of sharp separation by using the polymer phase systems in conjunction with the elution centrifuge. With further improvements in apparatus and the use of shallower gradients, separation of biological macromolecules having only small differences in partition coefficient may be possible.

YOICHIRO ITO
ROBERT L. BOWMAN
Laboratory of Technical Development, National Heart and Lung Institute, Bethesda, Maryland 20014

References

1. Y. Ito and R. L. Bowman, *Science* **173**, 420 (1971); *Anal. Chem.* **43**, 69A (1971); R. E. Hurst and Y. Ito, *Clin. Chem.* **18**, 814 (1972); Y. Ito and R. L. Bowman, *J. Chromatogr. Sci.* **11**, 284 (1973).
2. Y. Ito, R. L. Bowman, F. W. Noble, *Anal. Biochem.* **49**, 1 (1972).
3. P. A. Albertsson, *Partition of Cell Particles and Macromolecules* (Wiley, New York, 1960).
4. ———, *Biochim. Biophys. Acta* **103**, 1 (1965).
5. ———, in *Progress in Separation and Purification*, E. S. Perry and C. J. Van Oss, Eds. (Wiley, New York, 1968), vol. 2, pp. 105–120; H. Walter, in *ibid.*, pp. 121–145; D. E. Pettejohn, in *ibid.*, pp. 147–166; G. Johansson, A. Hartman, P. A. Albertsson, *Eur. J. Biochem.* **33**, 379 (1973).

25 May 1973

Monocular Spatial Distortions Induced by Marked Accommodation

Abstract. *Contraction of the ciliary muscle during marked accommodation causes the leading edge of the retina to advance as much as 0.5 centimeter. Near the posterior pole of the eye, the upward and downward extensional strains on the retina should be reasonably balanced. In the horizontal meridian an asymmetry is introduced because of the nasal location of the optic nerve head. Observers were asked to bisect the space between two parallel lines while fixating a movable line lying near the midpoint of the two lines. The test was conducted with the target far from and near the subject, in the horizontal and vertical meridians, and was repeated with accommodation paralyzed by a cycloplegic agent. Marked accommodation induced significant spatial distortions in the horizontal meridian. The effect is largely retinal.*

Contraction of the ciliary muscle during marked accommodation allows the eye lens to increase in convexity and also causes the leading edge of the retina to advance forward. The retina, attached to the choroid, rides forward with ciliary muscle contraction. This forward displacement of the retina has been measured in a number of ways. Hensen and Voelckers (*1*) recorded the movement of the head of a needle anchored in the sclera, its tip in the choroid, with each accommodative movement in an intact dog's eye. They found the anterior choroidal displacement at the equator amounted to approximately 0.5 mm and diminished on approaching the optic nerve. Van Alphen (*2*), working with cats, observed a forward movement of the entire choroid through small holes in the sclera at the posterior pole, the equator, and several points in between. Moses (*3*), with human subjects, photographed the position of the scalloped margin of the anterior retina, the ora serrata, made visible by transillumination. He found that the ora advanced about 0.05 mm with each diopter of accommodation. The retina is attached to the choroid at the ora serrata.

It follows that with the forward movement of the choroid with accommodation the retina would become elongated anteriorly over the incompressible fluid spherelike vitreous body. Enoch (*4*) has calculated an increase in retinal area of 30 mm^2 with ten diopters of accommodation. Near the posterior pole of the eye, the upward and downward extensional strains on the retina caused by marked accommodation and the advance of the choroid should be reasonably balanced (Fig. 1C). However, across the horizontal meridian the strains on the retina will be asymmetrical because of the nasal location of the optic nerve head; the retina is fixed in position at this point of exit of the optic nerve from the eye. One would then expect there to be a graded retinal advance across the horizontal meridian during strong accommodation from a maximum at the ora to zero at the optic nerve. This statement in no way defines the nature of that gradient.

Because under particular conditions each retinal point has associated with it a direction in visual space (*5*), any unevenness in retinal stretch in the horizontal meridian should result in a change in the apparent relative position of objects in space (*6*). Disruptions in space perception due to accommodative retinal elongation should be demonstrable when a monocular bisection experiment is conducted. This test requires an individual to bisect the space between two lines while fixating the bisecting line. The classical technique for this experiment has its origin in the work of Kundt and Münsterberg (*7*). They found that there is typically some asymmetry—that is, errors in the placement of the bisecting midpoint—in unaccommodated bisection judgments. Kundt reported that subjects overestimate the nasal visual field, thereby physically setting the temporal field larger for the match, while Münsterberg described the reverse asymmetry.

In accordance with what is known about accommodative retinal elongation, we would predict that a monocular bisection experiment in the horizontal meridian near the posterior pole may be altered by marked accommodation, while we would predict little or no effect when the same property is measured in the vertical meridian. To test our hypothesis, a series of bisections were made by several nearly emmetropic subjects of college age, all with normal, uncorrected vision (*8*). Using one eye at a time, subjects steadfastly fixated a short movable black bar and indicated when it was exactly midway between the two fixed parallel black bars separated by 22°. The background was a uniformly illuminated white cardboard surface. This bisection experiment was conducted both vertically and horizontally, and in each orientation judgments were compared with the target far from the subject and near him. The tests, with the target far from the subject—208 cm away from him—called for only about 0.5 diopter of accommodation. The tests with the target near the subject were made with the stimulus display placed just beyond the nearest point at which the subject could still hold the target in focus; these tests employed nearly maximum accommodation (8 to 13 diopters). The luminance in (millilamberts) of the near target, 1.75 log units, was greater than that of the far target, 1.2 log units. This was done in order to keep the stimulus, the retinal illuminance, constant, to compensate for the decrease in pupil size with accommodation. Retinal illuminance (in trolands) was high enough (3.1 log units) to provide minimal variability in accommodation (*9*).

In accordance with the hypothesis, the data (Fig. 1) evidence a significant change in monocular space perception in the horizontal meridian with marked accommodation. That is, judgments of the placement of the bisecting line with accommodation showed highly significant differences in spatial asymmetries compared with the spatial asymmetries existing at the far point. In only 3 of the 18 eyes tested was the change in the bisection between far and near not significant ($P > .05$). Differences between far and near vertical bisections were not significant ($P > .05$) in any of the six eyes tested vertically. It seems likely that in a larger subject population some differences in vertical bisections might occur because of naturally occurring imbalances in retinal stress. The directions and magnitudes of the horizontal and vertical shifts with accommodation can be seen in Fig. 1.

That the changes in spatial asymmetries in the horizontal meridian were caused by accommodation per se was confirmed by repeating the tests with accommodation paralyzed by a cycloplegic agent, 1 percent cyclopentalate hydrochloride (*10*). No significant difference was found between far and near bisections when accommodation was prevented by means of cycloplegic action (and vision optimally corrected for test distances) as opposed to the highly significant changes found with accommodation active (*11*). The cycloplegic trials also eliminate awareness of nearness as inducing the change. Accommodative pupil size changes were controlled in this part of the study. There were no significant differences between trials with the dilated pupil of diameter 7 to 8 mm (with centered correction) and with the subject viewing the stimulus display through a 1.5-mm aperture. Therefore, changes measured in the horizontal meridian are not caused by a decreased pupil size with accommodation. Also, the close agreement between the far tests with and without the cycloplegic (no significant difference) assures the validity of the far test as a bisection test using minimal accommodation.

The horizontal spatial distortions caused by marked accommodation could be caused, in part, by optical factors related to changes occurring in the eye lens. The vertical bisection tests are important in differentiating between effects of accommodation on the retina and on the eye lens. Moses (*3*) reviews accommodative eye lens changes. Lens changes with accommodation are not limited to one meridian. Therefore, if the spatial distortions were largely an eye lens effect, one might expect a closer agreement between changes in the horizontal meridian and changes in the vertical meridian with marked accommodation. But there was a lack of significant change in the vertical meridian. This finding supports the conclusion that the distortion effect is largely (but not necessarily totally) retinally based.

The changes in spatial asymmetries caused by accommodation are not measures of the actual retinal displacement, but instead indicate any imbalance or nonlinearity of displacement within the retinal area tested (*12*). Figure 2, showing schematic drawings of the right eye, helps illustrate this important distinction. A subjective equality has been established by the observer at the far point: distance $A'B' = B'C'$. The image B' of the center line B is fixed foveally, F. Here the reason for the choice of a 22° target separation becomes evident. The blind spot is located in the visual field about 13° from the point of fixation. Hence, the image C' of an object C lying 11° from the point of fixation in the temporal visual field corresponds to a retinal locus R adjacent to the optic nerve head. It can be assumed that even during marked accommodation the retina at point R is not appreciably translated. However, with fixation at the near point, the fovea and the more peripheral retinal locus S positioned about 24° from the optic nerve (this corresponds to an object 11° in the nasal visual field) should be displaced to a greater extent when the ora is advanced during accommodation. Accommodated loci of R, F, and S (on the retina) are designated as R', F', and S', with $R = R'$.

With marked accommodation, if $R'F' = F'S'$, transretinal stress is equal in the retinal area tested. Although the retina has undergone displacement, all parts of the retina (within the area tested) would have been stretched equally. Therefore distance AB would

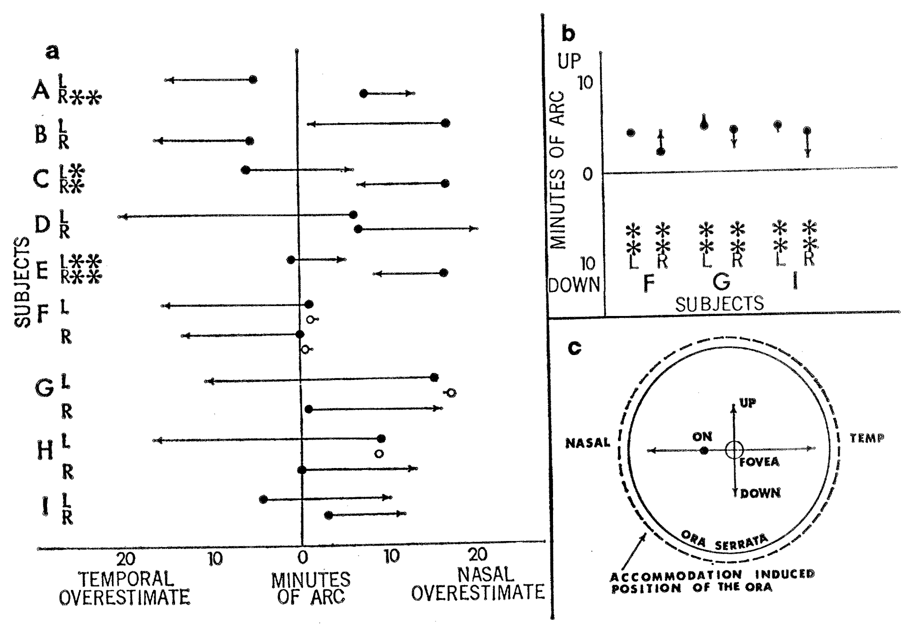

Fig. 1. (a) Black points are the means of horizontal bisections at the far distance. The arrow points are the means of horizontal bisections at the near point, with marked accommodation. The length of the arrow is a measure of the change in the bisection caused by accommodation. Letters A to I denote individual subjects; *L*, left eye; *R*, right eye. (Note that "nasal" involves the opposite direction in the two eyes.) The open circles (subjects F, G, H) show the effects of the cycloplegic agent; they represent the mean far and near judgments with accommodation paralyzed. Single asterisks indicate change significant at $P < .05$ (Student's *t*-test); double asterisks indicate shifts not significant at $P < .05$. All other shifts were significant at $P < .01$. (b) Black points show the mean far judgments made in the vertical meridian. The arrows indicate the resultant change in the mean when the vertical bisection was conducted with accommodation. None of the shifts were significant at $P < .05$. In the horizontal bisections all six of these eyes had shown changes significant at $P < .01$. (c) Schematic view of the retina showing the advance of the retina with substantial accommodation. One would expect relatively balanced vertical forces acting near the fovea (located near the posterior pole of the eye). The nasal position of the optic nerve head (*ON*) should result in an unbalanced force acting on the retina in the horizontal meridian near the posterior pole during marked accommodation.

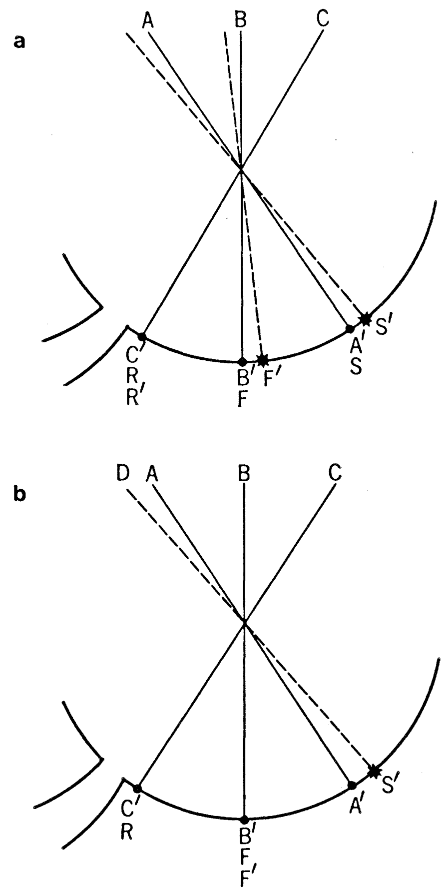

Fig. 2. (a) Schematic drawing of the retina of the right eye. Letters A, B, and C denote objects in space. Their retinal images are A', B', and C' formed at retinal points R, F, and S (F, fovea). With marked accommodation, the retinal points F and S shift to F' and S'. Since the retina is fixed at the optic nerve head, $R = R'$. (b) To conceptualize the alterations in the bisection experiment with accommodation, it is convenient to assume that only one of the two halves of the bisection is altered. The case in which retinal stretch causes $R'F' < F'S'$ is modified here so that $RF = R'F' < F'S'$. When S is moved to S' by accommodative action, AB would appear shorter than BC. For bisection equality to occur, object A would have to be translated to point D in space, causing DB to be longer than BC. Thus, an added monocular asymmetry occurs, and the temporal field is overestimated (that is, the distance BC is physically shorter at the match point) during marked accommodation. This would correspond to a Münsterberg-type asymmetry.

still look equal to BC with accommodation, but the total angle subtended would change. Note that the bisection judgments reflect the linearity or nonlinearity of the retinal elongation with accommodation rather than the actual displacement of the retina itself.

If, with marked accommodation, $R'F' < F'S'$, the more peripheral retinal region would undergo greater elongation than areas close to the optic nerve. The previously determined far point bisection would no longer look equal; an added Münsterberg-type asymmetry at the near distance would result from this type of retinal stress (see Fig. 2b and explanatory legend).

If accommodative retinal stress causes $R'F' > F'S'$ then the retinal tissue near the optic nerve would exhibit greater elongation per unit arc length than the more peripheral retinal areas within the retinal area tested (although the more peripheral areas would undergo a greater total physical translation). Again, the previously established far point bisection would no longer look correct with accommodation. An added Kundt asymmetry, overestimation of the nasal visual field, would occur.

The measured spatial asymmetries in the horizontal meridian induced by marked accommodation fell in all three of these categories. It has been suggested that differences in asymmetries could be due, in part, to local variations in choroidal vasculature in the vortex veins and in the "circle of Zinn" area (*13*). These vessels might cause resistance to accommodative retinal translation at various retinal locations in different directions in different individuals. In some instances, different nonlinearities occurred in the two eyes of the same observer, with one eye showing an added Münsterberg asymmetry while the other showed an added Kundt asymmetry. The changes which occurred were reproducible for a particular eye in a particular individual over several weeks or (for some) months of testing. Changes in monocular space perceptions should be reflected when binocular vision is tested.

Marked accommodation can produce a distortion in monocular space perception in the horizontal meridian, and the effect is largely retinally based. This effect is of interest from several points of view. It is essential to define all factors tending to put stress upon the retina if we are to understand factors influencing retinal adherence to its substrate. For example, the use of the powerful miotic agent phospholine iodide, which also causes ciliary muscle contraction, is significantly correlated with the occurrence of characteristic tears and detachments of the peripheral retina (*14*). The work reported here is part of an extensive investigation of photoreceptor orientation (*15*). The question has arisen: How is the extraordinarily precise alignment of photoreceptors maintained? In this context it is important to evaluate the effect of those factors which might serve to alter the precise alignment, such as the stretch and asymmetry in the elongation of the retina with marked accommodation.

KAREN BLANK
Department of Psychology, Washington University, St. Louis, Missouri 63130
JAY M. ENOCH*
Department of Ophthalmology, Washington University School of Medicine, St. Louis, Missouri 63110

References and Notes

1. A translation of V. Hensen and C. Voelckers' original paper is given by W. H. Luedde, *Trans. Amer. Ophthalmol. Soc.* **25**, 251 (1927).
2. G. W. H. M. Van Alphen, *Acta Ophthalmol. Suppl. 142* (1961), p. 44.
3. R. A. Moses, *Adler's Physiology of the Eye* (Mosby, St. Louis, ed. 5, 1970), p. 359.
4. J. M. Enoch, *J. Opt. Soc. Amer.* **63**, 899 (1973).
5. For example, see H. Halldén, *Acta Ophthalmol.* **49**, 726 (1971).
6. An illustration of anatomical disturbances producing changes in visual space perception is provided by the Amsler grid test [M. Amsler, *Method of Using Test Charts of Qualitative Vision* (Hamblin Instruments, London, 1949), p. 1].
7. A brief review of the work of A. Kundt and H. Münsterberg is found in K. N. Ogle, *Researches in Binocular Vision* (Hafner, New York, 1964), p. 51.
8. Pertinent subject information

Subject	Age	Amplitude of accommodation (diopters)	
		Left	Right
A	19	13	12
B	18	11.5	11.5
C	19	8	10
D	24	9	10
E	23	8	8
F	21	10	9
G	21	10	10
H	21	9	9
I	22	10	10

9. M. Alpern, *J. Opt. Soc. Amer.* **48**, 193 (1958); ——— and H. David, *Ind. Med.* **27**, 551 (1958).
10. Cyclogyl, manufactured by Schieffelin and Co., New York, N.Y.
11. The presence of a centered plus lens to correct vision in the eye with the cycloplegic agent did not significantly alter the bisection, as evidenced by comparison with the results obtained when a small aperture was used to minimize blur instead of a lens.
12. A 22° span equals 1320 minutes of arc. One percent of this angle is 13.2′. This makes it possible to judge the effective magnitude of the inequity of stretch in Fig. 1.
13. A. Cohen, personal communication.
14. H. H. Lemcke and D. K. Pischel, *Trans. Pac. Coast Oto-Ophthalmol. Soc.* **47**, 157 (1966). This effect was called to our attention by E. Okun.
15. J. M. Enoch, *Amer. J. Optom.* **49**, 455 (1972); A. M. Laties and J. M. Enoch, *Invest. Ophthalmol.* **10**, 69 (1971); J. M. Enoch and A. M. Laties, *ibid.*, p. 959; J. M. Enoch and G. M. Hope, *ibid.* **11**, 765 (1972); *ibid.*, p. 1017.
16. Supported in part by National Eye Institute grant EY 00204 (to J.M.E.). We would like to thank R. A. Moses and S. Batra for critically reading this manuscript.
* Send requests for reprints to J.M.E.

18 April 1973