6

CUES FOR ACCOMMODATION

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One of the challenges for those seeking to understand accommodation is the nature of those factors associated with the initially blurred retinal image of an out-of-focus object that triggers an appropriate accommodation response. In practice, it appears that ocular accommodation responds to a wide array of cues to image focus, distance, and depth. These cues include ray or wavefront vergence of light from objects in the environment and the wavefront aberrations of the eye itself;[1-6] monocular depth cues such as linear perspective, interposition, and changing size (looming); and binocular depth cues, such as disparity.[7-10] In addition to optical cues, accommodation responds to perception per se and to cognitive and voluntary behaviors such as attention, intention, and prediction.[11-13]

Disagreement about the role of contrast, spatial frequency, and aberrations stems from the instructions given to subjects before and during experiments, voluntary accommodation and training, use of stationary targets that are relatively easy to focus rather than using moving targets, and wide interpatient variation in accommodation among the population. Blur feedback and voluntary focusing behaviors can obscure the role of contrast, spatial frequency, aberrations, and depth cues when the target is stationary. Moving targets (eg, step, sine, sum-of-sine) and instructions to "keep the target clear by using the same amount of effort as when reading a book" expose the response to cues more readily than instructions to "use maximum effort to eliminate blur and keep the target absolutely clear." Automatic reflexive focusing of the eye with limited voluntary accommodation is best examined using random step changes in focus and sinusoidal modulations of wavefront vergence at temporal frequencies between 0.2 and 2.0 Hz (see Chapter 5).[14]

LUMINANCE CONTRAST AND SPATIAL FREQUENCY

Accommodation responds using retinal cones at photopic luminances[15] above approximately 1 candela/m^2 (1 nit) and at illuminances above approximately 1 lumen/m^2 (1 lux). At lower light levels, accommodation is biased toward the resting position of accommodation or dark focus,[16,17] which averages approximately 1.50 D and varies widely among the population (0 to 4.00 D; see Chapter 4, Figure 4-7). Contrast or modulation of a grating target ($E_{max} – E_{min}/E_{max} + E_{min}$) is the difference between the illuminance of bright bars (maximum) and dark bars (minimum) divided by their sum. Some patients can accommodate to stationary targets that have very low contrast (eg, 3%), whereas others require contrast to be above approximately 20%.[18] Dynamic accommodation to step and sinusoidal changes in target distance (wavefront vergence) increases linearly with contrast between zero and approximately 25%, with minimal increase in

Pallikaris IG, Plainis S, Charman WN.
Presbyopia: Origins, Effects, and Treatment (pp. 51-58).

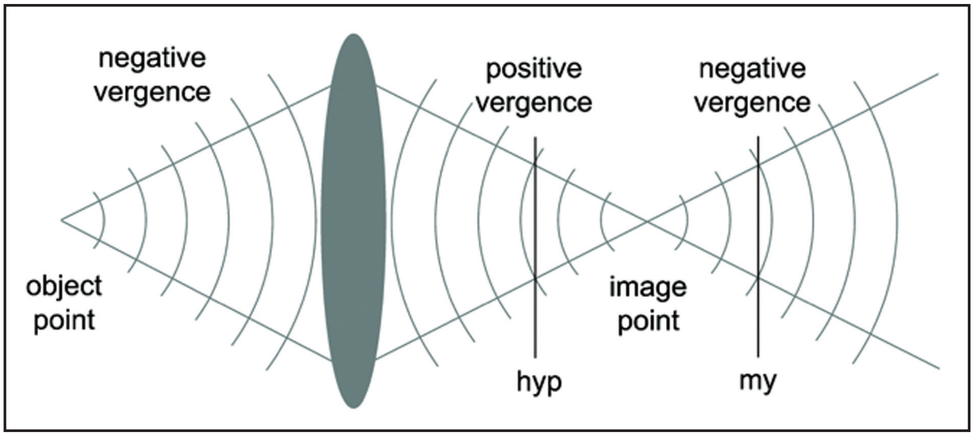

Figure 6-1. Ray and wavefront vergence from an object point reaches the eye (shown as a lens) with negative vergence. After refraction, wavefront vergence is positive at the retina in hyperopic defocus (hyp) and negative in myopic defocus (my).

gain at higher contrasts.[19,20] At low spatial frequencies (below approximately 0.3 c/deg), wavefront vergence and aberrations of the eye have no effect on contrast of the retinal image and do not drive accommodation. Dynamic accommodation responds best at intermediate spatial frequencies between 0.5 and 10 cpd with maximum gain between 3 and 5 cpd, where effects of aberrations, especially defocus and chromatic aberration, are moderate and together provide strong, reliable, directional cues.[6,14,18,19] At higher spatial frequencies (15 to 30 cpd), the retinal image is blurred by higher-order aberrations and by small amounts of defocus that obscure cues to wavefront vergence.

In the standard photographic camera model of the accommodating eye, perfect optics and precise focus are an ideal, and aberrations are regarded as abnormalities, imperfections, flaws, and distortions that blur fine details, reduce spatial contrast, and alter phase, especially at high spatial frequencies (eg, 30 cpd corresponding to a visual acuity of 20/20). In the camera model, the eye accommodates to focus an image on the retina by maximizing luminance contrast at high spatial frequencies, using feedback from defocus-blur as an even-error cue. In an ecological approach,[7,21,22] the accommodating eye adapts its refracting power to wavefront vergence from the environment as part of the perceptual-motor process. This approach uses effects of aberrations on chromaticity-contrast and luminance-contrast to focus and examine image and environment. The polychromatic blur spread function has a high degree of ecological validity, especially at intermediate spatial frequencies, where it supplements and confirms perspective and pictorial cues to distance and relative depth while dynamic accommodation oscillates an image behind and in front of the retina.

OPTICAL VERGENCE OF RAYS AND WAVEFRONTS

A long line of evidence suggests that the visual system detects and responds to optical; ray or wavefront vergence for everyday accommodation[23]; emmetropization[24] (ie, the long-term coordinated growth and development of cornea, lens, and axial length of the eye toward emmetropia); and perception of edges, distance, and depth.[25,26] Figure 6-1 shows optical vergence of rays and wavefronts from a point in the environment. Diverging rays and spherical wavefronts have negative vergence that specifies distance as the radius of the wavefront's spherical curvature at the eye. A biconvex lens (model eye) changes the vergence of rays and wavefronts from negative to positive. Rays converge to an image point and diverge beyond the image point so that wavefront vergence then becomes negative. Retinal location is indicated for myopic and hyperopic defocus; in the hyperopic case, the vergence at the retina is positive, whereas it is negative in the myopic case.

Accommodation

Most striking is that accommodation responds to tiny changes in wavefront vergence (<0.10 D) that are much smaller than DOF and well below the threshold for perception of blur.[27] In addition, accommodation responds to wavefront vergence without blur feedback from defocus, chromatic aberration, or higher-order aberrations.[23,28] This suggests that something more than blur of the retinal image specifies wavefront vergence and drives accommodation.

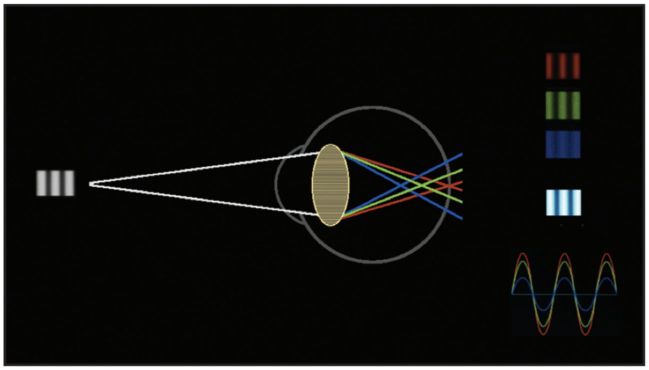

Figure 6-2. Negative wavefront vergence from a white grating target. Grating targets are alternating bright and dark bars where contrast or modulation $(E_{max} - E_{min} / E_{max} + E_{min})$ is the difference between the illuminance of the bright bars (maximum) and dark bars (minimum) divided by their sum. At the eye, refraction and chromatic dispersion alter wavefront vergence as a function of wavelength. For the case of the relatively myopic eye as illustrated, the longitudinal chromatic aberration of the eye results in the red image being in better focus than the green and blue images. Ratios of contrasts of red, green, and blue waveband components of the image specify myopic defocus. The illuminance profiles for the grating images at 3 wavelengths are shown in the bottom right of the figure.

Animal Models of Myopia and Emmetropization

The developing eyes of fishes, chicks, guinea pigs, tree shrews, cats, marmosets, and monkeys compensate for positive and negative wavefront vergence induced in lenses by changing axial length.[24] Hyperopic defocus accelerates the rate of elongation and thins the choroids of chicks, whereas myopic defocus slows the rate of elongation and thickens the choroid. Scotopic luminances (dark rearing) and low contrast at intermediate spatial frequencies trigger myopia development, but the monochromatic directional signal for the sign of wavefront vergence (Zernike defocus) remains obscure.[24]

Perception of Distance and Depth

Wavefront vergence is also a cue for depth perception.[25,26] Depth order can be detected from wavefront vergence in broadband white light, but most observers have difficulty in monochromatic light where the effects of chromatic aberration of the eye are absent. Ocular longitudinal chromatic aberration[29] amounts to more than 2.00 D when extrapolated across the entire visible spectrum (360 to 760 nm). In white light, ratios of red, green, and blue contrasts of the retinal image, measured separately by cone type (L-, M-, and S-cone contrasts), specify relative depth at intermediate spatial frequencies (Figures 6-2 and 6-3). Note in Figure 6-2 that, for the relatively myopic eye shown, contrast is highest at long wavelengths. This suggests that the grating object is farther away than the object on which the eye is sharply focused. Alternatively, the information could provide a cue to the accommodation response required to focus on the grating. Similarly, in Figure 6-3, longitudinal chromatic aberration provides information on both the relative distance of an edge and the direction of the accommodation response required to focus it.

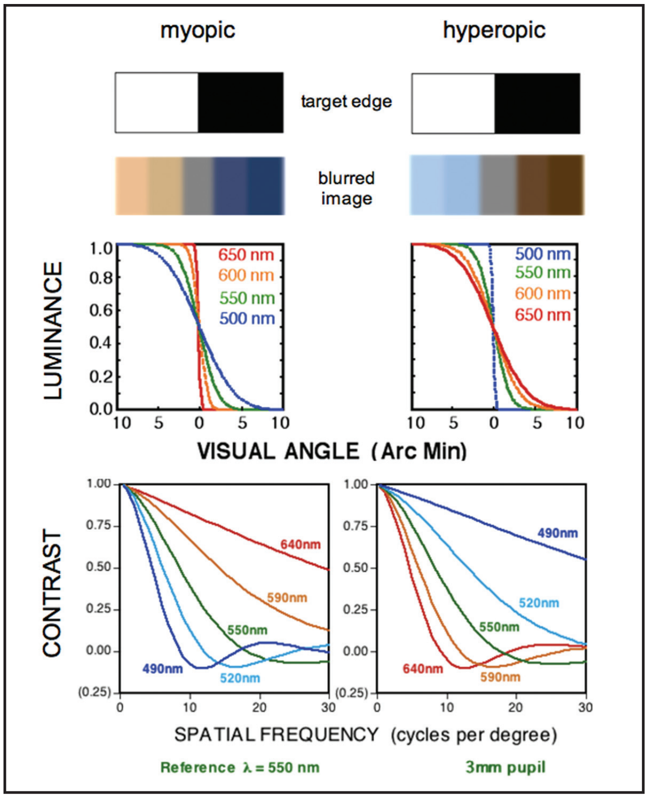

Figure 6-3. Luminance edges are shown (white-black targets) at the top of the figure with blurred images for myopic and hyperopic defocus. Edge spread functions (middle) and modulation transfer functions (lower) for diffraction-limited images with and without defocus and longitudinal chromatic aberration. Higher-order aberrations are not included. In the left-hand case, the slightly myopic eye brings the red image at 650 nm into focus so that shorter wavelengths are out of focus, which results in the bright side of the edge appearing slightly red and the dark side slightly blue (top). In contrast, if the eye is slightly hyperopic (right side), the blue image will be in focus, and the edge will appear slightly blue on the bright side and slightly red on the dark side, as shown schematically in the figure. The lower part of the figure shows the corresponding modulation transfer functions at different wavelengths for a 3-mm pupil.

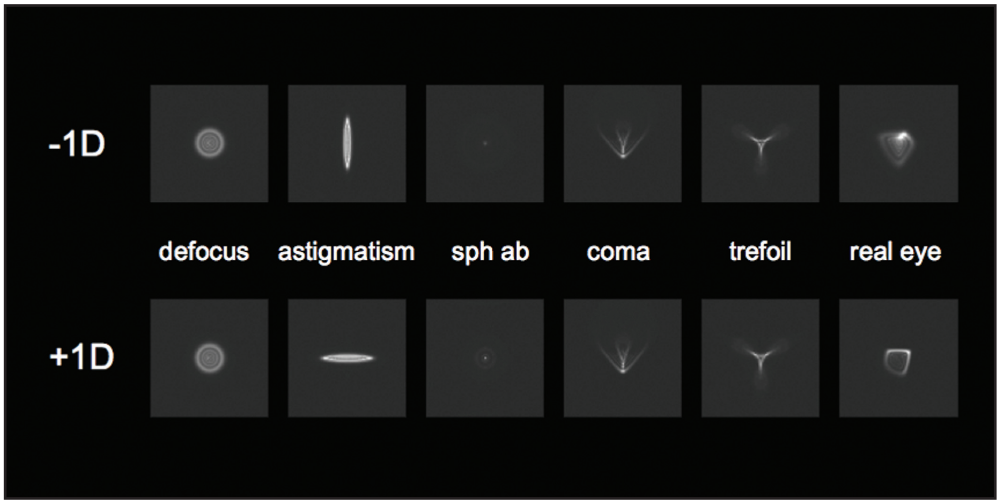

Figure 6-4. Point-spread functions for positive and negative defocus alone and with astigmatism, spherical aberration, coma, trefoil, and for a real eye. The assumed pupil diameter is 5 mm, and the Zernike coefficients for each of the individual higher order aberrations is 1 μm.[30]

ABERRATIONS OF THE EYE

Refraction and chromatic dispersion across the pupil area change wavefront vergence as a function of wavelength, providing dioptric cues at edges for accommodation, emmetropization, and perception in the form of polychromatic blur of the retinal image.

Blur From Defocus

Monochromatic blur from defocus alone is essentially the same for over- and under-accommodation (Figure 6-4).[30] In engineering terms, defocus blur is an even-error signal with amplitude but without sign (+ or -). Both myopic defocus and hyperopic defocus reduce contrast of the image, and computer-generated images that simulate blur from defocus alone do not drive accommodation.[31]

Blur From Chromatic Aberration

Longitudinal chromatic aberration alters wavefront vergence as a function of wavelength,[29] providing the sign of defocus and relative depth as ratios of contrasts of red, green, and blue waveband components of the retinal image (see Figures 6-2 and 6-3). Thus, ratios of contrasts measured separately by long, middle, and short wavelength-sensitive cones specify wavefront vergence and relative depth and drive accommodation and emmetropization.[32,33] In this model, L-cone-contrast > M-cone-contrast specifies myopic defocus and reduces accommodation, whereas M-cone-contrast > L-cone-contrast specifies hyperopic defocus and increases accommodation for near. The color signal is mediated by 2 chromatic opponent mechanisms—(L–M) that compares L-cone and M-cone contrasts and [S–(L+M)] that compares S-cone contrast and luminance (L+M) contrast.

Blur From Higher-Order Aberrations

Higher-order aberrations, including coma and spherical aberration, skew and distort the intensity distribution of the point-spread-function (blur disc) so that blur is asymmetric and has a different shape for myopic and hyperopic defocus, thus providing a potential odd-error cue (see Figure 6-4). Six recent investigations of the effect of higher-order aberrations are summarized below to demonstrate the diversity of accommodative responses.[28,30,31,34-36]

In theory, blur of the retinal image from even-order aberrations (second and fourth orders) is different for myopic and hyperopic defocus, but blur is the same for odd-order aberrations (third and fifth orders).[30] Thus even-order aberrations, such as second-order astigmatism and fourth-order spherical aberration, provide the sign of defocus; but odd-order aberrations such third-order coma and trefoil do not (see Figure 6-4). Theory assumes round, centered pupils, although these are unusual for most eyes. To test the theory, normal and large amounts of coma (0.34 and 0.94 μm for a 5-mm pupil diameter) or trefoil (0.25 and 1.03 μm) were added to the aberrations of the eye.[30] Normal amounts of additional coma or trefoil had no effect on gain and temporal phase of accommodation, and large amounts reduced gain and increased temporal phase lag. On the other hand, the velocity of accommodation to step changes of negative vergence decreased, whereas latency and accommodative error remained unchanged when coma and trefoil were removed by adaptive optics.[34]

Two studies found 1 of 5 patients unable to accommodate in monochromatic light when higher-order aberrations were removed by adaptive optics.[28,35] A minority of observers (perhaps 20%) cannot respond to wavefront vergence alone (Zernike defocus) without blur from high-order aberrations. On the other hand, 4 of 5 patients in both studies continued to accommodate effectively to unpredictable positive and negative step changes of wavefront vergence when higher-order aberrations were removed. Inversion of even-order aberrations (astigmatism and spherical aberration) reduced gain to positive (outward) steps but not to negative (inward) steps of wavefront vergence.[35]

In another study, accommodation was evaluated using staircase changes of wavefront vergence (0 to 6.00 D) with and without the patient's normal higher-order aberrations and with additional positive or negative spherical aberration (±1 µm for a 6-mm pupil diameter) or vertical coma (-2 µm).[36] Four of 5 patients accommodated more accurately without their natural high-order aberrations, but 1 accommodated most accurately with natural higher-order aberrations present. When additional negative spherical aberration was added, lag of accommodation decreased, and lag increased when additional positive spherical aberration or coma were added. Fluctuations of accommodation increased when additional high-order aberrations were added, especially at near distances (-3.00 to -6.00 D).

In a different approach, computer-generated blurred images were used to simulate 3 levels of defocus (-1.00 D, 0 D, +1.00 D) for 4 experimental conditions consisting of combinations of the absence or presence of blur from the patient's own higher-order aberrations and Stiles-Crawford function.[31] Eleven patients viewed the simulations of blurred images through a 0.75-mm pinhole pupil. Defocus-blur did not drive accommodation with or without the patient's own Stiles-Crawford effect. However, blur from defocus with the patient's own higher-order aberrations produced a small, statistically significant, accommodative response (gain = 0.14). Although higher-order aberrations produced a small response for the group, some individuals rely on higher-order aberrations in reduced cue environments.

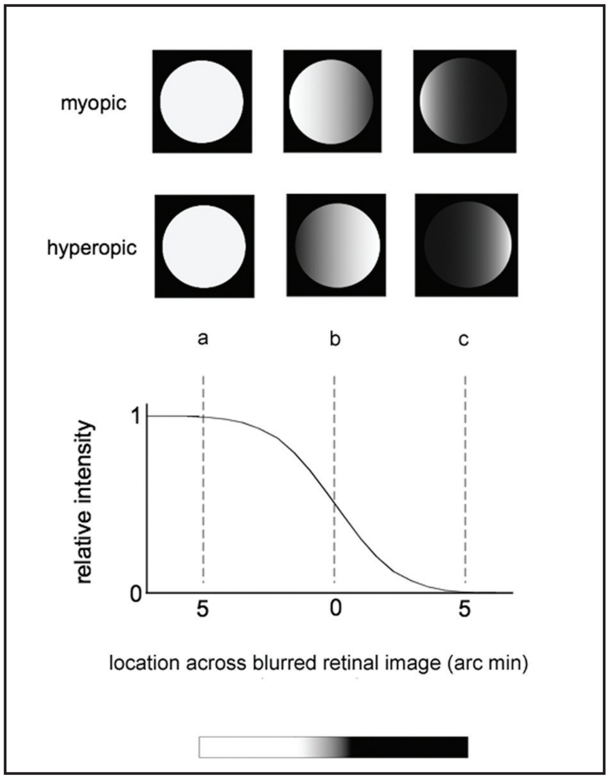

Figure 6-5. Modulation of light across the exit pupil of the eye as a function of location across an edge blurred by defocus.

Synchronized Modulation Across Pupil and Retina

The small response to open-loop simulations of monochromatic blurred images[31] compared with the large response to wavefront vergence per se[23] suggests that something besides blur specifies the amplitude and sign of defocus. One possibility is that the eye monitors wavefront vergence across the pupil in conjunction with blur across the retina. Images of moving edges that are blurred by inaccurate focus (defocus) are characterized by changes in the angle of incidence of light across the blurred edge, accompanied by modulation of light across the exit pupil of the eye, similar to the "with" and "against" motions of clinical retinoscopy. Figure 6-5 shows static modulation of light across the pupil (top) as a function of location across the retinal image of a vertical edge blurred by inaccurate focus (Gaussian defocus-blur). At the brightest margin of the blurred edge, light from all parts of the pupil contributes to the retinal image, and the mean direction of light is from the pupil center. At the middle of the blurred edge, mean direction of light is midway between pupil center and one side of the pupil. Finally, at the darkest margin of the blurred edge (dark tail), mean direction is from the pupil margin alone. For a vertical edge, the phase of modulation across the pupil (bright on the right or left side), compared with phase of modulation across the visual field or retina, provides the sign of defocus (myopic or hyperopic). Thus, relative motion across the retina and pupil ("with" or "against" motion) is a potential cue to wavefront vergence, distance, and relative depth.

WIDE INTERPATIENT VARIATION AND MECHANISMS FOR OPTICAL VERGENCE DETECTION

Remarkably, wide interpatient variation in accommodation to the variety of optical cues is a hallmark of accommodation. Voluntary accommodation, and the variety of physiological mechanisms that each individual develops to detect and respond to wavefront vergence, may explain this variation. Some observers accommodate strongly in monochromatic light, whereas others respond poorly or not at all. Proposed mechanisms for detecting changes in the angle of incidence of light at edges blurred by defocus include modal patterns in individual cones that changes as wavefront vergence changes, and comparison of signals from small clusters or subgroups of cones that sample from slightly different areas of the pupil. Accommodation to chromatic aberration also varies among observers. Some may not develop the retinal neurophysiology to measure contrast separately by L-cones and M-cones and then compare contrasts at intermediate spatial frequencies (3 to 5 cpd).[32] The retinal neurophysiology for wavefront vergence detection per se remains largely unknown.[24]

PERCEPTION AND DEPTH CUES

Accommodation also responds to the perception of depth from cues such as linear perspective, interposition, and binocular disparity.[7-10] Similar to accommodation to wavefront vergence, the response to perspective and pictorial cues varies widely among observers and is best examined under open-loop conditions where the response is not restrained or masked by feedback from blur. Without blur feedback, accommodation responds strongly to "looming" targets that appear to approach and recede over time. The patient's familiarity with characteristics of the target plays a role in the magnitude of the looming response.[37]

These findings support a mutual or "transactional" relationship[7] between accommodating observer and environment, mediated by optical cues that describe the surroundings with varying degrees of ecological validity.[21,22] In an ecological approach, the accommodating eye exhibits prehensile behaviors[38]; oscillating the 3-dimensional aerial image in front and "behind" the retina; reaching, grasping, manipulating, and releasing cues that specify ocular focus, edge type, distance, and depth. Here, dynamic accommodation, binocular convergence, eye and head movements, and locomotion are coordinated exploratory behaviors mediated by optical cues.

As clinicians and scientists develop new therapies for treating presbyopia and myopia, including advanced optical devices for restoring functional accommodation, individual differences in accommodation to wavefront aberration, depth cues, and perception become a relevant clinical concern.

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