Visibility of interference fringes near the resolution limit

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The contrast sensitivity of the visual system to interference fringes has been measured in the range from 10 to 65 cycles/deg with a forced-choice psychophysical procedure. Masking produced by the spatial-noise characteristic of coherent fields was avoided by diluting the interferometric field with a fixed amount of uniform, incoherent light. The loss of contrast sensitivity between 10 and 60 cycles/deg ranged from 0.85 to 1.5 log units depending on the observer. Despite these individual differences, the mean contrast sensitivity for six observers at 60 cycles/deg was more than a factor of 8 higher than the most sensitive previous estimates, suggesting that the neural visual system is much more sensitive to fine detail than previously believed. The most sensitive observer required only 4% contrast to detect a 60-cycle/deg interference fringe. Even the shallow interferometric contrast-sensitivity functions reported here are too steep to be explained solely by scattered light at the retina. It is argued that the optical properties of the photoreceptor mosaic make a negligible contribution to the contrast-sensitivity loss between 0 and 60 cycles/deg, and neural factors must be implicated.

The contrast sensitivity of the visual system to interference fringes provides a lower estimate of the contrast sensitivity of the retina and the brain alone, because interference fringes are immune to most sources of optical blurring in the eye.[1] Le Grand[2] was the first to exploit this property of interference fringes to measure neural visual acuity. Since then investigators have used the technique to estimate the optical quality of the eye[3–5] and neural contrast sensitivity[3–12] in addition to neural acuity.[3–20] Laser interferometry is used clinically to estimate the integrity of the neural visual system in patients with optical defects such as cataracts.[5,6,9,19,20]

Measurement of interferometric contrast sensitivity has been hampered by technical difficulties associated with producing and controlling interference fringes on the retina. Williams[12] has recently developed an interferometric technique that, in addition to circumventing optical degradation, offers many of the advantages previously available only with conventional grating stimuli displayed on a cathode-ray tube. His results show that the interferometric contrast-sensitivity function obtained with a forced-choice procedure does not cut off in the vicinity of the resolution limit. Instead, it has a broad shoulder extending to frequencies as high as 150 cycles/deg. Fringes can be resolved in the sense of seeing regular bars for spatial frequencies up to 60–70 cycles/deg. However, above this frequency, observers can still detect the presence of fringes because of the moiré patterns or zebra stripes formed between the fringe and the cone mosaic[4,12,13] and because of color and brightness changes associated with a nonlinear response to the fringe presentation.[4,7,12] The surprisingly high contrast sensitivity found above the resolution limit with the new interferometric technique prompts a careful reassessment of interferometric contrast sensitivity for spatial frequencies up to the resolution limit.

This paper describes an improved method for measuring interferometric contrast sensitivity in the range over which fringes can be resolved in the usual sense, from 10 to 65 cycles/deg. These measurements show that the neural visual system is substantially more sensitive to spatial frequencies near the resolution limit than previously believed. Furthermore, it is argued that the foveal cone mosaic cannot account for much of the loss in contrast sensitivity between 10 and 60 cycles/deg and that most of the loss probably results from neural factors such as spatial summation between cones.

METHOD

Apparatus

The laser interferometer and its calibration have been described elsewhere[12]; only its essential features are outlined here.

Contrast Control

Interference-fringe contrast could be controlled by computer with any desired temporal waveform. Light from a helium–neon laser (632.8 nm) was split into two beams. Each beam was pulsed with an acousto-optic modulator, producing 1-msec-duration rectangular pulses at 400 Hz, a rate well above critical flicker fusion. The two beams were recombined, forming a Maxwellian field containing the interference fringe. A computer controlled the temporal overlap of pulses from the two beams. When the pulses alternated without overlap, no interference was possible, and fringe contrast was zero; when they arrived simultaneously at the retina, the two beams interfered, and fringe contrast was unity. Intermediate fringe contrasts could be produced with partial overlap of the pulses.

This technique manipulates contrast without changing other properties of the field, permitting contrast-sensitivity measurements to be made with a forced-choice psychophysical procedure. Fringe pulses could be presented without changing the space-averaged retinal illuminance of the field and without changing the entry point or the polarization of light in the pupil, reducing the possibility that extraneous cues might signal fringe presentation. Furthermore, the observer always viewed the same field of light regardless of whether an interference fringe was present. Thus any inhomogeneities in the field, such as those produced by inevitable dust parti-

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cles, were continuously present and were not time locked to the fringe presentation.

Spatial-Frequency Control

Spatial frequency could be controlled smoothly without the need to realign the observer. The two point sources, whose separation in the entrance pupil determines the fringe spatial frequency, could be moved symmetrically relative to the Stiles–Crawford maximum. In addition, the path lengths in the two arms of the interferometer were always equal. This ensured that laser coherence length, which can be as short as 10–20 cm in helium–neon lasers,[21] did not reduce fringe contrast.

Stimulus Display and Psychophysical Procedure

The stimulus consisted of a centrally fixated disk of light containing the fringe in a dark surround. Field size was either 1 or 1.5 deg. The interference fringes filling the field were horizontal for all observers except DG, for whom they were vertical.[22] The field was composed of a mixture of 632.8-nm coherent light, used to form the interference fringe, and incoherent light of nearly the same wavelength (630 nm). The incoherent light was obtained from a tungsten source and was added to the coherent field with a beam splitter between the field stop and the final Maxwellian lens of the interferometer. A 2-mm artificial pupil in the incoherent beam was imaged in the entrance pupil of the observer's eye. The image was centered with respect to the interferometric point sources and the Stiles–Crawford maximum.

Figure 1 shows an illuminance profile of the stimulus. The definition of interference-fringe contrast C is

$$C = \Delta I_{\mathrm{coh}}/(I_{\mathrm{coh}} + I_{\mathrm{inc}}),$$

where ΔI_{coh} is the amplitude of the cosinusoidal illuminance variation on the retina, I_{coh} is the space-averaged illuminance of the coherent portion of the total field, and I_{inc} is the illuminance of the incoherent portion of the field. Note that

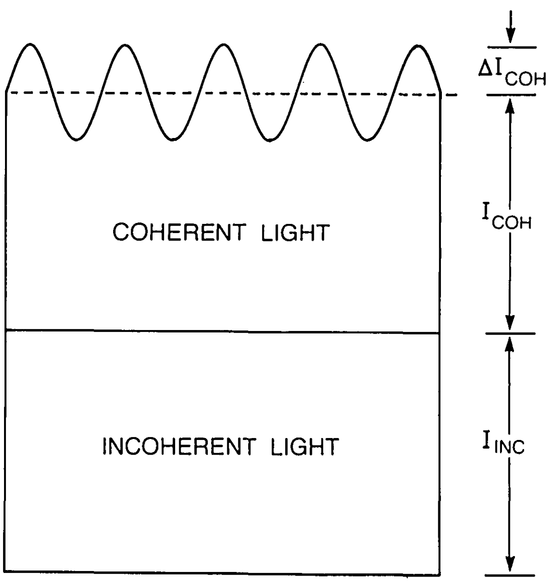

Fig. 1. Components of the field containing interference fringe. I_{inc} is the retinal illuminance of 630-nm incoherent light. I_{coh} is the retinal illuminance of 632.8-nm coherent light. ΔI_{coh} is the amplitude of the cosinusoidal interference fringe. The average retinal illuminance across the field $I_{\mathrm{coh}} + I_{\mathrm{inc}}$ was always 500 Td.

contrast defined in this way is equivalent to the Michelson contrast: the difference between the maximum and the minimum intensity divided by their sum. The retinal illuminance of the combined field ($I_{\mathrm{coh}} + I_{\mathrm{inc}}$) was always 500 Td.

In some experiments the proportion P of the total retinal illuminance that was coherent light was manipulated. It will be referred to as the coherent fraction and is simply

$$P = I_{\mathrm{coh}}/(I_{\mathrm{coh}} + I_{\mathrm{inc}}).$$

Contrast thresholds were measured with a two-interval forced-choice procedure.[12] Threshold was defined as that contrast, estimated with a maximum-likelihood procedure involving 50 trials, that yielded 75%-correct performance. Stimuli were 500-msec rectangular-grating pulses in an otherwise uniform field of equal space-averaged retinal illuminance. On each trial, feedback about whether a correct response had been made was given. Unless otherwise indicated, data represent the mean of four threshold estimates, each based on 50 trials, and error bars represent plus and minus one standard error of the mean. All means and standard errors in this paper are calculated in $\log_{10}$ units.

Observers

All observers had apparently normal color and spatial vision. Right eyes were tested in all cases. The observers, their ages, and their spherical corrections were, respectively, MD, 26 years, −0.75 D; DG, 48 years, +1.5 D; PL, 36 years, −1.0 D; LL, 25 years, 0 D; WM, 49 years, −5.0 D; DW, 30 years, −1.5 D. Although low-order aberrations in the eye do not affect fringe contrast, it is necessary to refract the eye so that the fields formed from the two point sources in the entrance pupil are coincident on the retina. For most observers, this could be done by sliding the field stop defining the interferometric field in the collimated beam just before the final Maxwellian lens. However, for observer WM, an optical correction of −5.0 D was used. This changed the separation of the point sources in the entrance pupil, and a correction factor was applied to produce the appropriate spatial frequencies at the retina. All observers made at least four runs of 50 trials each at each spatial frequency before data collection except DG, who had a single practice run at each spatial frequency.

RESULTS

Masking Effect of Coherent Spatial Noise

Coherent fields viewed by the eye inevitably contain spatial inhomogeneities not present in fields formed with incoherent light. Some of this spatial noise originates in the apparatus, despite meticulous attempts to keep the optics clean. However, the eye itself is a source of noise; irregularities at optical interfaces (particularly the interface between the cornea and the air) and vitreal floaters produce annoying nonuniformities in the field on the retina. Previous interferometric studies have not considered the impact of this noise on contrast sensitivity. The following experiment shows that it can produce potent masking effects.

Figure 2 shows contrast sensitivity for interference fringes when the coherent fraction of the retinal illuminance was 100% (filled symbols) and when it was only 10% (open symbols). Results are shown for two observers, MD (circles) and DW

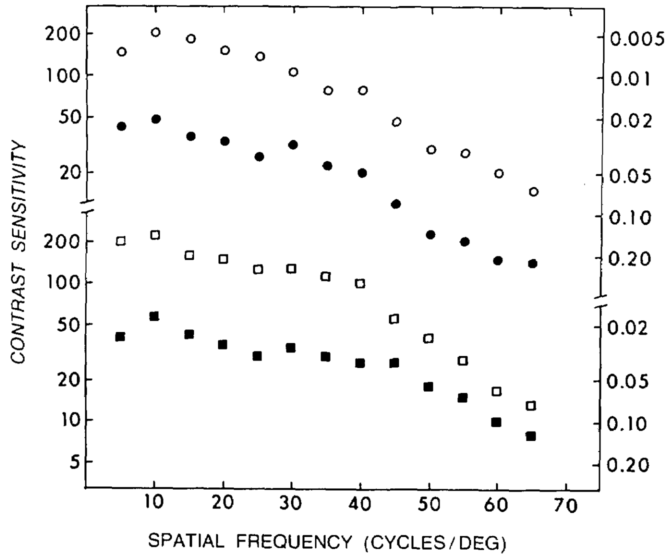

Fig. 2. Interferometric contrast-sensitivity functions obtained with the coherent fraction of the total retinal illuminance P equal to 100% (filled symbols) and 10% (open symbols). Data are shown for two observers, MD (circles) and DW (squares); field size, 1.5 deg.

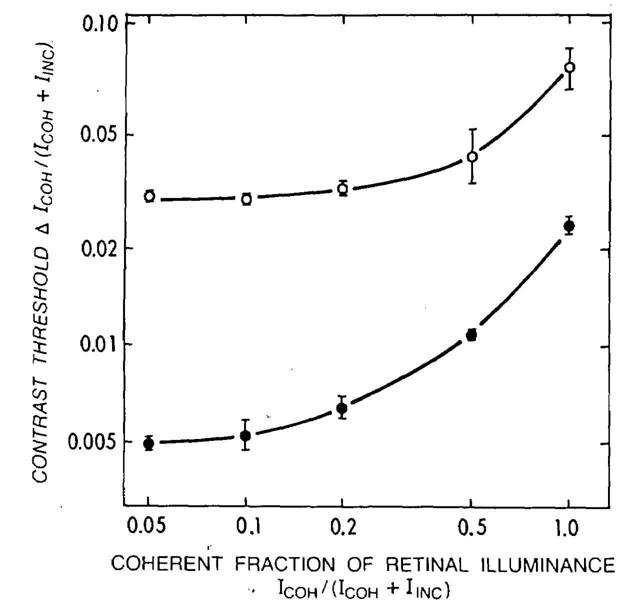

Fig. 3. Contrast threshold as a function of the coherent fraction of the retinal illuminance P for two spatial frequencies, 10 cycles/deg (filled circles) and 50 cycles/deg (open circles). Observer, DW; field size, 1 deg.

(squares). Data represent the mean of two threshold determinations at each spatial frequency. Over the entire range of spatial frequencies from 5 to 65 cycles/deg, fringes could be detected with contrasts less than the 10% maximum imposed by a coherent fraction of 10%. For both observers, reducing the proportion of coherent light in the field increases contrast sensitivity. At low spatial frequencies, this increase is about a factor of 4–5 for both observers. The masking effect for observer MD was not spatial-frequency dependent; it simply vertically displaces the contrast-sensitivity function without changing its shape. However, for observer DW (and for two additional observers not shown), masking was greater at low frequencies than at high, distorting the shape of the contrast-sensitivity function as well as displacing it. Despite the difference between observers, these data are consistent with the hypothesis that the broadband spatial noise in purely coherent fields can markedly reduce sensitivity to interference fringes.

Figure 3 shows the effect of varying the coherent fraction of the total retinal illuminance on contrast threshold for observer DW. Contrast threshold is plotted as a function of the coherent fraction, so that the form of the function resembles contrast-increment threshold functions.[23] Data are shown for two spatial frequencies, 10 cycles/deg (filled circles) and 50 cycles/deg (open circles). When the coherent fraction exceeds about 10%, corresponding roughly to when the spatial noise becomes visible in the field, contrast threshold begins to rise. These results, along with supplementary observations on a second observer, show that the masking effects of coherent spatial noise can be avoided by diluting the interference fringe with a fringe amount of incoherent light, provided that the coherent light accounts for 10% or less of the total retinal illuminance.

Interferometric Contrast Sensitivity for Six Observers

Figure 4 shows contrast-sensitivity measurements for six observers. For clarity, error bars are not shown. However, the standard error of the mean based on four threshold determinations at each spatial frequency rarely exceeded 0.05 log unit for any of the observers. All the data were obtained with a coherent fraction of 10%, except for the data at 55, 60, and 65 cycles/deg for the three least-sensitive observers (DG, WM, and LL). In these cases a coherent fraction of 50% was used because contrast threshold exceeded the 10% maximum contrast available with the coherent fraction set at 10%. For observers DG and WM, measurements made at the same frequency (50 cycles/deg) with coherent fractions of 10 and 50% showed no difference, suggesting that masking effects were negligible for these observers at high spatial frequencies. However, observer LL showed a masking effect at 50 cycles/deg of 0.21 log unit, and the data for observer LL (filled circles) have been slid upward by this amount for these three frequencies.[24]

All the observers reported that their forced-choice decisions

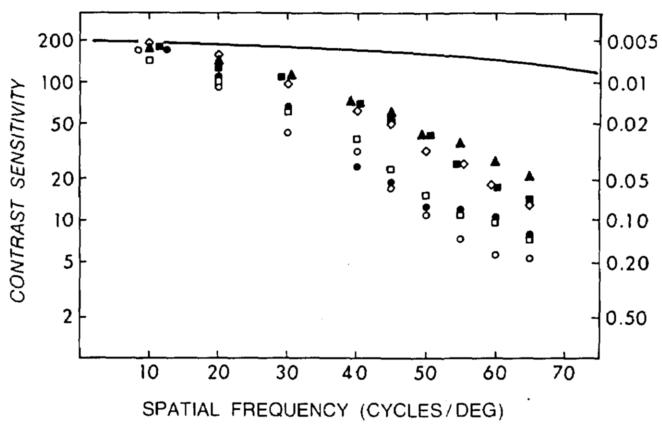

Fig. 4. Forced-choice interferometric contrast sensitivity for six observers between 10 and 65 cycles/deg. The solid line is the modulation transfer function for a circular receptor aperture with a diameter of 0.46 min of arc (2.3 μm). Vertical position of curve is arbitrary. Observers, MD (open diamonds), DG (open circles), PL (filled triangles), LL (filled circles), WM (open squares), and DW (filled squares); field size, 1 deg.

at threshold for fringes of 60 cycles/deg were mediated by the percept of a fine grating. The three most sensitive observers insisted that this was also true at 65 cycles/deg. At higher frequencies, the grating percept was replaced with the aliasing effects described by Williams.[12] As a check that observers were not using some other cue at 60 cycles/deg to detect interference fringes, an orientation-identification experiment was performed on observer DW. The spatial frequency of the fringe was fixed at 60 cycles/deg and the contrast at 10%. The observer was presented with 500-msec grating pulses whose orientation was randomly chosen to be horizontal or vertical on each trial. No feedback about the true orientation of the grating was given. In 20 trials, the observer correctly identified the orientation of the grating 100% of the time.[25]

DISCUSSION

Comparison with Previous Studies

The contrast threshold at 10 cycles/deg for all six observers in this study ranged from 0.5 to 0.7%, roughly the same as the most sensitive previous estimates.[4–6,9,10] At high spatial frequencies (40–60 cycles/deg), however, all six observers were substantially more sensitive than the most sensitive previous estimates, those of Campbell and Green.[4] The mean contrast threshold for the six observers at 60 cycles/deg was 8%, more than a factor of 8 lower than that obtained on the two observers studied by Campbell and Green. Differences in experimental procedure, interferometer design, and observers complicate comparison among this and previous studies. Still, an evaluation of several of these differences yields some insight and suggests several pitfalls in measuring interferometric contrast sensitivity.

Masking by Spatial Noise

The masking effect demonstrated here probably accounts for some of the differences among studies. Williams[12] suggested that masking explained the reduced contrast sensitivity at low spatial frequencies in his measurements with purely coherent fields. The field used by Burton[7] also contained purely coherent light. He modulated interference-fringe contrast by trading the illuminance of the fringe for the illuminance of a coherent field from a second laser. The mean data for the two observers in his study are shown as a dashed line in Fig. 5. The pinstriped area represents the total range of the measurements made on the six observers in the present study. The difference in contrast sensitivity at the lowest spatial frequencies is roughly a factor of 6, not much more than the observed effect of masking at these frequencies, which was a factor of 4–5.

It is tempting to speculate that the low contrast sensitivity at all spatial frequencies obtained by Westheimer[11] (whose data are shown as open squares in Fig. 5) and by Arnulf and Dupuy[3] (filled squares) partly results from coherent noise masking. These investigators, who pioneered the use of interferometry in vision before the invention of the gas laser, formed interference fringes with partially coherent light falling upon a pair of slits, and it is difficult to estimate how much spatial noise might have been present in their fields.

Many studies[4–6,8–10] used polarizers to modulate fringe contrast. *Incoherent* light was exchanged for the coherent light forming the interference fringe. When contrast threshold was low, the coherent field was diluted with homogeneous incoherent light, and masking was probably not a problem. These studies typically reported higher contrast sensitivities at low spatial frequencies than those that used other techniques. However, because the spectral density of the spatial noise in the field covaried with fringe contrast in these studies, masking could occur under conditions for which the contrast sensitivity of the observer was low, i.e., at high spatial frequencies. Thus masking could produce a steepening of the contrast-sensitivity function at high frequencies. Under the assumption that the spectral density of the noise in these studies was comparable with that found here, only measurements made at spatial frequencies for which contrast threshold exceeded about 10% might have been affected. The method of contrast control in the present study has the advantage that contrast can be manipulated without changing the coherent fraction of the retinal illuminance, and noise masking can be avoided with some certainty.

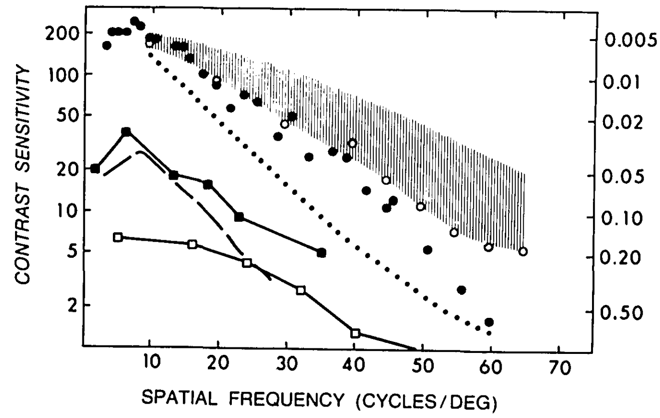

Fig. 5. Comparison with previous studies. The range of interferometric contrast-sensitivity data shown in Fig. 4 for six observers is represented by the pinstripe area. Observer DG, present study (open circles); observer DG, study of Campbell and Green.[4] Dotted line shows second observer (FWC) from Campbell and Green. Arnulf and Dupuy[3] (filled squares), mean of three observers; retinal illuminance, 126 Td; wavelength, 546 nm. Burton[7] (dashed line), mean of two observers; retinal illuminance, 2950 Td; wavelength, 632.8 nm. Westheimer[11] (open squares), mean of three observers; retinal illuminance, 2200 Td; wavelength, 555 nm.

Individual Differences

Contrast-sensitivity measurements with the new interferometric technique were made on DG, who was an observer in the Campbell and Green study.[4] DG's new data are the open circles in Fig. 5, replotted from Fig. 4. His average data from Campbell and Green's study are shown as filled circles; the dotted line shows contrast sensitivity for the second observer (FWC) in that study. The two studies used the same retinal illuminance and wavelength. At high spatial frequencies, DG was the least sensitive of the six observers in the present study and the more sensitive of the two observers in Campbell and Green. This suggests that individual differences in contrast sensitivity at high spatial frequencies account for some of the difference between the two studies. Comparison of the two sets of data is complicated by the fact that they were collected 20 years apart. However, large individual differences at high spatial frequencies were also found by Mitchell *et al.*[10] In the present study, at 60 cycles/deg, the standard deviation of contrast threshold was 0.24 log unit among observers with contrast thresholds spanning a range from about 4 to 18%.

Stimulus Presentation

Above about 40 cycles/deg, DG's contrast sensitivity measured in the present study becomes increasingly higher than that reported in 1965, so that at 60 cycles/deg the data differ by roughly a factor of 3. Part of the discrepancy seems to result from the fact that Campbell and Green used steadily presented fringes instead of pulsed fringes. DG's resolution of interference fringes, assessed with a method-of-adjustment technique in the present interferometer, showed a modest increase when flashed stimuli were used instead of steady ones. High-frequency interference fringes, which can be seen only at the very center of the fovea, fade rapidly with steady viewing. The present technique permits interference fringes to be pulsed, while maintaining a steady state of light adaptation. Pulsing the fringes reduces the problem of habituation and may provide temporal information that helps the observer to distinguish the fringe from the noise that is continuously present in the field.

Psychophysical Method

Previous techniques for measuring interferometric contrast sensitivity have used method of adjustment or method of limits. The forced-choice procedure used in the present study has two advantages: It provides a criterion-free estimate of interferometric contrast sensitivity, and feedback can be provided. Some observers improved by more than a factor of 2 at high but not low spatial frequencies during practice.

In summary, it seems that the discrepancies between the present data and previous work could have resulted from some combination of several factors: masking by coherent noise, individual differences, flashed versus steady stimulus presentation, and psychophysical method.

Factors Affecting Contrast Sensitivity to Interference Fringes

Under ordinary, incoherent viewing conditions, low-order aberrations of the eye and diffraction reduce contrast sensitivity to high spatial frequencies.[26,27] With the use of interference fringes that circumvent these effects, it is of interest to determine what factors then limit contrast sensitivity. It is argued below that the distribution and the size of foveal cones have little effect on contrast sensitivity in the range up to 60 cycles/deg. In addition, stray light cannot account for all the attenuation over this range, and neural factors must be implicated.

Photoreceptor Mosaic

To evaluate the effect of the photoreceptor mosaic on contrast sensitivity, it is useful to consider separately the effects of the size of foveal cones and the pattern of cones in the mosaic. The size of foveal cones could potentially reduce the contrast sensitivity to interference fringes because they integrate light over a finite area. Under the assumption that the aperture of a foveal cone is circular, the contrast of a sinusoidal grating imaged upon the cone is a damped first-order Bessel function of the grating's spatial frequency.[28] Because aliasing can be observed at frequencies at least as high as 150–160 cycles/deg, the photoreceptor aperture at the central fovea is not larger than 2.3 μm.[12,29] The loss of contrast caused by receptor integration is therefore no greater than that shown by the solid curve in Fig. 4. The vertical position of the curve is arbitrary. The curve is nearly flat in the range over which the visual system normally operates (0–60 cycles/deg). It eventually plummets to minus infinity at about 155 cycles/deg, ringing thereafter. Light integration by individual foveal cones can account for only about 0.15 log unit of attentuation at 60 cycles/deg. Over the range from 10 to 60 cycles/deg, contrast sensitivity drops by much more than this, 0.85–1.5 log units depending on the observer, so that the effects of receptor aperture are relatively unimportant.

The effect of cone spacing on contrast sensitivity can be evaluated independently of the effect of receptor aperture by considering a sinusoidal grating of fixed contrast falling on a hexagonal array of points, each point representing the location of the center of a foveal cone. The spacing of these infinitely small points has no impact on the contrast of the output of the array. This is because, over the extent of the grating, samples are likely to be taken at the peak and at the trough of the waveform, and this is sufficient to preserve its contrast in the output of the array. Discrete sampling can, in rare and physiologically unrealistic circumstances, reduce contrast. For example, a singularity occurs if a perfectly regular array samples a grating only at precisely those locations for which the local intensity equals the average intensity. This could happen when a grating is sampled at exactly the Nyquist frequency, and the contrast at the array output would be zero. In real mosaics, however, there is sufficient variation in cone spacing across the central fovea so that at any instant some receptors are centered on bright bars and others on dark bars no matter what the spatial frequency, and contrast would be preserved.

Though photoreceptor sampling does not produce contrast attenuation and therefore does not affect *contrast sensitivity*, it can limit *visual resolution*, in the sense of seeing interference fringes as regular and oriented stripes. Psychophysical[12] and anatomical[30,31] evidence agrees that the minimum spacing between rows of hexagonally packed foveal cones is about 0.5 min of arc. The Nyquist limit for the human foveal mosaic is then expected to be about 60 cycles/deg, and it is at roughly this frequency that the percept of stripes gives way to the distortions expected by photoreceptor aliasing.[4,12] Increasing the frequency above this resolution limit resulted in a scintillating pattern at the center of the fovea. At high contrasts, color and brightness changes also accompany fringe presentation, even at spatial frequencies above the resolution limit.[4,7,12] Because of these phenomena, the resolution limit, in the sense of resolving the stripes of the interference fringe, is not revealed by forced-choice measurements, and contrast-sensitivity measurements show a broad plateau extending from 60 to 120 cycles/deg.[12]

Stray Light

Though the optical properties of the photoreceptor mosaic have little effect on the loss of contrast sensitivity with increasing spatial frequency, effects of intraocular stray light are more difficult to exclude. Some fraction of stray light is scattered by the anterior optics of the eye and some by the retina. Because the scattering source is distant from the retina in the case of anterior scatter, its effect is probably to cast a relatively uniform veil of light across the fovea, reducing contrast sensitivity about equally at all spatial frequencies.

Retinal scatter, on the other hand, could produce a reduction in contrast sensitivity that is spatial-frequency dependent.

Ohzu and Enoch[32] have attempted to measure the effect of retinal scatter by measuring the contrast of gratings imaged onto the isolated human retina. Their technique is likely to overestimate the effect of retinal scatter for at least two reasons. First, the optical quality of the isolated retina deteriorates rapidly following enucleation, and there is no assurance that the measurements reflect optical quality in the intact eye. Second, it may be that the modulation at the site of photon capture, i.e., the outer segments, is higher than the modulation in the image transmitted through the whole retina. In the central fovea, there is little that could produce scatter, since the lips of the inner segments lie near the internal limiting membrane at the floor of the foveal pit. The foveal excavation contains no overlying blood vessels or retinal neurons besides the photoreceptors themselves. Still, if we consider the results of Ohzu and Enoch as an upper bound on the effects of retinal scatter, it becomes clear that stray light cannot account for all the attenuation in interferometric contrast sensitivity between 10 and 60 cycles/deg. Ohzu and Enoch's measurements would suggest, at most, a 0.55-log-unit attenuation over this freuquency range, whereas the contrast-sensitivity measurements drop by 0.85–1.5 log units depending on the observer.

Furthermore, Williams[12] has shown that contrast sensitivity falls more rapidly in this range than at spatial frequencies above 60 cycles/deg, where contrast sensitivity is essentially independent of spatial frequency up to about 120 cycles/deg. Even at 150 cycles/deg, there is sufficient modulation in the retinal image to permit detection, suggesting that stray light is probably not very important up to 60 cycles/deg. These results do not rule out some contributions from stray light, but an additional factor must be invoked to account completely for the drop in contrast sensitivity.

Neural Factors

Since the photoreceptor mosaic has a negligible impact on the attenuation of contrast sensitivity to interference fringes, and stray light cannot account for all of it, neural factors must be implicated. One possibility is that the limitations at high spatial frequencies are really temporal and that fringe visibility is reduced by eye tremor. Eye tremor does not obliterate the detection of interference fringes at frequencies as high as 150 cycles/deg, suggesting that it may not be a highly important factor.

The simplest interpretation is that the residual attenuation of interferometric contrast sensitivity not accounted for by stray light is caused by spatial summation in the fovea, resulting from receptor coupling or neural convergence at some higher stage. The high contrast sensitivity to fine interference fringes reported here places an upper bound on the amount of spatial summation that can occur in the mechanisms mediating high-frequency fringe detection. Indeed, there must be cortical neurons with oriented receptive fields at the center of the fovea that have contrast sensitivity at high spatial frequencies comparable with that reported here.

ACKNOWLEDGMENTS

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24. The implicit assumption in the correction for this observer is that the masking effect is frequency independent within the range of frequencies from 50 to 65 cycles/deg. Although the data of Figs.

2 and 3 for DW show that this is not strictly true for all observers, the change in masking is probably sufficiently small over this small range of frequencies that it can be ignored.

25. This experiment does not rule out the possibility that the observer used the moiré pattern (alias) formed between the grating and the cone mosaic to discriminate between horizontal and vertical gratings, although he insisted that the fringe did not appear distorted in the manner of zebra stripes. In any case, it suggests that the observer did not use the color and brightness changes associated with high-contrast interference fringes to detect 60-cycle/deg fringes near threshold.
26. It may seem that the high-contrast sensitivity to high-frequency interference fringes reported here combined with the known contrast sensitivity to incoherent gratings would yield unreasonably low estimates of the optical quality of the eye. Estimates of optical quality made on a subset of the observers studied here will be given elsewhere. However, preliminary measurements of the incoherent contrast sensitivity of the three most sensitive observers yielded estimates of optical quality falling within the range of estimates from other studies, such as those of Campbell and Green[4] and Campbell and Gubisch.[27]

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