

Convergence accommodation

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Steady-state accommodation responses were measured in both eyes as a function of vergence angle and direction of lateral gaze. The measurements were made with a binocular laser optometer. Small speckle patterns were used as fusional stimuli in an otherwise dark field. These patterns have the advantage of providing no blur stimulus to accommodation. Convergence accommodation for vergence angles ranging from 0 to 25 deg was measured for lateral-gaze angles of +32, -32, and 0 deg. The average accommodation of the two eyes was linearly related to vergence angle over the observer's accommodative range but was independent of the angle of lateral gaze. The mean convergence accommodation/convergence ratio for three subjects, in diopters per meter-angle, was 0.9. Our measurements of convergence accommodation using laser-speckle targets are in good agreement with previous studies that used small pupils. Accommodation responses for binocular viewing of letters of a Snellen chart were also measured. When luminance was reduced, night myopia was observed. No similar effect was found for convergence accommodation. Accommodation to a dim target corresponded closely to the convergence accommodation.

INTRODUCTION

Convergence accommodation is an accommodative response that accompanies a change in the state of convergence of the eyes. The existence of some form of interaction between convergence and accommodation has been known at least since the work of Porterfield in 1759.¹ Donders² was probably the first person to study convergence accommodation quantitatively.

Convergence accommodation can be demonstrated by holding the light vergence at the retina constant while the accommodation is measured as a function of the convergence of the eyes. As the angle of convergence is increased, the eyes accommodate as if to focus objects nearer and nearer.

In 1940, Fry³ defined convergence accommodation as "that amount of accommodation which is fully associated with convergence when the need for exact focusing has been eliminated." We use Fry's definition in this paper. It suggests that convergence alone, in the absence of blur, can drive accommodation. However, it was not until the mid-1950's that convergence accommodation was clearly demonstrated.⁴⁻⁸ For a review, see Ref. 9.

The most thorough study was probably that of Fincham and Walton.⁶ They found that accommodation was linearly related to convergence angle. For young subjects (to age 24), accommodation in diopters was approximately equal to the convergence in meter-angles. For older subjects, equal changes in convergence led to smaller changes in accommodation.

Several questions remain from the studies of convergence accommodation. First, the effect of lateral-gaze angle on convergence-accommodation responses has not been examined. For convergence upon a point along the midline, Fincham and Walton reported that convergence accommodation in young subjects leads to a state of focus that is "appropriate" for the point fixated.⁶ Accommodation is said to be appropriate when the accommodation in diopters equals the convergence in meter-angles. However, it is not known whether

convergence upon points off the midline leads to appropriate accommodative responses as well. We measured steady-state accommodation in both eyes while varying not only the convergence angle but also the angles of lateral gaze.

Second, questions have been raised concerning the adequacy of small pupils for eliminating the blur stimulus to accommodation in earlier studies.^{10,11} Recently, Miller,¹¹ using very small fusion targets (0.08 mm) found a considerably weaker dependence of accommodation on convergence than had been found previously. Ripps *et al.*¹² and Alpern¹⁰ have suggested that, even with small pupils (0.5 mm), there might be sufficient blur stimulus to accommodation. They suggested that the problem might be overcome by using interference patterns as fusional stimuli in measurements of convergence accommodation. The sharpness of an interference pattern formed by coherent light on the retina is independent of the eye's refractive state. Speckle patterns used in laser optometers have this property.¹³ We have independently confirmed this property.¹⁴ In our experiments, we used a laser-speckle fusional stimulus for convergence that remained sharp regardless of the state of accommodation of our observers.

The third question concerns night myopia. There is a considerable body of evidence that points to the tendency of accommodation to return to an intermediate resting state in the absence of adequate stimulus to accommodation. This is manifest in night, instrument, and empty-field myopia.^{13,15,16} If a fusional stimulus is sufficient for appropriate convergence accommodation, we would not expect accommodation to fail in low illumination so long as fusion could be maintained; we would not expect night myopia to occur for binocular viewing in the absence of diplopia. But Owens and Leibowitz¹⁷ report exactly such a result for their subjects when they viewed dimly lit acuity charts. Moreover, Fincham¹⁸ reported that accommodation and convergence are uncorrelated in the dark. We approached this problem by measuring convergence accommodation using fusional targets of low and high luminances.

BINOCULAR LASER OPTOMETER

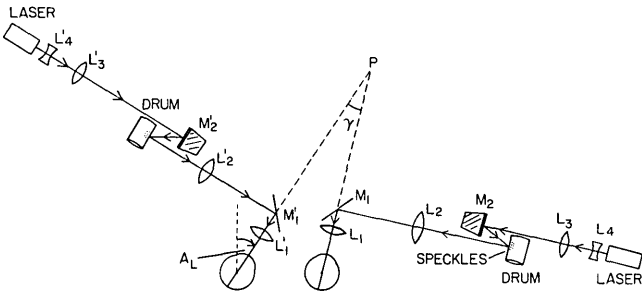


Fig. 1. Schematic diagram of the binocular laser optometer. Laser-speckle-fusion targets appear to be at position P. Position P was varied by pivoting the two arms of the optometer about points beneath the centers of rotation of the eyes.

METHODS

Apparatus

We constructed a binocular laser optometer for measuring steady-state accommodation in both eyes. Figure 1 presents a schematic representation. The optometer actually consists of two monocular laser optometers. The principles underlying the laser optometer method for measuring accommodation have been described by Charman¹⁹ and by Hennessy and Leibowitz.²⁰

The two monocular optometers can be pivoted about points directly below the center of rotation of the eyes. For the right eye's monocular optometer, a He-Ne laser beam is broadened and collimated by lenses L_3 and L_4 in Fig. 1. The collimated light passes over the top of the drum and is then reflected by mirror M_2 onto the drum's diffusing surface. The right eye views the drum through supplementary lens L_1 and Badal lens L_2 . The light reflected from the drum's surface generates an interference pattern on the retina known as a speckle pattern. When the drum is made to rotate slowly, the apparent velocity of speckles in the speckle pattern seen by the observer depends on the distance between the drum's plane of stationarity and the conjugate image of the retina. The observer moves the drum along an optical rail between L_2 and L_3 until there is no apparent net velocity of the speckles. This position uniquely determines the accommodation of the eye. The left eye's monocular optometer works in exactly the same way.

Because the speckle pattern is an interference pattern formed on the retina, it remains sharp independently of the state of focus of the eye. This property suggested its use as a convergence stimulus. The speckle pattern can be thought of as a random-dot pattern whose spatial statistical properties are independent of focus. It has only a statistically defined border. The power spectrum of the speckle pattern is independent of any aberration.²¹ Although the speckle pattern for each eye is uncorrelated with the other, the subjects had no difficulty fusing the patterns because the mean speckle size is small in comparison with the 1-deg diameter of the speckle pattern.

To make a measurement of accommodation in one of the eyes, the following procedure was used. The two drums were initially stationary. The optometers were rotated about their pivot points until the two speckle patterns fell in visual directions that intersected at the desired point of fixation, point P in Fig. 1. In this way, the speckle patterns were used to form a target for convergence at point P. Then one of the

drums was set to rotate. While maintaining fusion on the convergence target, the observer adjusted the position of the drum on the rail to null the motion of the speckles.

Definitions

In Fig. 1, γ represents the vergence angle and A_L the left angle of lateral gaze. The definitions of these angles are elaborated in Fig. 2.

The circle of equal vergence angles is defined as the circle through the centers of rotation of the two eyes and the fixation point. This is closely related to the Vieth-Mueller circle, which passes through the nodal points of the two eyes and the fixation point. The angle made between the two lines of sight is the vergence angle γ . From geometry, it can be shown that, as the point of fixation P moves along the circle of equal vergence angles, the vergence angle is constant. The left angle of lateral gaze A_L is defined as the angle between the left eye's line of sight and the straight-ahead. The right angle of lateral gaze is defined similarly. Counterclockwise angles are taken as positive. If the interocular distance is known, the lateral-gaze angles uniquely specify any point in the horizontal plane. Points in the horizontal plane can also be specified in terms of vergence angle γ and version angle ϕ . The version angle ϕ is the angle between the midline and the line joining the point of fixation to the midpoint C of the arc between the two eyes.

It is convenient at times to express vergence in meter-angles.¹⁰ The vergence in meter-angles is equal to the vergence in radians divided by the interocular distance in meters.

Procedure

We conducted two experiments on convergence accommodation. The first experiment addressed the question of appropriate asymmetric convergence accommodation. The results were compared with results of previous researchers who used small pupils. The second experiment addressed the issue of binocular night myopia. Accommodation was measured in diopters relative to the cornea.

The first experiment examined the effects of convergence angle and lateral-gaze angle on accommodation. A given experimental session was devoted to the measurement of accommodation in both eyes while the lateral-gaze angle was held constant for one eye and the vergence angle was varied. There were four conditions for each observer. In two condi-

CIRCLE OF EQUAL VERGENCES

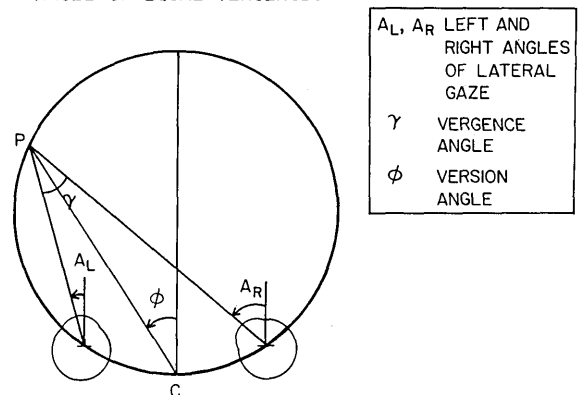


Fig. 2. Diagram illustrating definitions of various angles. The large circle passes through the centers of rotation of the two eyes.

tions, left lateral-gaze angles were held constant at 0 and -32 deg. In the other two conditions, right lateral-gaze angles were held constant at 0 and $+32$ deg. For example, suppose that the right lateral-gaze angle is 32 deg. The left lateral-gaze angle is now varied from 32 deg to 7 deg, and vergences ranging from 0 to 25 deg result. For each condition, convergence was incremented six times in 5 -deg steps. At each position, two readings were taken, one from below and one from above. The session was repeated, providing a total of four readings for each point. The order in which the data were collected was randomized.

In a related measurement, we sought to make a more-direct assessment of the role of lateral-gaze angles on convergence accommodation. We measured accommodation for vergence targets on contours of constant vergence angle. Data were collected along three circles of equal vergence specified by vergence angles of 0, 10, and 20 deg. The version angles for which accommodation measurements were taken ranged from $+30$ to -30 deg. The version angle was varied in 10 -deg steps. Two readings were taken at each point.

In the second experiment, we measured accommodation responses to letters (subtending 1 deg), on a Snellen chart consisting of black letters on white cardboard, as a function of distance. Different-sized letters were used at different distances to maintain the 1 -deg subtense. There were three conditions. In the first and second conditions, the observer viewed a bright (85 -cd/m²) and a dim (0.1 -cd/m²) Snellen chart, respectively. In the third condition, the convergence accommodation was measured. The speckles had an average luminance of 100 cd/m². The subjects were instructed to maintain best focus on an edge of a letter. In order to assess the effects of target luminance in the absence of a blur stimulus, we also measured convergence accommodation using dim (1 -cd/m²) speckle-fusion stimuli.

Observers

Five emmetropic observers participated in the experiments. All had $20/20$ acuity or better and normal stereopsis. TP is a 20 -year-old female. HK is a 23 -year-old female. DP is a 20 -year-old female. GR is a 30 -year-old male. DK, one of the authors, is a 28 -year-old male. Each observer used a dental impression to maintain stable head position, and the binocular optometer was separately calibrated for each, taking into account differences in interocular distance. Table 1 shows the subjects' ages, interocular distances and amplitudes of accommodation, and further data, which are discussed below.

Table 1. Subject Data

Observer	Age (years)	Interpupillary Distance (cm)	Amplitude of Accommodation (diopters) ^a	CA/C (diopters/meter angle)		
				This Study	Kent ^b	Fincham and Walton ^c
TP	20	5.9	9.6	0.95	1.40	1.0
DP	20	5.5	9.3	0.78	1.40	1.0
HK	23	6.3	10.6	0.90	1.34	1.0
DK	28	6.5	7.8	0.93	0.88	0.85
GR	30	6.2	7.8	0.99	0.90	0.79

^a The amplitude of accommodation was measured by the push-up method relative to the spectacle plane. It is the mean for both eyes.

^b Ref. 7.

^c Ref. 6.

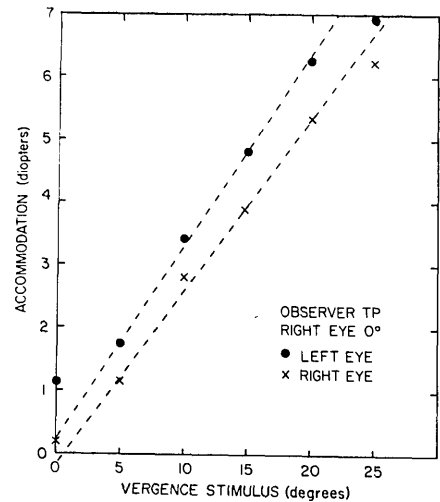


Fig. 3. Speckle targets: Accommodation responses for left and right eyes as a function of vergence angle. The right-eye angle of lateral gaze was 0 deg. The dashed lines are fits to the data made by eye. Data are for observer TP.

RESULTS

Effects of Angle of Convergence and Angle of Lateral Gaze

Figure 3 presents convergence accommodation measurements for observer TP when the right lateral-gaze angle was held fixed at 0 deg. Accommodation in diopters is represented along the ordinate and vergence angle in degrees along the abscissa.

The filled circles represent the average of four left-eye settings, and the x's represent the average of four right-eye settings. Each set of data can be well fitted by a straight line over the middle range of vergence angles. Thus each set of data can be characterized by the slope and intercept of the best-fitting straight line through it. The slopes of lines through the two sets of data are 0.30 and 0.27 diopter/deg for the left and right eyes, respectively. The rough equality in the left- and right-eye slopes for a given observer was typical of our data at all angles of lateral gaze. An analysis of variance indicated no significant ($p > 0.05$) difference in slopes for the two eyes across all conditions tested. Apparently, the accommodative responses of the two eyes are yoked together in convergence accommodation, as would be predicted by Hering's law of equal innervation. The mean difference between corresponding left- and right-eye data points over the linear portion of the curve is 0.76 diopter. Accommodation differ-

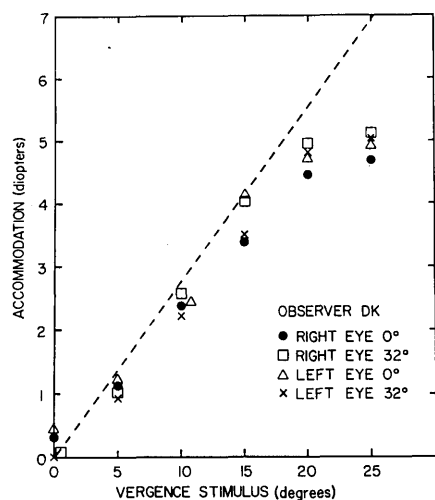


Fig. 4. Speckle targets. Accommodation is plotted as a function of vergence angle. Data are shown for four conditions. The legend indicates which eye's lateral gaze angle was fixed and at what angle. Each point is the arithmetic mean of four settings. The dashed line represents vertical accommodation for a red target. Data are for observer DK.

ences of slightly less than this magnitude occurred in other sets of data for this observer, with an average difference of 0.57 diopter. The other observers showed smaller mean differences. However, we are concerned primarily with changes in accommodation as a function of vergence angle rather than with constant anisometric differences. Accordingly, in subsequent graphs, points represent accommodation measurements averaged across observers' right and left eyes.

In Fig. 4, data for the four different conditions of lateral gaze are shown for observer DK. Filled circles and squares are data for right lateral-gaze angles fixed at 0 and 32 deg. The triangles and x's are data for left lateral-gaze angles fixed at 0 and -32 deg. The dashed line represents ideal accommodation along the midline. It represents the accommodation required to bring a red object on the midline to ideal focus as a function of vergence angle.²² The slopes for the filled circles, squares, triangles and x's are 0.22, 0.26, 0.24, and 0.26, respectively. They show close agreement. The mean slope over the linear

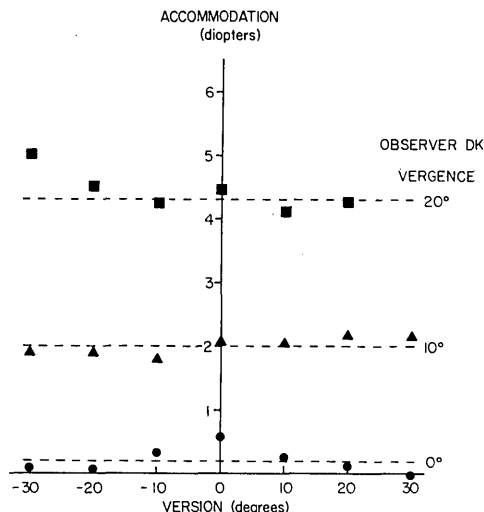


Fig. 5. Speckle targets: Accommodation as a function of version angle. The data were collected on three circles of equal vergence angle: 0, 10, and 20 deg, indicated by filled circles, triangles, and squares, respectively. The data were all collected in one session. The dashed lines are fits to the data made by eye. Data are for observer DK.

portion of the graphs is 0.245 diopter/deg. A mean slope of 0.24 was obtained from this observer on a replication of these measurements. This slope is approximately equivalent to a slope of 0.9 diopter/meter-angle.²³ The important result here is that lateral-gaze angle has little or no effect on convergence accommodation. For a given vergence angle, data points from the four conditions of lateral gaze generally lie within 0.5 diopter of one another. Table 2 summarizes the results for DK and the other two observers, TP and HK. Slopes are shown with 95% confidence intervals indicated. An analysis of variance showed no significant ($p > 0.05$) dependence of slope on lateral-gaze angle.

Table 1 shows the average convergence accommodation/convergence (CA/C) ratios in diopters per meter-angle for our five subjects. For comparison, CA/C ratios are shown from studies by Fincham and Walton⁶ and Kent⁷ for subjects of similar age and amplitude of accommodation.

Figure 5 presents convergence accommodation results for

Table 2. Slopes of the Convergence Accommodation Functions

Observer	Condition ^a	Slope ^b	
		Left Eye	Right Eye
DK	Right eye 0°	0.216 ± 0.024	0.220 ± 0.024
	Right eye 32°	0.266 ± 0.033	0.261 ± 0.016
	Left eye 0°	0.229 ± 0.068	0.259 ± 0.026
	Left eye 32°	0.259 ± 0.025	0.259 ± 0.026
TP	Right eye 0°	0.298 ± 0.013	0.273 ± 0.019
	Right eye 32°	0.292 ± 0.027	0.273 ± 0.025
	Left eye 0°	0.260 ± 0.031	0.231 ± 0.037
	Left eye 32°	0.275 ± 0.029	0.325 ± 0.022
HK	Right eye 0°	0.204 ± 0.027	0.192 ± 0.023
	Right eye 32°	0.280 ± 0.047	0.258 ± 0.029
	Left eye 0°	0.255 ± 0.019	0.267 ± 0.032
	Left eye 32°	0.233 ± 0.027	0.269 ± 0.025

^a The condition specifies the fixed eye and its direction of lateral gaze.

^b The slope is given in diopters per degree of vergence with the 95% confidence intervals indicated. The slope was computed over the 5–25-deg vergence range.

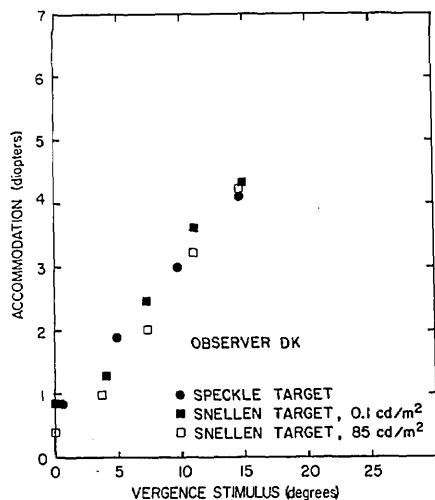


Fig. 6. Blur targets: Accommodation as a function of vergence angle. The data represent the results of three conditions corresponding to binocular viewing of bright and dim Snellen letters and speckle fusion targets. Each data point is the mean of four settings made with the left eye. Data are for observer DK.

observer DK along three contours of constant vergence angle. The ordinate represents accommodation, and the abscissa represents the version angle rather than vergence angle. Each symbol is the mean of four measurements, two from each eye. All the data in this graph were collected in one session, with measurements made in random order. Two measurements stretched the capabilities of both the optometer and the observer. These were the two extreme version angles on the 20-deg circle of equal vergence angles. Except for the -30 -deg version angle, the data can be fitted very well by horizontal lines, indicating no significant dependence of convergence accommodation on version angle. Linear-regression fits to the data gave slopes of 0.001, 0.005, and -0.016 diopter/deg for vergences of 0, 10, and 20 deg, respectively.

Effects of Luminance on Convergence Accommodation

Figure 6 shows data for observer DK's left eye. Each symbol is the mean of four settings. The open and filled squares represent the data for the binocular viewing of the bright and the dim Snellen charts, respectively. The filled circles represent convergence-accommodation data collected using speckle-fusion targets.

Except for the largest vergence, accommodation was more myopic for the dim Snellen target than for the bright Snellen

target, in agreement with previous observations of night myopia. Linear-regression lines were fitted to the data. Table 3 shows the slopes and intercepts with their corresponding 95% confidence intervals. There was only a slight increase in slope when the bright Snellen chart was viewed. The intercept, however, increases significantly by 0.5 diopter with lower luminance. As can be seen from Table 3, the slope and the intercept were 0.27 diopter/deg and 0.2 diopter for the bright chart. For the dim chart, the slope and the intercept were 0.25 diopter/deg and 0.7 diopter.

The slope for the convergence-accommodation data (filled circles) was 0.22 diopter/deg. The intercept (0.8 diopter) was almost equal to the intercept for the dim chart. Thus, as luminance is reduced, the Snellen-target data approach the speckle-only data. The results were similar for two other observers (see Table 3). All three observers show a significant increase of the intercept as luminance goes down. The effect of luminance on the slope, however, is only modestly significant for observers DK and DP and not at all significant for GR.

When we measured convergence accommodation using dim and bright speckle targets, we found an average of only 0.2-diopter difference in accommodation for bright (100-cd/m^2) and dim (1-cd/m^2) speckle targets for two observers. Thus there seemed to be no dependence of convergence accommodation on the luminance of the fusion target.

DISCUSSION

Does the linear relation that we have found between accommodation and vergence angle, which is independent of lateral-gaze angle, lead to appropriate accommodation responses for targets throughout the horizontal plane? We can begin to address this question by recalling that dioptric distance is approximately proportional to vergence angle along the midline. This is also true for asymmetric convergence, except for the complication that a target off the midline lies at unequal dioptric distances from the two eyes, so an average must be taken. Hence we would expect an ideal convergence-accommodation system to show an approximately linear relationship between accommodation and vergence angle. Our observers showed such a linear relationship under all conditions of lateral gaze, but the slopes describing their data were slightly less than the ideal. Observed slopes ranged from 68 to 110% of ideal slopes, with a mean of about 91%. There is some ambiguity concerning the absolute level of accom-

Table 3. Slopes and Intercepts of Convergence Accommodation Functions for Various Fusion Targets^a

Observer	Fusion Target	Slope	Intercept
DK	Bright Snellen, 85 cd/m^2	0.266 ± 0.016	0.188 ± 0.016
	Dim Snellen, 0.1 cd/m^2	0.248 ± 0.019	0.667 ± 0.024
	Speckles only	0.219 ± 0.030	0.822 ± 0.048
DP	Bright Snellen, 85 cd/m^2	0.336 ± 0.037	0.502 ± 0.040
	Dim Snellen, 0.1 cd/m^2	0.274 ± 0.034	1.108 ± 0.035
	Speckles only	0.249 ± 0.027	1.269 ± 0.022
GR	Bright Snellen, 85 cd/m^2	0.265 ± 0.030	0.278 ± 0.020
	Dim Snellen, 0.1 cd/m^2	0.249 ± 0.032	0.705 ± 0.023
	Speckles only	0.284 ± 0.044	0.777 ± 0.038

^a The slopes are given in diopters per degree and the intercepts in diopters. The 95% confidence intervals are indicated. The slopes were computed over the 0–15 deg vergence range.

modation. The shift in spectral sensitivity together with chromatic aberration leads to an effective increase in refractive power at low light levels.²⁴ Spherical aberration at larger pupil sizes can also lead to an effective increase in refractive power for low spatial frequencies.^{24,25} These factors imply that a lens that is appropriately focused for optical infinity in high illumination may be as much as 1.5 diopters myopic in low illumination, although the lens itself has not changed shape. To maintain appropriate accommodation at optical infinity as illumination decreases, the lens would have to flatten. An ideal convergence accommodation system would be designed to take account of this fact by resetting its absolute value (intercept) as luminance changes. According to our data, this does not occur. Thus, although the changes in convergence accommodation seem to be nearly appropriate, the absolute accommodation becomes less appropriate as the luminance is decreased.

In the experiment summarized in Fig. 5, the role of the convergence angle independent of version angle is clearly demonstrated. This is in accord with both eye-movement²⁶ and neurophysiological²⁷ studies, which demonstrate two eye-movement systems subserving version and vergence. The accommodation response is part of the near response, which consists of a vergence movement, a pupil, and accommodation response.

In our experiments, we used laser-speckle patterns as fusional targets. Since these patterns produce sharp interference patterns on the retina, independently of the refractive state of the eye, they contain no blur stimulus to accommodation. Nevertheless, our measurements of convergence accommodation along the midline are in good agreement with those of Fincham and Walton.⁶ Since they used small (0.5-mm) pupils, the agreement indicates that the use of small pupils is probably adequate for the elimination of blur when measuring convergence accommodation at least over a range of 5 diopters.

Miller¹¹ measured convergence accommodation using small (0.08-mm) point sources of light as fusion targets. After averaging over 10 subjects, the slope of his convergence accommodation curve was 0.53 diopter/meter-angle. This is less than the slopes that we found for DK, TP and HK, the average slope being 0.9 diopter/meter-angle. Miller suggests that his small slopes might be due to a better elimination of blur stimuli than that achieved by previous experimenters. The higher slopes that we observed with speckle targets suggest otherwise. Perhaps this apparent discrepancy is due to individual differences in the ability to use convergence information. Miller's mean slope of 0.53 may result from values near 0.9 for some subjects but much lower values for some others.²⁸

For binocular viewing of all but the closest Snellen target, the observers were more myopic for the dim than for the bright target. The possibility that the luminance of the fusional target alone could account for the binocular night myopia was excluded by measuring convergence accommodation for dim and bright speckle fusion targets. Leibowitz and Owens⁷ have argued that night myopia is best interpreted as a tendency to return to the dark focus in the absence of sufficient focusing information. This would account for the small trend for slopes to decrease as luminance is decreased. The convergence information, however, appears to control accommodation strongly under dim viewing conditions.

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22. This allows for the wavelength of the red He-Ne laser light, which is 632.8 nm.
23. If IPD represents the interpupillary distance in meters, the CA/C ratio in diopters/meter-angle is given by $IPD \times 57.3 \times CA/C$ diopters/deg. However, this is only an approximate equivalence. For large version and vergence angles, dioptric distance in meter-angles is no longer closely proportional to vergence. For

asymmetric convergence there is ambiguity because of the differences in the right- and left-eye distances from the fixation point.

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28. It should also be pointed out that if all subjects have lines with equal (and perhaps steep) slopes but different intercepts, the averaged data produce a line of smaller slope.