average retinal illuminance corresponds to 78 td. The Stiles-Craw-
ford effect was not taken into account because of practical difficulties with our set-up in exactly localizing its maximum with oblique incidence.

**Procedure.** The fixation mark was set to provide the desired obliqueness of incidence. The subject centered the tropicamide-dilated pupil of his dominant eye on the optic axis of the apparatus by careful adjustments of the bite bar. This was then locked in position. The other eye was covered.

Following 10 minutes of adaptation to the background, a 10-step staircase up and down procedure was used to find the approximate threshold value. Forty presentations were then made on this and neighboring levels according to a fixed forced-choice procedure designed to prevent training and tiredness skew. There was no limit on the time of exposure.

The same procedure was then repeated with the other type of stimulus, alternatingly finishing with interference fringes and gratings. About 30 minutes of observation were spent on each eccentricity. No more than two locations were explored on one day.

**Subjects.** The two emmetropic subjects (LF, 34 years of age, and AG, 31 years of age) were experienced in visual discrimination tests. Unaided visual acuities (letter chart) were 2.0 and 1.5, respectively. There was neither history, nor objective evidence of any visual problems whatsoever.

**Statistical analysis.** All frequency-of-seeing curves were subjected to probit analysis. The 50 per cent values were taken as threshold values. The BMDOS program (Health Sciences Computing Facility, University of California, Los Angeles, Calif.) was used in an IBM 360/65 computer. The change in acuity with eccentricity was described by fitting second-degree polynomials to the observations, weighted with the inverse variance for single observations, using a least-squares procedure.

**Results**

A positive effect of training on peripheral visual acuity was obvious at the start of this study. This effect seemed to be non-specific with regard to location: once the observer had reached a stable level of performance in the peripheral training area, day-to-day reproducibility of acuity anywhere along the same meridian stayed within 0.06 log units, i.e., slightly more than one stimulus interval. Training was considered complete following about 2,000
target presentations per subject (about 40 frequency-of-seeing curves). Standard deviations for a single observation ranged between 0.0237 and 0.0889 log units for trained observers, with an arithmetic average of 0.0454. There were no systematic differences in variance between interference fringes and sinusoidal gratings, between various eccentricities, or between the two subjects.

The results given in Figs. 4 and 5 are those obtained following the training period. As expected, there is a monotonic decrease in visual acuity with increasing eccentricity for both interference fringes and sinusoidal gratings. The latter acuity drops more rapidly, however, reflecting an increasingly important image-degrading effect of the dioptric apparatus of the eye. The difference between the two sets of observations for the two observers is statistically significant already from the fact that no more than three out of 24 grating thresholds exceed thresholds for interference fringes. The probability for such an outcome if the two acuities are equivalent is < 0.0013.

The smooth curves fitted to the observed threshold values are second-degree functions, weighted with the inverse variance for single observations. The foveal observations were not included in the regression curves as it was felt that the rapid change in acuity between 10° and 0° of eccentricity needs closely spaced observations to provide meaningful regression functions. The fitted curves explain 98.2 to 99.9 per cent of the total variance. Third-degree functions were also tried but the change in the fraction of explained variance was marginal. It is probable that the inclusion of still more peripheral observations would require higher-degree functions for an equally good fit, however. The parameters of the regression curves are given in Table 1.

The image-degrading effect of the dioptric apparatus of the eye can be demonstrated more clearly by expressing acuity for gratings as a percentage of acuity for interference fringes (Fig. 6). The asymmetry between the nasal and temporal limbs of the curves is not unexpected as refractive errors with oblique incidence frequently show a similar distribution. Likewise, the concavity of the nasal limb of
subject AG may reflect a local deviation from normal retinal curvature, a so-called refraction scotoma.

The results given above for interference fringes must represent nearly maximal performance of the human eye in peripheral vision. There is little, if any, influence by optical aberrations like spherocylindrical ametropia, chromatic aberration, or coma. Scattering of light in the ocular media affects both test methods, however. Diffraction effects in the margin of the dilated pupil are not expected to influence the results inside about 80° of eccentricity (the 3 mm. diameter artificial pupil prevents interaction of the 8 mm. diameter, dilated pupil of the eye inside this angle). An increase of average target luminance above the level used here is not expected to enhance peripheral acuity.\(^1\) Visual acuity for monochromatic targets also appears independent of wavelength and equal to achromatic acuity.\(^1\) Finally, targets were of high contrast, and the observers were well trained. The central visual acuities obtained here (Figs. 4 and 5) compare well with those reported by other investigators.\(^1\)  

**Discussion**

For fully exploiting its inborn potential, the visual system requires an optically satisfactory input during its early developmental period. Uncorrected, major anisometropia (a difference in refraction between the two eyes) is a well-known cause of unilateral amblyopia in childhood. Such amblyopia is usually reversible with an early spectacle correction.\(^1\) Similarly, high astigmatism that is not corrected at an early age appears to result in an irreversibly impaired neural discrimination of targets oriented perpendicularly to the astigmatic axis.\(^1\) Experimental animals deprived from a diversified optical input will likewise suffer an imperfect neural development (see Mitchell and co-workers\(^1\) for references). By analogy, the considerable amounts of spherical ametropia, astigmatism, and coma that characterize refraction in the peripheral field of vision would be expected to set a permanent upper bound on off-axis discriminative ability. It is, therefore, an unexpected finding that interference fringes formed directly on the retina can be better resolved than external sinusoidal gratings imaged in the custom-
Table I. Relationship between peripheral visual acuity (Y, in cycles per degree) and eccentricity angle, ≥ 10°

<table>
<thead>
<tr>
<th>Subject</th>
<th>Target type</th>
<th>Nasal meridian</th>
</tr>
</thead>
<tbody>
<tr>
<td>LF</td>
<td>Grating</td>
<td>[\log_{10} Y = 1.339 - 2.866 \times 10^{-2} X - 1.876 \times 10^{-5} X^2]</td>
</tr>
<tr>
<td></td>
<td>Interference</td>
<td>[\log_{10} Y = 1.361 - 2.865 \times 10^{-2} X + 3.123 \times 10^{-5} X^2]</td>
</tr>
<tr>
<td>AG</td>
<td>Grating</td>
<td>[\log_{10} Y = 1.001 - 2.963 \times 10^{-2} X + 9.733 \times 10^{-5} X^2]</td>
</tr>
<tr>
<td></td>
<td>Interference</td>
<td>[\log_{10} Y = 1.218 - 4.012 \times 10^{-2} X + 3.734 \times 10^{-5} X^2]</td>
</tr>
</tbody>
</table>

ary way. Why does not the peripheral visual system adapt to the limits imposed by the optical system? Although it is possible that optical faults are less pronounced during the early developmental period, it may suffice to consider the fact that different types of visual stimuli are differentially degraded optically. It may thus be that natural stimulation during development with less degraded types of targets keeps acuity for these targets high, and that this discriminative capacity can carry over to, e.g., pattern detection (even if the eye previously never saw such fine patterns), once optical blur is reduced. Incidentally, the fundamental advantage in using sinusoidal test patterns is that these are degraded in terms of contrast content only.

The present results with gratings may actually overrate the performance of the eye under natural conditions. The use of an artificial pupil on the optical axis of the instrument keeps diffraction effects at a low, constant level. With the natural pupil, diffraction effects increase strongly with increasing obliquity of incidence.24

The fact that the peripheral retina of the living eye only exceptionally is optically conjugated to any given distance may in part explain the great variation in results in earlier studies of unaided acuity across the visual field (see Low28 for a review).20-22

Also, many different targets and contrast levels have been used, and little attention has been paid to the size and shape of the pupil as a limiting factor or to training effects.24, 25

Spherocylindrical correction of peripheral refractive errors has been observed to enhance peripheral visual sensitivity.26-28 Most of these studies have been restricted to one or a few directions in the visual field. Only one study covering a full meridian is known to us. Leibowitz, Johnson, and Isabelle29 have documented a substantial improvement in the ability to detect moving targets following spherocylindrical correction of retinoscopically determined refractive errors. The inter-subject variability was also observed to decrease. These differences would probably have been found still more pronounced if coma and other high-order optical aberrations also had been corrected.

Green17 and Enoch and Hope16 also have determined acuity for interference fringes along the temporal meridian, out to 8° of eccentricity. In spite of the use of very similar instruments, depending on Ronchi rulings for beam doubling, these authors obtained widely divergent results outside 2°. It appears that this may be due to difficulties inherent in the Ronchi ruling approach in producing, in the low-frequency range, symmetrical interference fringes free from harmonics and irregularities. Enoch and Hope16 stated that fringe definition was satisfactory only for spatial frequencies exceeding approximately 12 cycles per degree. Such a limit does not occur when a Wollaston prism is used as a beam doubling device, at least not within the frequency range used in this study. It is worthy of note, however, that we found it necessary to introduce a "discontinuity spoiler" in our apparatus to ensure a proper uniformity of the test field (Figs. 2 and 3). Enoch, VanLoo, and Okum30 now use a Wollaston prism instead of Ronchi rulings.

Green17 extended his study of the paracentral temporal area to include determinations of acuity for external sinusoidal grat-
along horizontal meridian (X, in degrees of

<table>
<thead>
<tr>
<th>Temporal meridian</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\log_{10} Y = 1.338 - 2.872 \times 10^{-5} X + 1.217 \times 10^{-4} X^2$</td>
</tr>
<tr>
<td>$\log_{10} Y = 1.375 - 3.009 \times 10^{-5} X + 1.632 \times 10^{-4} X^2$</td>
</tr>
<tr>
<td>$\log_{10} Y = 1.252 - 2.755 \times 10^{-5} X + 1.367 \times 10^{-4} X^2$</td>
</tr>
<tr>
<td>$\log_{10} Y = 1.236 - 2.550 \times 10^{-5} X + 1.289 \times 10^{-4} X^2$</td>
</tr>
</tbody>
</table>

ings. The gratings were generated on an oscilloscope screen, placed 105 cm. from the eye under test. Inside 5° of eccentricity Green's results were analogous to ours, but Green was unable to demonstrate a superior acuity for interference fringes outside this area. Green concluded that peripheral optical aberrations were of little importance in limiting visual acuity outside 5°. While this finding may be due to a regional absence of major optical faults in his two subjects, cautious interpretation of these results seems well advised in view of Enoch and Hope's notes on technical limitations.16

The present study documents a contribution of the optical apparatus in limiting peripheral visual acuity for gratings, and points to the need to include an optical blur factor whenever results from studies on peripheral vision, using external targets, are to be analyzed in terms of retinal architecture. Lack of exact knowledge of the relationship between target position in the visual field, and location of the retinal image, presently hinders a meaningful analysis of this kind.

Marianne Frisén, Ph.D., Department of Statistics, University of Göteborg, performed the statistical analysis. Christian Sjögren, M.A., programmed the computer.

REFERENCES