Optical limitations of the Maxwellian view interferometer

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Le Grand's technique for producing interference fringes directly on the retina was analyzed to determine the effect of ocular chromatic aberration on fringe parameters. For monochromatic light, fringe period is largely independent of refractive index of the ocular medium and of the axial location of the interferometer relative to the eye. Lateral displacement of the interferometer, however, shifts the retinal fringes by an amount which depends on wavelength. To close approximation, the relative shift between fringes of different colors is directly proportional to the amount of lateral displacement of the instrument, with the constant of proportionality equal to the longitudinal chromatic aberration of the eye. The net effect is a significant loss of retinal contrast for polychromatic fringes. *Key words:* Ocular chromatic aberration, Maxwellian view interferometer, vision.

I. Introduction

In everyday life, vision begins with the formation of a light image on the retina by the optical system of the eye. Ocular imperfections and diffraction inevitably reduce image quality which may lead to reduced visual performance. In many instances, both in the clinical assessment of potential visual performance and in basic research, it is useful to have available a technique which avoids these optical limitations placed on vision, thus allowing unimpeded stimulation of the remainder of the visual system. Over 50 years ago, Le Grand[1,2] described such a technique based on the formation of Thomas Young interference fringes (Fig. 1). Le Grand's idea was to image a pair of coherent points of monochromatic light in the eye's pupil, a type of arrangement called Maxwellian viewing.[3] Once inside the eye, the coherent sources produce high contrast interference fringes directly on the retina. Because the optical system of the eye is not required to form a retinal image in the conventional sense, Le Grand's method is often said to "bypass the optics of the eye" and for this reason it has been widely used in vision reserch,[4–14] in clinical research,[15–20] and it is the basis for several clinical instruments which are commercially available.

An ingenious extension of Le Grand's technique devised by Lotmar[21,22] avoids the requirement for a costly monochromatic light source (such as a laser) by using white light from an ordinary incandescent bulb. Lotmar's idea was to replace the pair of monochromatic spots with two tiny rainbows containing the full spectrum of wavelengths emitted by the bulb. By arranging for the spacing of corresponding points to vary in direct proportion to their wavelength, the resulting interference pattern on the retina consists of a multitude of sinusoidal fringes, each of a different wavelength but of the same spatial frequency. If the instrument is accurately centered with respect to the optical axis of the eye, and if the only aberrations present are symmetrical about this axis, each of the sinusoidal fringes will have the same spatial phase and the net result will be a high contrast white pattern. However, if the instrument is misaligned, the eye's chromatic aberration may cause a wavelength-dependent phase shift in the component fringes and the net result will be a loss of retinal contrast.[23] Thus, unlike its monochromatic counterpart, the achromatic interferometer is not independent of the eye's optical aberrations. To assess the impact of ocular chromatic aberration on measurements of visual performance by Lotmar's technique, the following theoretical analysis was conducted.

The physical principle responsible for retinal stimulation by Le Grand's method is described above in terms of interference between coherent sources. One method for producing a pair of coherent sources uses a diffraction grating, as illustrated in Fig. 1(B). In this case, the diffraction grating itself might be considered a conventional, transilluminated target seen in Maxwellian view.[3,22] If the grating is located in the first focal plane of the second lens, it will appear to the eye as a distant target and so will be clearly imaged on the retina by an emmetropic eye. Since these two ways of

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treating the Maxwellian view interferometer are so distinctly different, it ought to be possible to trace the interaction between the optical systems of the eye and the interferometer by two entirely separate lines of argument yet arrive at the same conclusions. Accordingly, the problem will be analyzed first as an interferometer and then as a classical Maxwellian view imaging system.

II. Monochromatic Interferometer

The principle of the Maxwellian view interferometer is shown schematically in Fig. 1. Without the eye in place [Fig. 1(A)], collimated monochromatic light of wavelength λ in air is impressed on a diffraction grating which, for simplicity, is assumed to be sinusoidal. A lens focuses the diffracted rays into two spots of light with separation s in air, while the undeviated rays are blocked by a suitably placed stop (not shown). If a viewing screen is placed at a distance x from the sources, where $x \gg s$, the resulting interference pattern will have a sinusoidal profile of period p. Since the separation of adjacent bright fringes corresponds to exactly one wavelength difference in optical path length from the two sources, the linear period p is easily calculated from the geometry[24] to be

$$p = \lambda x/s. \tag{1}$$

When the coherent point sources are moved inside the eye to achieve Maxwellian viewing [Fig. 1(B)], three important changes occur. First, the wavelength of light changes because of the greater refractive index of the ocular media. Second, the spacing of the coherent sources changes because of refraction by the eye's optical system. Third, the axial distance from the coherent sources to the retina changes, also due to optical refraction. Furthermore, each of these changes varies with wavelength because the refractive index of the ocular media varies with wavelength. Thus, to determine the consequences of Maxwellian viewing of the retinal fringes requires an optical model of the eye and its chromatic aberrations.

Emsley's[25] reduced eye model was chosen over more elaborate schematic eye models because it greatly simplifies the analysis and yet accounts well for the chromatic aberration of the human eye.[26] This reduced eye is designed to have the same primary focal length (f = 16.67 mm) and the same secondary focal length (f' = 22.22 mm) as Gullstrand's schematic eye and consists of a single, spherical, refracting surface enclosing a volume of water with variable refractive index n_λ as determined from Cornu's formula.[27] The nodal point of the model lies at the center of curvature of the refracting surface, which has radius $r = f' - f = 5.55$ mm and therefore is invariant with wavelength. Given these parameters, the model is emmetropic for light of nominal wavelength $\lambda_D = 589$ nm (i.e., the sodium D-line) for which $n_D = 1.333$. In what follows, retinal distances will be expressed as angles subtended at the nodal point. To this end, note that the distance d from the nodal point to the retina is

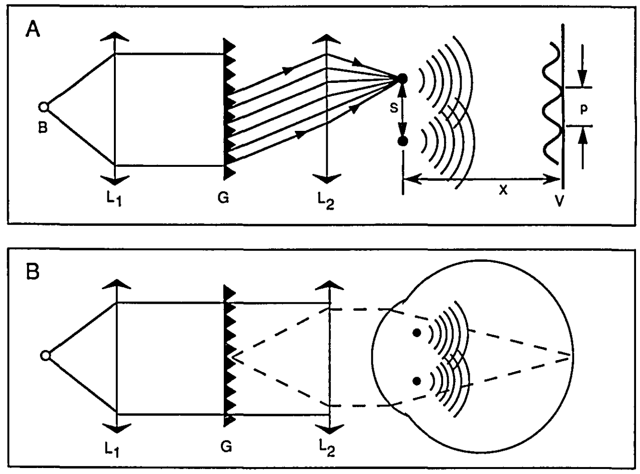

Fig. 1. Principle of operation of monochromatic interferometer seen in Maxwellian view. (A): Interferometer in air. Light of wavelength λ emitted by bulb B is collimated by lens L_1 and diffracted by sinusoidal grating G. Diffracted rays are focussed by lens L_2 into two point sources of separation S. Sinusoidal interference fringes are formed on viewing screen V located at distance X from sources. Linear period of fringes is $P = \lambda x/s$. (B): Interferometer seen in Maxwellian view. Optical system of the eye alters the spacing and location of coherent sources relative to (A) and changes the wavelength of light. Alternative interpretation treats grating as a transilluminated target located in the focal plane of L_2 and thus appearing to be at optical infinity (dashed rays).

$$d = f' - r = f = r/(n_D - 1). \tag{2}$$

The axis of symmetry for the model is the line connecting the retinal locus of interest with the nodal point. For foveal vision by the model eye, this corresponds to the visual axis. To keep the discussion in concrete terms, the foveal locus will be assumed with the understanding that the results have broader scope.

Analysis begins by observing that the two coherent sources that would have been produced in air by the interferometer become virtual objects which are imaged by the refracting surface of the eye, as illustrated in Fig. 2(A). Within the paraxial region, the spacing of the pair of images inside the eye is equal to their spacing in air multiplied by the eye's lateral magnification m. Magnification for the emmetropic wavelength λ_D is found by Newton's formula

$$m = x/f' = x/dn_D, \tag{3}$$

which indicates that the optical magnification varies linearly with x, falling from an initial value of 1.0 when the sources are at the refracting surface ($x = f'$) to the value $1/n_D = 0.75$ when the sources are located in the nodal plane ($x = d$). If this were the only factor to be considered, the effect would be an increase in the period of the retinal fringes by an amount which would depend on the exact location of the sources inside the eye. However, the concurrent reduction in both x and λ counteract this change in spacing so that the fringe period in the reduced eye is exactly the same as it would be in air. Furthermore, this cancellation of

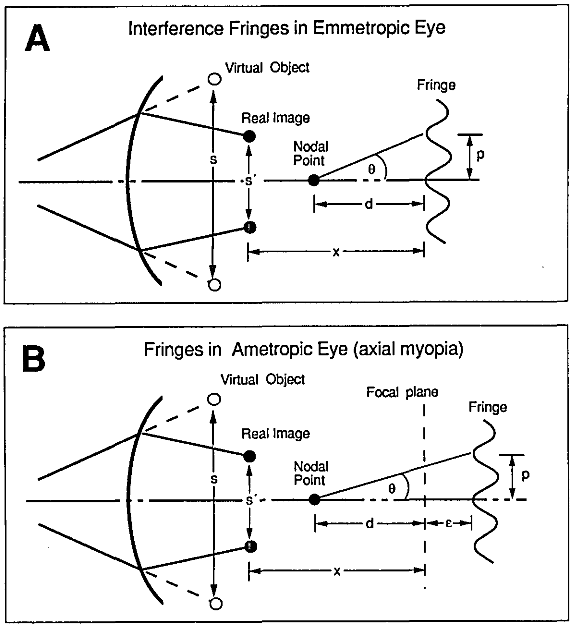

Fig. 2. Geometrical optics of interferometer in Maxwellian view. Coherent sources produced by interferometer in air become virtual sources imaged by refracting surface of reduced eye model. For emmetropic eye (A) fringes are formed in focal plane of refracting surface. For ametropic eye (B) fringes are formed at a distance ϵ from focal plane.

factors occurs for all axial locations of the sources as long as the eye is emmetropic for the wavelength of the sources. To verify these claims, we calculate fringe period on the retina from Eq. (1) by substituting the new wavelength in water λ_D/n_D and the new spacing ms using Eq. (3) and the result is

$$p = \lambda_D d/s. \qquad (4)$$

The practical consequence of this is that the instrument may be calibrated in air according to Eq. (1) even though the interference pattern will be formed ultimately in the watery medium of the eye, possibly without precise control over the axial location of the sources inside the eye.

Although the result embodied in Eq. (4) applies for all x only when the light source is of the emmetropic wavelength λ_D, it may be extended to include any other monochromatic source if the virtual objects are restricted to lie in the nodal plane ($x = d$). In this case the images, which will also fall in the nodal plane, are magnified by an amount $m = 1/n_\lambda$ which depends on wavelength. However, since spacing and wavelength in the eye are both reduced by the same factor, $1/n_\lambda$, their ratio remains unchanged and so must the fringe period according to Eq. (1). Thus the technique can, in principle, avoid the effects of chromatic difference of magnification, caused by variable refractive index of the ocular medium to produce monochromatic fringes which have the same period in the eye as in air.[28]

For vision studies, it is useful to express the retinal period p by the angle subtended at the nodal point of the eye. By this convention, the angular period θ is

$$\theta = \lambda/s. \qquad (5)$$

As argued above, this relation holds for any wavelength of light when the coherent sources are in the nodal plane, or for any axial placement of the sources when the light is of the emmetropic wavelength λ_D. The remaining case of interest occurs when the sources are not in the nodal plane and the eye is not emmetropic. Refractive errors could arise for a variety of reasons including changes in refractive index, curvature of the refracting surface, or axial length of the eye. Regardless of the cause, the effect is the same: retinal fringes will be formed at an axial distance ϵ from the focal plane as illustrated in Fig. 2(B). By retaining x as the distance from coherent sources to the focal plane of the refracting surface and d as the distance from nodal point to the focal plane, Newton's magnification formula still applies but now the full distance from sources to fringes is $x + \epsilon$. Similarly, the angular subtense of one period of the fringe is reckoned according to the distance $d + \epsilon$ and so the angular period becomes

$$\theta = \frac{\lambda}{s} \cdot \frac{1 + \epsilon/x}{1 + \epsilon/d} \cdot \qquad (6)$$

A similar result was obtained previously by distinctly different approaches.[29,30] Note that if the coherent sources are imaged in the nodal plane of the eye, $x = d$ and the angular period θ is exactly the same as in the emmetropic eye, regardless of the magnitude of the refractive error ϵ. Even if the sources are only close to the nodal plane, the change of angular period will be slight as long as $x \approx d$ and ϵ is relatively small. In practice, the limiting factor for employing the interferometric technique with ametropic eyes is that the patches of retina illuminated by the two coherent sources begin to separate and fringes are formed only in the region of partial overlap.

Application of the above result illustrates the small effect of ocular chromatic aberration on fringe period. Chromatic difference of focus causes the focal planes corresponding to the red and blue ends of the visible spectrum to be separated by ~0.5 mm. Chromatic difference of magnification has its greatest effect on fringe period when the coherent sources are just inside the refracting surface. Under these conditions, the change in fringe period across the visible spectrum is <1%.

III. Polychromatic Interferometer

Extension of the design principles of the monochromatic interferometer to include polychromatic light is accomplished by recalling that the spacing of the coherent sources produced by a diffraction grating is proportional to the wavelength of light.[24] Consequently, if the wavelength doubles, the spacing of the coherent diffraction pattern shown in Fig. 2 also doubles. Therefore, the ratio λ/s remains unchanged and, according to Eq. (5), the angular period of the resulting fringes remains unchanged. Thus Lotmar's technique takes advantage of a physical property of the diffraction grating to systematically vary spacing of the coherent sources in a way that exactly compensates for the wavelength variation of the grating's spatial frequency.[31] The result is a polychromatic family of retinal fringes with common spatial frequency.

Although the component fringes produced by a polychromatic interferometer will have a common spatial frequency, they must also have a common spatial phase (i.e., peaks and troughs must align) to achieve high contrast white fringes on the retina. This condition will be obtained if the coherent sources are placed symmetrically about the visual axis as illustrated in Fig. 2(B). However, if the interferometer axis is displaced from the visual axis, the retinal fringes will be displaced. If the direction of displacement is parallel to the fringes the consequences are slight. However, displacement in other directions causes a change of spatial phase of the fringes. As will be shown below, the resulting phase shift varies with wavelength because of the chromatic aberration of the eye, and the end result is reduced fringe contrast. To assess the severity of this contrast attenuation, it is first necessary to determine the amount of phase shift induced by lateral displacement of the interferometer.

Figure 3 illustrates the consequences of displacing the interferometer upwardly in the plane of the diagram by an amount h from the visual axis. To expose the core of the problem for analysis, four simplifying assumptions are adopted. The first is that the virtual objects are located in the nodal plane, which implies the images are also in the nodal plane and that the lateral magnification is $m = 1/n_\lambda$. Second, the spots are assumed to remain in the paraxial range so that translation of the spots does not affect magnification. Third, to reduce the problem to the geometry of right triangles, we assume that the chief rays of the two bundles forming the coherent objects are approximately parallel to the visual axis. Finally, to show the maximum effect, the direction of displacement is assumed to be orthogonal to the retinal fringes (e.g., horizontal displacement of vertical fringes).

We may now conceive of interferometer displacement as having two competing effects on the fringe pattern. First, since the images of the two coherent point sources move upward with the interferometer, the retinal fringe pattern must also move upward. However, a second effect partially counteracts this fringe movement. Note that the displacement of the interferometer increases the distance traveled by light rays in air but decreases the amount of distance traveled in water as they pass to form the image of the upper point source. Conversely, the rays traveling to the lower image travel less in air and more in water. Because light travels faster in air than in water, light will arrive at the upper image before it arrives at the lower image. In other words, displacement causes a change in the optical path lengths to the two coherent images which results in a relative temporal delay. Since the upper source leads the lower source in time, the retinal fringe pattern will move downward. If the net amount of movement due to these two factors were independent of wavelength, displacement of the interferometer would have little consequence. However, as shown next, net phase shift varies with wavelength in a manner that can be related directly to the amount of chromatic aberration of the eye.

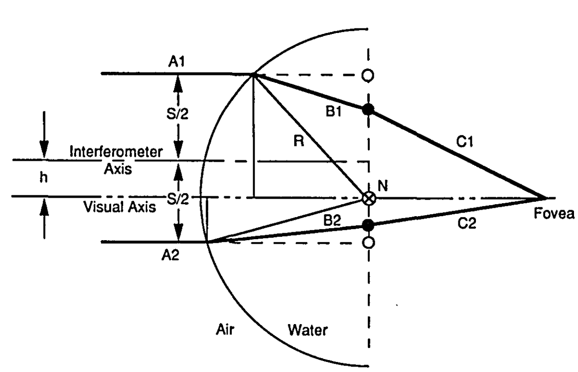

Fig. 3. Changes in location of coherent sources and optical pathlengths when interferometer is decentered distance h from visual axis. Images (closed points) of virtual objects (open points) are shown in nodal (N) plane. Paths of two rays which interfere at the fovea are each divided into three segments: (A) from center of exit lens L_2 of the interferometer to the refracting surface of the eye, (B) from refracting surface to the image of the coherent source, (C) from source image to retina.

Consider first the translation effect. If the point midway between the two virtual objects moves upward by an amount h, the midpoint of the two images moves by an amount $mh = h/n_\lambda$. When referenced to the nodal point, this linear translation of the retinal fringe corresponds to an angular shift ϕ of amount

$$\phi = h/n_\lambda d. \tag{7}$$

Substituting for d according to Eq. (2) yields

$$\phi = h(n_D - 1)/n_\lambda r. \tag{8}$$

This analysis shows, as perhaps might have been expected, that the angular shift ϕ of the retinal fringe is directly proportional to the amount of displacement h. To see how ϕ varies with wavelength, let $\Delta\phi$ be the relative difference in ϕ for gratings of two wavelengths, denoted by subscripts R (red) and B (blue). Then from Eq. (8) we find the chromatic difference of position for the fringes to be

$$\Delta\phi = \phi_R - \phi_B = \frac{h(n_D - 1)}{r}\left(\frac{1}{n_R} - \frac{1}{n_B}\right). \tag{9}$$

The fact that this expression is positive indicates that although the red and blue fringes both move upward when the interferometer moves upward, the red fringes move slightly more.

Now consider the temporal delay effect caused by a difference in optical path length for rays passing to form the two coherent images. The portion traveled in air is shown in Fig. 3 by segments A_1 and A_2. By the Pythagorean theorem, their difference is

$$A_1 - A_2 = \sqrt{r^2 - (s/2 - h)^2} - \sqrt{r^2 - (s/2 + h)^2}. \tag{10}$$

If $h + s/2$ is small compared to r, application of the power series approximation $(1+x)^m = 1 + mx$ simplifies Eq. (10) to

$$A_1 - A_2 = hs/r. \tag{11}$$

To find the phase shift induced by this difference in path length we divide by λ because the interference fringes will shift one full period for each wavelength difference in path length. Then, multiplying by the angular period of the fringes, λ/s, gives the angular shift ϕ of the pattern on the retina

$$\phi = h/r. \tag{12}$$

This approximate result indicates that the angular shift caused by a change in the path length in air is nearly independent of wavelength and so makes insignificant contribution to the chromatic difference of position that is of interest here.

By a similar line of argument, the difference in path length taken by rays in water leads to angular displacement

$$\phi = h(1 - 2n_\lambda)/n_\lambda r. \tag{13}$$

The chromatic difference of position for red and blue gratings is then

$$\Delta\phi = \phi_R - \phi_B = \frac{h}{r}\left(\frac{1}{n_R} - \frac{1}{n_B}\right). \tag{14}$$

The fact that this expression is positive indicates that although the red and blue fringes both move downward because of the change in optical path length, the red fringes move slightly less.

Comparing Eqs. (9) and (14) reveals that the chromatic difference of position due to translation is only ~1/3 as great as that due to temporal delay. Since both effects leave the red fringe above the blue in the foregoing example, the two equations may now be added to find the total relative displacement of red and blue fringes due to lateral displacement of the interferometer. The result is

$$\Delta\phi = \frac{hn_D}{r}\left(\frac{1}{n_R} - \frac{1}{n_B}\right). \tag{15}$$

This result may be interpreted in terms of the eye's chromatic aberration as follows: The chromatic difference of power ΔP of the refracting surface of the reduced eye is $(n_B - n_R)/r$. However, it is more common to express the eye's longitudinal chromatic aberration as a chromatic difference of refraction.[32] This amounts to the dioptric difference between those red and blue points in object space which are conjugate to the fovea. For the reduced eye, the difference of refraction ΔR_X is just $\Delta P/n_D$ or

$$\Delta R_X = (n_B - n_R)/rn_D. \tag{16}$$

Combining Eqs. (15) and (16) gives

$$\Delta\phi = \frac{n_D^2}{n_R n_B}(h\Delta R_X). \tag{17}$$

Since the refractive index of water varies by <1% over the visible spectrum, the ratio of indices in Eq. (17) is very nearly unity. This leads to the final approximate result

$$\Delta\phi = h\Delta R_X. \tag{18}$$

In summary, we have found that, to first approximation, the chromatic difference of position for interference fringes on the retina is directly proportional to the amount of lateral displacement of the interferometer from the visual axis. The constant of proportionality is the longitudinal chromatic aberration of the eye, expressed as a refractive error. In physical units, if h is in meters and R_X is in diopters $\Delta\phi$ is in radians.

IV. Numerical Analysis

Although conceptually it is helpful to partition the effect of displacement of the interferometer from the visual axis into two factors, translation and temporal delay, the problem may be solved numerically simply by computing the total path length difference:

$$\Delta\text{path} = (A_1 + n_\lambda B_1 + n_\lambda C_1) - (A_2 + n_\lambda B_2 + n_\lambda C_2), \tag{19}$$

and proceeding as above to find the corresponding angular displacement of the interference fringes. Such a numerical approach has the advantage of avoiding the simplifying assumptions made earlier and so extends the analysis to the nonparaxial region. Using standard methods of geometrical optics,[33] the exact locations of the coherent images formed by the refracting surface of the reduced eye model were calculated by computer. From the results we determined the change of path length and the corresponding shift of a red and a blue interference pattern. The resulting chromatic difference of position was evaluated as a function of displacement of the interferometer. The wavelengths chosen for analysis were the Fraunhofer G (434 nm) and B (687 nm) lines, which are the wavelengths for which the spectral sensitivity of the CIE standard observer falls to 1% of maximum. The chromatic difference of refraction of the reduced eye for these wavelengths is 1.36 diopters or 4.67 min of arc/mm. Calculations were performed for that range of values of s corresponding to the limits of visual acuity (0 to 60 cycles/deg) and for a variety of longitudinal positions of the coherent sources within the eye. The results depended little on these parameters and representative results are shown in Fig. 4 for a low (3 cycles/deg) and high (30 cycles/deg) fringe frequency when the coherent sources are imaged in the nodal plane (A) or in the pupil plane (B). The straight line in the figure is the paraxial prediction given by Eq. (18). As expected, this linear function describes the results well in the paraxial region but becomes increasingly inaccurate for large displacements of the interferometer.

To help gauge the significance of these results, consider the case where the red and blue fringes have shifted one-half period so that the peak of one aligns with the valley of the other. The corresponding angular shift is 10 min of arc for a 3 cycles/deg fringe (20/200 Snellen equivalent) and 1 arcmin for a 30 cycles/deg fringe (20/20 Snellen equivalent). From Fig. 4 we may conclude that these amounts of angular shift will occur

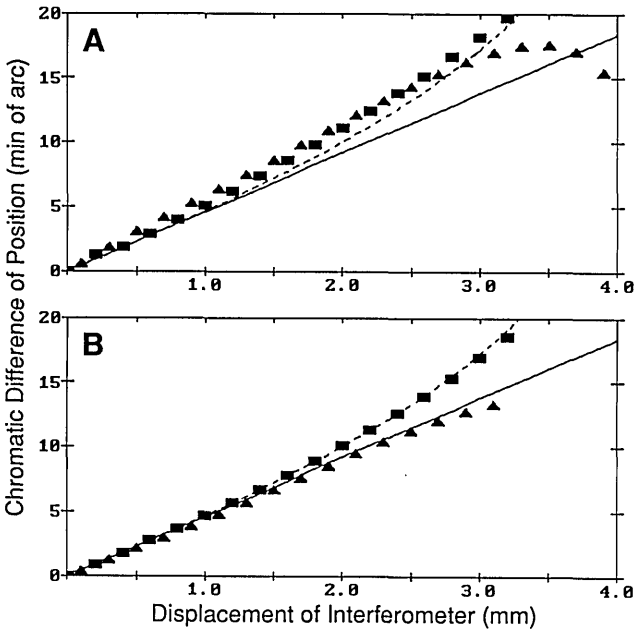

Fig. 4. Relative displacement of red (687 nm) and blue (434 nm) fringes caused by displacement of interferometer. Paraxial theory predicts solid curve (slope = 4.67 min/mm = 1.36 diopters) and symbols show numerical results for fringe frequency of 3 cyc/deg (squares) and 30 cyc/deg (triangles). Coherent sources are imaged in nodal plane (A) or in pupil plane (B). Dashed curve shows transverse chromatic aberration (referenced to object space) for natural viewing through a displaced, artificial pupil.[26]

when the interferometer is displaced by ~2.0 mm and 0.2 mm, respectively. Thus even small amounts of interferometer displacement may have significant effect on the relative position of fringes of different wavelength.

V. Maxwellian View Analysis

When treated as a conventional Maxwellian view optical system, the stimulator presents the sinusoidal diffraction grating as a distant transilluminated target. Such a target might at first be thought the same as an ordinary self-luminous grating. However, there is one important difference which is relevant here. For ordinary targets, it is the pupil of the eye which selects that bundle of rays which will pass on to stimulate the retina. For the interferometer, the rays are constrained to travel as two narrow bundles on opposite sides of, and nearly parallel to, the optical axis of the instrument as they pass through two small, closely spaced regions within the pupil plane. Consequently, parallel displacement of the interferometer relative to the visual axis will strongly affect the angle of incidence of incoming rays at the surface of the eye. This in turn will determine the amount of chromatic dispersion of the refracted bundles and so the location of the retinal image will vary with wavelength.

To analyze the situation quantitatively, we follow the path of a hypothetical chief ray traveling along the axis of the interferometer as illustrated in Fig. 5. Such a ray represents the mean direction of the two bundles

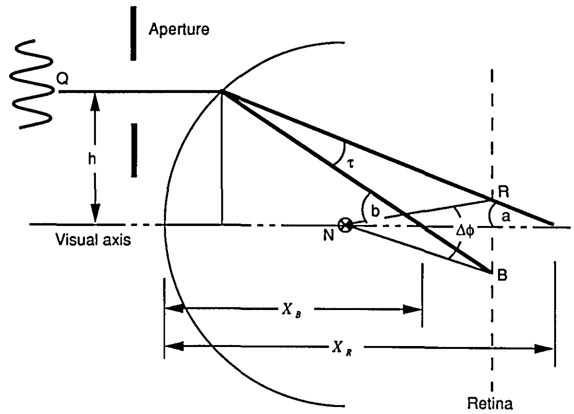

Fig. 5. Interferometer treated as a conventional view of distant target seen through a decentered aperture. Chief ray for red and blue wavelengths intersect visual axis at distances X_R and X_B, respectively. Chief ray for reference point Q on object intersects retina at points R and B, respectively, thus creating a chromatic difference of position $\Delta\phi$ for the two images.

of rays and will locate the geometric center of the retinal image. Because of the dispersive properties of water, the chief ray will be refracted more for blue wavelengths than for red. The angle τ between the refracted chief rays determines the relative position of the red and blue retinal images, expressed as the angle $\Delta\phi$ subtended at the nodal point. Let X_R and X_B represent the distances from refracting surface to the intersection of the visual axis with the red and blue refracted chief rays, respectively, and let a and b represent the corresponding angles between the axis and chief rays. Then from the Gaussian law of refraction we have

$$\frac{n_B}{X_B} = \frac{n_B - 1}{r}, \tag{20}$$

$$\frac{n_R}{X_R} = \frac{n_R - 1}{r}, \tag{21}$$

and applying the paraxial approximation $x = \tan(x)$ we find

$$\tau = b - a = h/X_B - h/X_R. \tag{22}$$

Combining Eqs. (20), (21), and (22) gives

$$\tau = \frac{h}{r}\left(\frac{1}{n_R} - \frac{1}{n_B}\right). \tag{23}$$

Recognizing that angles referenced to the nodal point are larger than those referenced to the refracting surface by the ratio $f'/d = n_D$ we conclude that

$$\Delta\phi = \frac{hn_D}{r}\left(\frac{1}{n_R} - \frac{1}{n_B}\right), \tag{24}$$

which is precisely the same answer obtained in Eq. (15) when the system was analyzed as an interferometer.

VI. Discussion

This study describes the interaction between the optical system of the eye, as represented by Emsley's[25] reduced eye model, and a Maxwellian view optical system for producing interference fringes directly on the retina. Because the light sources are imaged inside the eye in a Maxwellian view arrangement, changes occur in the spacing, axial position, and wavelength of the sources. However, analysis reveals that these changes have little or no effect on fringe period. For example, if the coherent images are placed in the nodal plane of the eye, fringe period in the eye is the same as it would be in air for any wavelength of light, regardless of the value of the refractive index of the ocular medium. On the other hand, if the eye is emmetropic for the wavelength of the coherent sources, the fringe period is independent of the axial location of the coherent sources within the eye and depends only on the wavelength and spacing of the two coherent sources in air. These surprising results may be understood as follows: The reason the change of index of refraction has no effect is because fringe period varies as the ratio of wavelength to spacing. Since both of these factors vary inversely with n_λ, their ratio remains fixed. Similarly, the reason fringe period is insensitive to the axial location of the coherent sources within the eye is that fringe period varies as the ratio x/s (see Fig. 2), but s varies directly with x according to Newton's magnification formula [Eq. (3)] so their ratio remains fixed. Thus, as the sources move across the refracting surface into the eye they get closer to the retina and so the period should decrease. However, the spacing of the sources also decreases due to the optical refraction of the eye, which increases period by the same factor so there is no net change.

Although the interferometric technique was described originally by Le Grand for monochromatic light, the method was subsequently extended by others to utilize polychromatic light.[21,22] This introduced the possibility that ocular chromatic aberration might affect the parameters of the retinal fringes. Analysis shows that because the interferometric method is largely insensitive to refractive error, chromatic difference of focus will have little effect on fringe period. However, if the interferometer is displaced from the visual axis of the eye in a direction other than parallel to the fringes, the fringes will suffer a change of spatial phase which is wavelength dependent. Three independent methods of analysis lead to the same conclusion that, within the paraxial region, the relative shift of fringes of different wavelengths is directly proportional to the amount of displacement of the interferometer. For displacement orthogonal to fringe orientation, the constant of proportionality in this equation is the longitudinal chromatic aberration of the eye, expressed as a chromatic difference of refraction.

A similar situation arises in the context of viewing ordinary targets. If the eye's natural pupil is displaced from the visual axis, or if the observer views through a displaced, artificial pupil, then the rays which pass on to stimulate the retina are those which strike the refracting surfaces of the eye obliquely. The resulting dispersion of the spectrum thus causes the image of a white point source to be spread out across the retina as colored fringes. By the same argument, red and blue points in object space must have different visual directions in order to form a common retinal image. This manifestation of the eye's transverse chromatic aberration has been analyzed previously for the reduced eye model and verified experimentally in human psychophysical experiments.[26] Within the paraxial region, the result is the same as found here for the Maxwellian view interferometer. That is, the chromatic difference of position of a red and a blue point of light having a common retinal image is directly proportional to the amount of displacement of the artificial pupil from the visual axis and the constant of proportionality is equal to the longitudinal chromatic aberration of the eye. Even beyond the paraxial region the two optical problems have a common solution as may be judged from the close fit of the numerical results in Fig. 4 to the theoretical curve (dashed line) describing the transverse chromatic aberration of the eye when viewing through a displaced aperture.

It is not coincidental that the amount of transverse chromatic aberration present for normal vision through a decentered pupil matches the chromatic displacement of fringes produced by a decentered Maxwellian view interferometer. Displacement of the interferometer and displacement of an artificial pupil both increase the angle of incidence of the bundle of light rays entering the eye in the same way. Since the angle of incidence determines the angle of refraction by Snell's law, it follows that the chromatic dispersion of the retinal image, as determined by chief ray analysis, will be the same in both cases.

Operationally, the most important consequence of chromatic phase shifts in the retinal fringes is loss of contrast. Given the equivalence established above, previous calculations of the modulation transfer function (MTF) for viewing through a displaced artificial pupil[34] are immediately applicable to the present case of a polychromatic, Maxwellian view interferometer. Since those earlier calculations considered only the demodulating effect of transverse chromatic aberration and ignored the effects of defocus or diffraction, they are appropriate also for the interferometer. For present purposes, calculations were repeated for values of displacement in the 0–3-mm range in steps of 0.5 mm and the resulting MTFs are shown in Fig. 6(A). Evidently even small amounts of displacement have a profound effect on retinal contrast.

Since the primary motivation for employing the interferometric technique is to produce retinal stimulation that is unaffected by optical aberrations of the eye, the results of Fig. 6(A) are rather discouraging. To help gauge the severity of the loss of contrast caused by ocular chromatic aberration, it is helpful to contrast these results with corresponding MTFs for natural viewing through a displaced pupil. To include the defocusing effects of longitudinal chromatic aberration, the procedures were augmented with Hopkin's[35] solution for the MTF of a defocused optical system. The results are shown in Fig. 6(B) for a 3-mm rectangular pupil. Comparison of the two data sets in Fig. 6

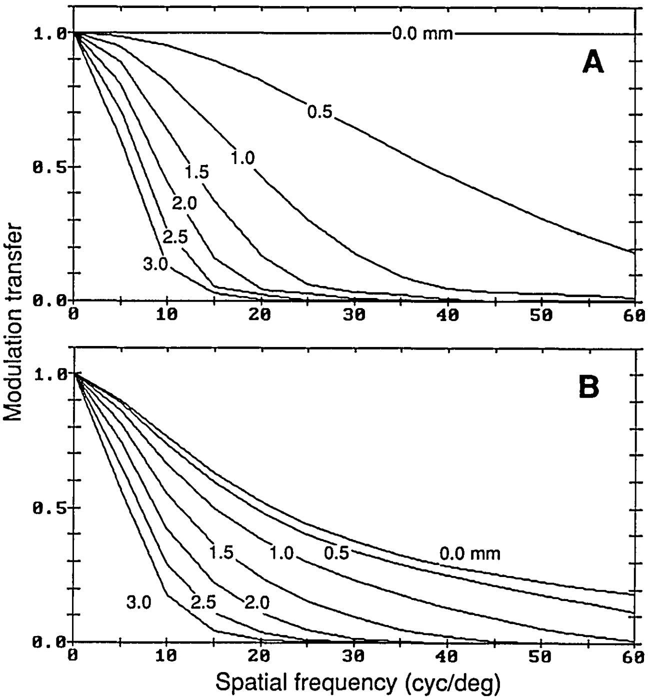

Fig. 6. Polychromatic MTF for displaced interferometer (A) and natural viewing (B) through a displaced artificial pupil (3 mm diameter). Numbers near curves indicate amount of displacement in mm. Tungsten (2798 K) source.

indicates that if the interferometer is displaced by >1.0 mm, retinal contrast will be less than that obtainable with ordinary viewing through a centered pupil. Thus, unless particular attention is paid to accurate centering of the interferometer on the visual axis of the eye, any potential benefits of the polychromatic interferometer are likely to be lost. Even with this precaution, the lack of a true optical axis or the presence of asymmetrical aberrations in real eyes could compromise retinal contrast.

Surprisingly, retinal contrast can actually be higher for natural viewing when the pupil and the interferometer are equally displaced. This result demonstrates an unexpected benefit of longitudinal chromatic aberration.[26,36] When significant amounts of transverse chromatic aberration are present, the addition of longitudinal chromatic aberration actually improves retinal contrast. The reason is the defocusing effect of longitudinal chromatic aberration narrows the range of wavelengths for which significant contrast is present in the retinal image, thus defeating the mechanism by which transverse aberration reduces contrast.

In summary, the combined MTF of the eye and polychromatic interferometer deteriorates rapidly as the instrument is moved off axis and so the technique loses its advantage over natural viewing. The advantage may be restored by appropriate choice of fringe orientation or by the use of monochromatic light.

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