Accommodation to stimuli in peripheral vision

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Can targets in peripheral vision elicit accommodation responses? We used a laser optometer to measure monocular steady-state accommodation for stimuli at retinal eccentricities ranging from 1° to 30°. The optical distance from the eye to the stimulus was varied from 0 to −6 D by introducing lenses in front of the eye. The accommodative response was plotted as a function of optical distance to produce an accommodative stimulus-response function. The magnitude of accommodative response was defined as the difference between the maximum and minimum values of this function. The magnitude declined from 4 D at 1° to 1–2 D at 30° eccentricity. The relation of the magnitude of accommodative response in peripheral vision to changes in acuity, contrast sensitivity, and depth of focus are considered. The role played by convergence accommodation is also discussed.

INTRODUCTION

It is generally believed that only stimuli presented to the fovea can evoke accommodative responses. In order to focus an object, one must fixate it. Fincham[1] found that when a 10-arcmin-diameter white disk was placed 10 arcmin or more away from the direction of vision, subjects did not show accommodative responses when a negative lens was placed in front of the eye. Campbell[2] found that in order for accommodation to be evoked, the illumination of the target must exceed a critical value, which is about twice the foveal threshold. This finding led Campbell to conclude that the foveal cones were the receptors for accommodation. Phillips[3] found that accommodative responses can be elicited only within a relatively small region around the fovea and are nearly absent at 10° retinal eccentricity.

On the other hand, three types of evidence suggest that peripheral accommodation is sometimes important. First, clinical experience indicates that accommodation can be present in people with central-field loss. Accommodation must be taken into account in prescribing reading aids for children with low vision.[4] Second, the phenomenon of instrument myopia, the unnecessary positive accommodation while looking through the eyepiece of an optical instrument, also suggests that peripheral stimuli may affect the state of accommodation. Hennessy[5] showed that instrument myopia was due, in part, to the influence on accommodation of the margin of the eyepiece in peripheral vision. In another experiment, Hennessy and Leibowitz[6] presented subjects with a small defused spot image to the fovea at 0.67-D optical distance. The spot was seen through a white aperture located at a different optical distance. Subjects accommodated at a distance falling between the two stimuli, suggesting that the peripheral stimulus, in addition to the foveal stimulus, influenced accommodation. They did not, however, measure accommodation to peripheral stimuli alone. Third, Semmlow and Tinor[7] provided indirect evidence for peripheral accommodation. They presented blur stimuli at various retinal eccentricities up to 6°, while the monocular accommodative convergence response of the nonviewing eye was continuously monitored. Their results show a significant convergence to peripheral stimuli, with the response amplitude decreasing as the eccentricity increases. Since accommodation to the off-foveal stimulus was the only factor driving convergence, the results of Semmlow and Tinor suggest the existence of peripheral accommodation.

The first purpose of our experiment was to measure the magnitude of accommodative response for stimuli presented at different retinal eccentricities. One technical problem associated with this purpose is how to present stimuli at specified retinal loci without a fixation point that itself controls accommodation. The properties of a laser speckle pattern make the laser optometer an ideal instrument for studying peripheral accommodation. Since the speckle pattern is generated by interference on the retina, it always looks sharp, independent of the state of accommodation of the eye. Thus it is not effective in eliciting accommodation.[8] In our experiment, we used the speckle pattern as the fixation mark.

The second purpose of our experiment was to determine whether the accommodative convergence/accommodation (AC/A) ratio remains constant in peripheral vision. Semmlow and Tinor[7] found that the amplitude of accommodative convergence decreased as the retinal eccentricity increased. The decreasing amplitude of convergence might have been due to either of two factors: a lower magnitude of accommodative response in peripheral vision or a lower AC/A ratio.

METHOD

Apparatus and Stimuli

We measured monocular steady-state accommodation with a laser optometer. The principles underlying the laser optometer have been described by Charman[9] and by Hennessy and Leibowitz.[8]

Figure 1 shows a diagram of the laser optometer. It consists of a helium–neon laser, lenses L_3 and L_4, which diverge and collimate the light, and a mirror M_2 that reflects the collimated light onto the surface of a slowly rotating drum. The observer's right eye views the surface of the drum through the trial lens L_1, a beam splitter M_1, and a badal lens L_2 of power 5.5 D positioned 18 cm from the eye. On the retina the coherent laser light generates an interference pat-

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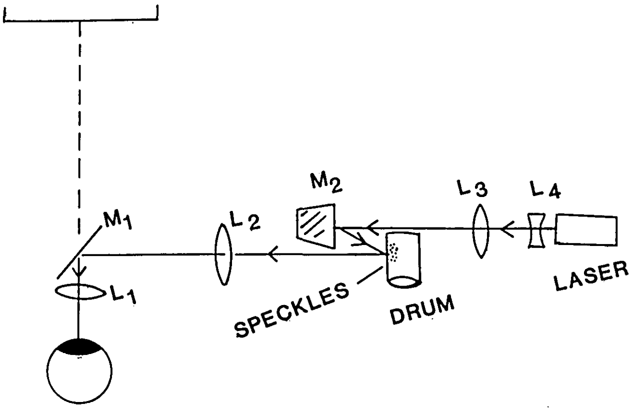

Fig. 1. A schematic diagram of the laser optometer.

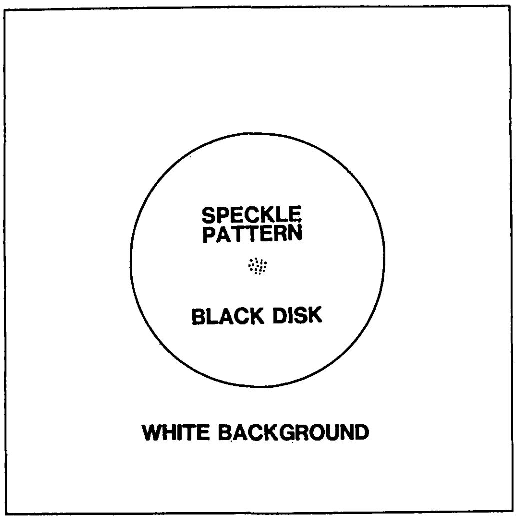

Fig. 2. The stimulus used in the experiment is a black disk superimposed upon a white background.

tern known as a speckle pattern. As the drum slowly rotates, the apparent velocity of the speckles in the pattern is determined by the distance between the drum's plane of stationarity and the plane of focus of the eye.[9] If the eye is focused in front of the plane of stationarity, the speckles appear to move in the same direction as the drum. If the eye is focused behind the plane of stationarity, the speckles appear to move in the opposite direction. During the experiment, the observer moved the drum along an optical rail between L_2 and L_3 until the observer found a point where the speckles moved neither up nor down but seemed to move randomly. From this position we calculated the accommodation of the eye.

In each condition, the stimulus was a featureless black disk of fixed radius superimposed upon a uniform white background (see Fig. 2). In different conditions, the radius of the disk was varied. The background was produced by a white Mylar screen, which was illuminated by a slide projector placed behind it. The luminance of the screen was 28 ± 2 cd/m^2. The luminance of the black disk was 0.05 cd/m^2. The distance between the screen and the observer was 1 m.

The laser speckle pattern also acted as a fixation target. It subtended 1° and was centered on the black disk. Because the black paper was smooth and lacked any visible feature, the circular contour of the black disk on the white background provided the only stimulus to accommodation. The stimulus to accommodation was presented at different retinal eccentricities by varying the disk radius. Four eccentricities were used in the experiment, 1°, 7°, 15°, and 30°.

Our results rely on careful fixation by observers. We did a control experiment in which electro-oculogram (EOG) recordings were used to monitor the eye movements during accommodation. Two observers participated in this control experiment. The EOG data showed that the observers did maintain fixation within ±2°.

Procedure

For each observer the stimuli were presented in the same order, from small to large radii. For a given disk radius, accommodation was measured as a function of the optical distance from the stimulus to the cornea. The optical distance was varied by introducing trial lenses (L_1 in Fig. 1) of different powers in front of the eye. Lens power first decreased from +1 D to −6 D and then increased from −6 D to +1 D. The step size was 1 D, with one exception: no measurements were made at −5 D. Because the trial lens L_1 was placed 2 to 3 cm in front of the cornea (the exact number varied from observer to observer), a correction for the equivalent power of L_1 had to be made. In Figs. 3 and 4, stimulus distance reflects this correction. Two measurements were taken for increasing lens powers and two for decreasing powers. The arithmetic mean of the four measurements at each lens power was calculated. Two means were obtained in this fashion at each lens power. Then the grand mean and the standard error were calculated from the two means.

Throughout the experiment, accommodation was measured under monocular viewing conditions with the observer's right eye. However, in order to evaluate the changes in the AC/A ratio we measured the convergence response. A second laser optometer was used to present a speckle pattern to the left eye. This pattern was located so that the two eyes fused the speckle patterns at a convergence of 1-m angle. The left eye was then occluded by a shutter when the observer accommodated using the right eye. While the observer was accommodating on one of the disk targets with the right eye, the shutter was opened briefly (<0.5 sec). The observer adjusted a variable prism, placed in front of the left eye, to reduce the positional disparity between the two speckle patterns. This process was repeated until the two speckle patterns appeared fused during the brief presentation. Convergence in meter angles was then calculated from the setting of the variable prism. The convergence measurements were done at stimulus distances of −1, −3.7, and −6 D for 1° and 30° stimuli.

Observers

Three observers with normal binocular vision participated in the experiment. The monocular steady-state accommodation was measured with the observer's right eye; the left eye was occluded from viewing. Table 1 shows each observer's age, acuity, and amplitude of accommodation. Since the instructions given to the observers may affect their performance,[10] all three observers were clearly instructed to "try to make the contours as sharp as possible while fixating the speckle pattern." All three observers were given ample practice before they performed the actual experiment.

RESULTS

Figure 3 shows accommodative stimulus-response functions at four eccentricities for observer TW. The solid diagonal lines indicate what would be found if accommodative response agreed precisely with stimulus distance. The upper-left-hand panel shows the accommodative stimulus-response function for 1° eccentricity. We defined the *magnitude of accommodative response* as the difference between the maximum and minimum values of this function. In the upper-left-hand panel, the maximum accommodative response is 5.7 D at a stimulus distance of −6 D, and the minimum response is 1.7 D at a stimulus distance of 0 D. Therefore, the magnitude of accommodative response is 5.7 − 1.6 = 4.1 D. In contrast, the magnitude for 30° eccentricity, lower right, is just over 1 D.

Figure 4 shows comparable data for observer GR. For 1° eccentricity, his magnitude of accommodative response was 3.1 D, less than TW's. Perhaps the small difference is age related. Like TW, GR showed a decreasing magnitude of accommodative response with increasing retinal eccentricity. For 30° eccentricity, GR's magnitude is 1.5 D. The data of the third observer, KD, also showed a similar pattern.

All three observers' stimulus-response functions became relatively flat at 30°. Had we used larger disk targets, we believe that the functions would have become still flatter. In the limit of large disk radii, the target becomes a uniform (empty) field. Under such conditions, we would expect an observer's stimulus-response function to level out at the value of the dark focus. We measured the dark focus for TW and found it to be about 2.5 D. As expected, this lies within the response range for the 30° stimulus—1.7–2.9 D.

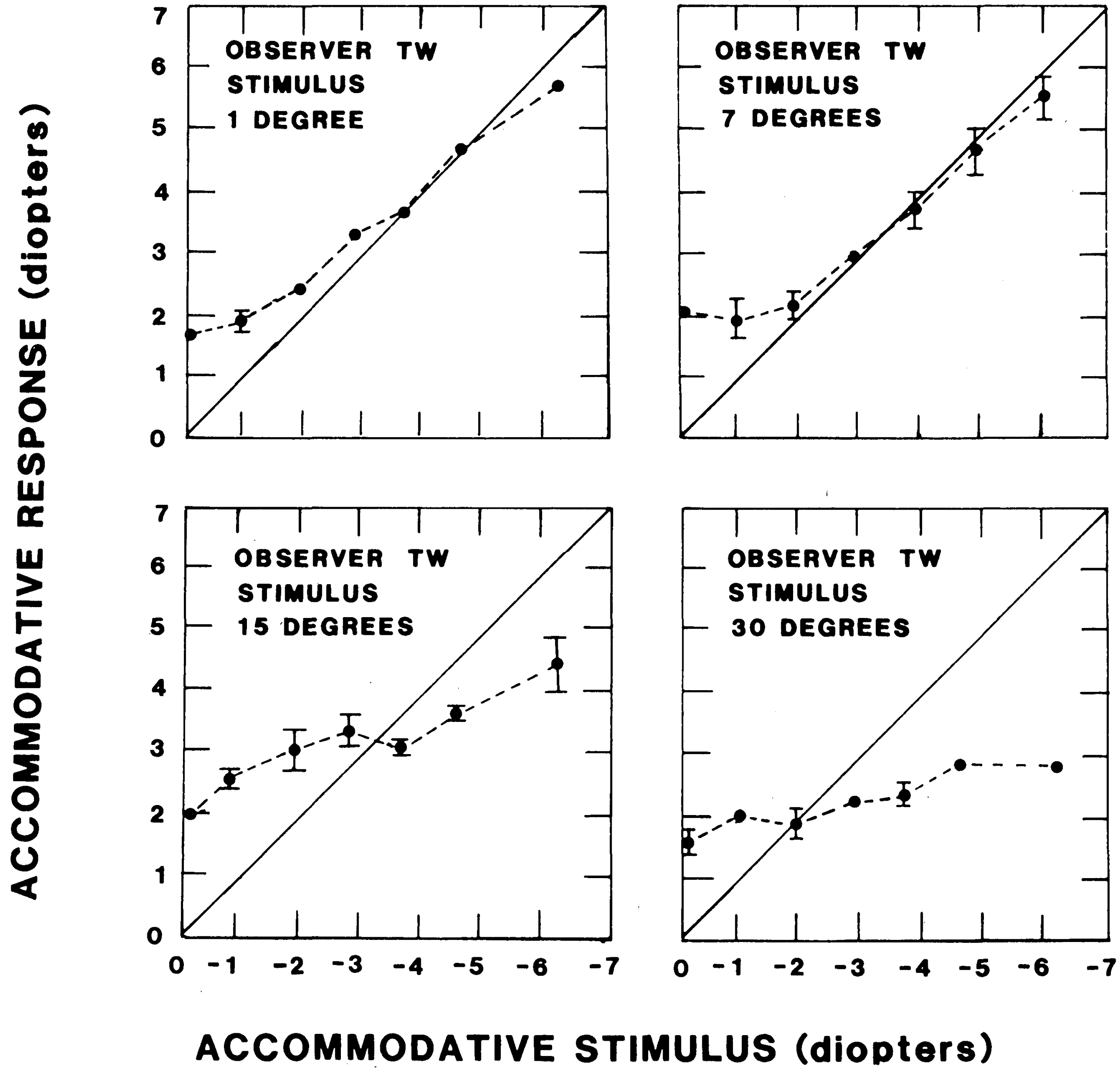

Fig. 3. Accommodative stimulus-response function at four eccentricities for observer TW. The diagonal solid lines indicate perfect accommodation. The error bars show ±1 standard error.

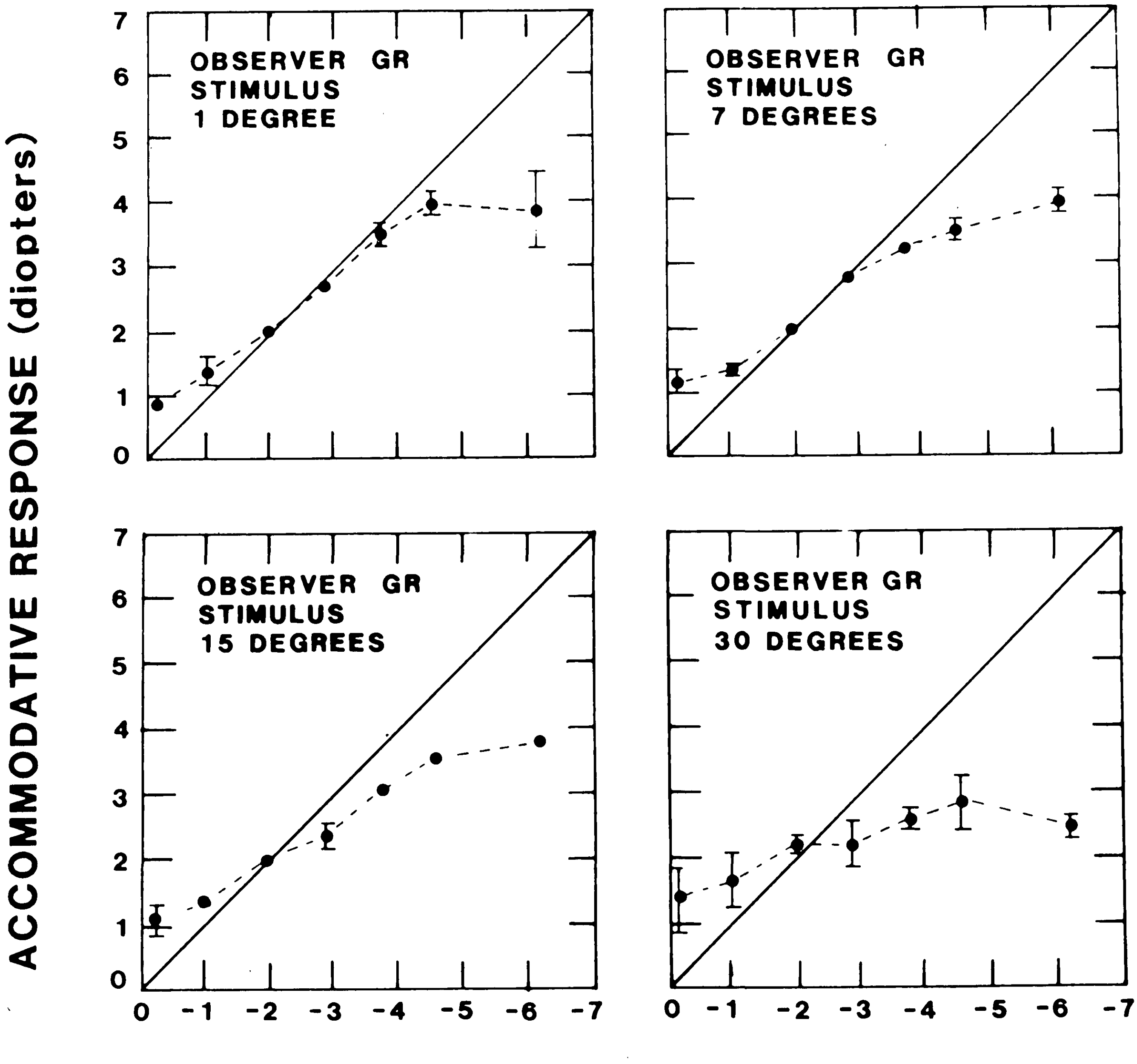

Fig. 4. Accommodative stimulus-response function at four eccentricities for observer GR.

Figure 5 shows the magnitude of accommodative response as a function of eccentricity for our three observers. The solid line represents the average. It is clear that the magnitude of accommodative response drops as eccentricity increases, but even at 30° it is still greater than 1 D.

Table 1. Observer Data

Observer	Age	Acuity	Pupil size (mm)[a]	Amplitude of Accommodation (D)[b]
KD	21	20/20	6–7	10.5
GR	32	20/20	5–7	6.1
TW	25	20/20	6–7	9.5

[a] The pupil size was measured in the 1° stimulus condition.

[b] The amplitude of accommodation shown here was measured by the push-up method.

Figure 6 shows convergence as a function of accommodation for 1° and 30° eccentricity. The solid diagonal line indicates what would be expected if the convergence agreed precisely with the accommodation. The results indicate clearly that convergence increases with accommodation for both foveally and peripherally viewed targets. For observers TW and GR, the 1° and 30° lines have almost the same slope, indicating that the AC/A ratio does not change for stimuli at different retinal eccentricities.

DISCUSSION

Phillips[3] has studied peripheral accommodation by measuring dynamic accommodative responses at various eccentricities. He found that at 10°, the magnitude of accommodative response dropped to almost zero. By comparison, our

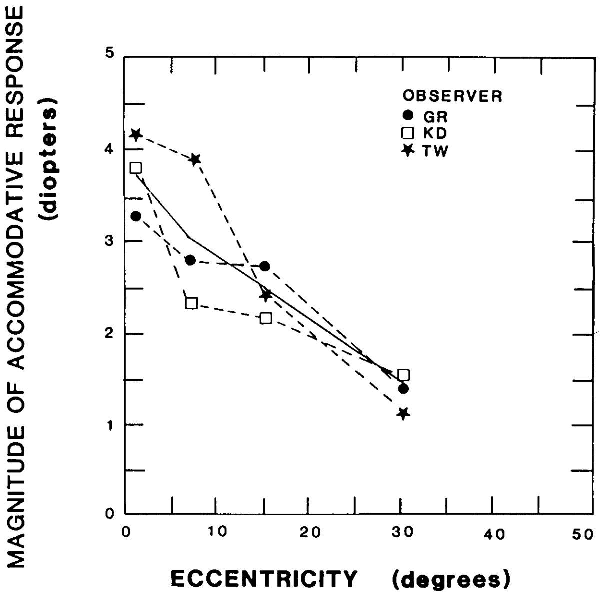

Fig. 5. Magnitude of accommodative response as a function of eccentricity. The solid line represents the average magnitude of the three observers.

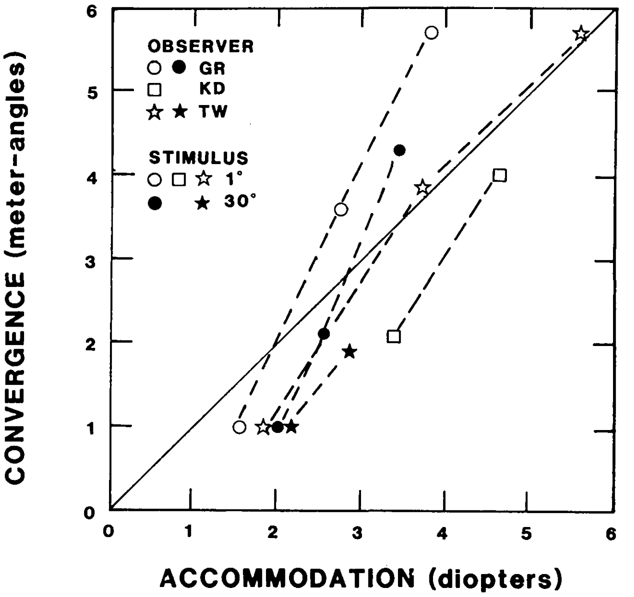

Fig. 6. The relationship between convergence and accommodation for 1° and 30° eccentricity. The solid diagonal line in the graph indicates that the convergence agrees precisely with the accommodation.

subjects showed an average magnitude of 2.7 D at 7° and 2.5 D at 15°. Although we do not know what accounts for the discrepancy, it may be related to one of the following three procedural differences: (1) We measured steady-state accommodation, while Phillips measured dynamic accommodation. (2) Our observers were given unlimited time to accommodate, while in Phillips' experiment observers only had 4 sec in which to respond. (3) We used stimuli covering a 6-D range of optical distance, while in Phillips' experiment, stimuli ranged over 3 D.

It is well known that there is a strong interaction between accommodation and convergence.[11] Fincham and Walton[12] found that, in the absence of blur information, accommodation was linearly related to convergence angle. Kersten and Legge[13] found that the linear dependence of accommodation on convergence leads to appropriate accommodation responses for targets throughout the horizontal plane. It is therefore possible that convergence facilitates accommodation to peripheral targets; the observer may converge the eyes until the peripherally viewed target appears to be in focus. The fact that the AC/A ratios are nearly the same for 1° and 30° suggests that the results of Semmlow and Tinor[7] can be traced to a decreasing magnitude of accommodative response in peripheral vision.

What accounts for the decreasing magnitude of accommodative response with increasing retinal eccentricity? We considered the relation of accommodation to peripheral changes in contrast sensitivity, acuity, and depth of focus.

Owens[10] has shown that in central vision the maximum magnitude of accommodative response was obtained at the peak spatial frequency of the contrast sensitivity function. The peak spatial frequency decreases with increasing retinal eccentricity. Kelly[14] measured spatiotemporal sine-wave contrast thresholds at four retinal eccentricities up to 12°. He gave a function that provided an excellent fit to his data:

$$f_s = 3/(1 + 0.174e),$$

where f_s is the peak spatial frequency in cycles per degree (c/deg) and e is the retinal eccentricity in degrees. We used this function to calculate the peak spatial frequencies for retinal eccentricities used in our experiments. The peak frequencies are 2.6, 1.4, 0.8, and 0.5 c/deg for 1°, 7°, 15°, and 30° respectively. It is possible that Fourier components of the targets at these spatial frequencies control the magnitude of accommodative response. When we compare our peripheral magnitudes of accommodative response with Owens' foveal data at corresponding spatial frequencies, the results are quite similar to those shown in Fig. 7. For instance, the mean magnitude of accommodative response for 0.5 c/deg in Owens' experiment was 1.75 D, while the mean magnitude in our experiment at 30°, where the peak spatial

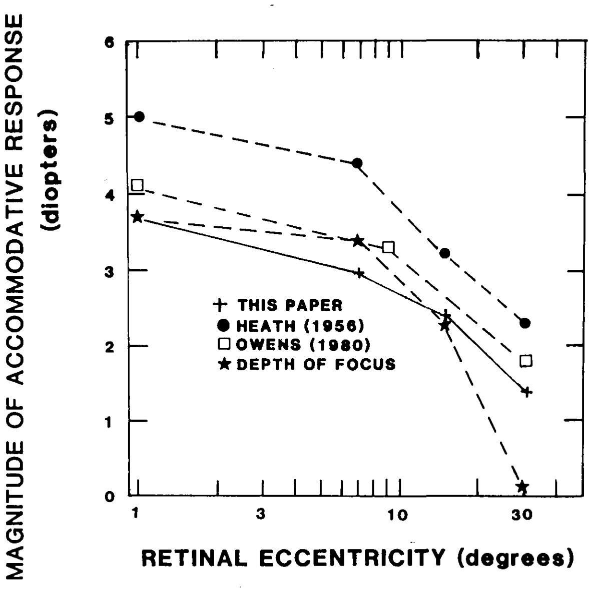

Fig. 7. Magnitude of accommodative response as a function of eccentricity: a comparison of data with three predictions.

frequency is 0.5 c/deg, was 1.60 D. Overall, the magnitudes predicted for peripheral accommodation on the basis of Owens' foveal data are about 15% larger than those we actually found. Perhaps this difference is related to the fact that Owens used high-contrast (65.4%) sine-wave targets, while the Fourier components of our disk targets had lower contrast at those corresponding spatial frequencies.

Charman and Tucker[15,16] reported that, unlike for Owens' data, the accuracy of accommodative response increased with the spatial frequency of stimuli. Since the high-spatial-frequency end of the contrast-sensitivity function and the visual acuity are closely related to each other, we also tried to relate the smaller accommodative response in the periphery to its lower acuity. Heath[17] has studied how acuity affects accommodation. He used ground-glass plates to blur a Snellen chart to simulate the effect of reduced acuity. In this way, he measured the magnitude of accommodative response for different levels of acuity. We computed acuities at the four retinal eccentricities used in our experiment based on an equation given by Anstis[18] that relates retinal eccentricity to acuity. We compared Heath's data with ours under equivalent acuity conditions. Although the absolute magnitudes of accommodative response are somewhat different, the changes with increasing eccentricity are similar to those shown in Fig. 7.

It is possible that the decreasing magnitude of accommodative response in peripheral vision is associated with increasing depth of focus. This possibility rests on two suppositions: first, that steady-state accommodation settles as close to its resting state as it can without the target's appearing blurred, and second, that the depth of focus increases with retinal eccentricity. In the absence of data on the latter, we may estimate the depth of focus at various eccentricities by means of its relation to acuity. There have been several studies of acuity and defocus in central vision.[19,20] In these studies, Snellen acuity was measured as a function of defocus for cyclopleged subjects with dilated pupils. Such data can be used to estimate the defocus that can be tolerated at different acuity levels.[20] For example, acuities of 20/40 and 20/320 are associated with depth-of-focus values of ±1.25 and ±5.5 D, respectively. Since 20/40 and 20/320 are acuity estimates for 1° and 30° of retinal eccentricity, it can be estimated that the magnitude of accommodative response will shrink by $5.5 - 1.25 = 4.25$ D from 1° to 30°. Because this shrinkage is greater than the mean value of 3.7 D measured for the 1° eccentricity, this model predicts zero magnitude of accommodative response at 30°. This is less than the 1.6 D actually observed. The reduction in magnitude at 7° and 15° can be estimated in the same way. The curve labeled DEPTH OF FOCUS in Fig. 7 shows the reduced values, assuming a magnitude of 3.7 D at 1°. The depth-of-focus predictions overestimate the decline in the magnitude of accommodative response. Perhaps the discrepancy is related to differences in the spatial structure of the stimuli—disks versus Snellen letters. Models of visual depth of focus often make reference to just-noticeable differences in contrast of Fourier components of targets.[16,20]

Figure 7 compares our data with predictions based on acuity, depth of focus, and contrast sensitivity in peripheral vision. In each case, the predictions are qualitatively similar to the data. The depth-of-focus model predicts a zero magnitude at 30°, in disagreement with the other two models and the data. The predictions based on contrast sensitivity (open squares) give a better fit to the data than the acuity predictions (filled circles).

CONCLUSIONS

We conclude that peripheral vision can evoke accommodative responses, although the magnitude decreases as retinal eccentricity increases. The magnitude of peripheral accommodation may depend on peripheral contrast sensitivity and may be mediated by convergence of the eyes. Our data also suggest that the AC/A ratio remains constant in peripheral vision.

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