The Development of Visual Accommodation during Early Infancy

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BANKS, MARTIN S. *The Development of Visual Accommodation during Early Infancy.* CHILD DEVELOPMENT, 1980, **51**, 646-666. 4 experiments were conducted concerning the development of visual accommodation in 1- to 3-month-old infants. In experiments 1 and 2 dynamic retinoscopy, was used to measure accommodation responses at 3 stimulus distances. The results of experiment I revealed better accommodative capability from I to 3 months than reported originally. The procedure of experiment 2 ,vas somewhat different but the results confirmed those of experiment 1. In experiment 3, accommodative responses at 7 stimulus distances were carefully measured in a small number of infants. These data provided estimates of the shape of infants' accommodation functions. In experiment 4, we used infrared photography to measure infants' pupil diameters while they viewed the stimuli of experiments 1 and 2. 2 simple hypotheses of the developmental mechanisms which underlie early accommodative development were considered. First, development of the motor component of the accommodative system might determine accommodative development. Second, development of the sensory component of the accommodative system might determine the observed development. The first hypothesis was tentatively rejected because it is inconsistent with some clinical findings. Evaluation of the second hypothesis involved calculating infants' depth of focus. We used those depth-of-focus values to predict hoe well infants of different ages should accommodate if their only limitation were in the sensory component of the accommodative system. The agreement between those predictions and observed accommodation was excellent, suggesting that changes in depth of focus in the first 3 months are largely responsible for growth in accommodation. The theoretical implications of this finding are discussed.

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The human eye is adapted for high-resolution sampling of the visual environment. To utilize fully this resolution for perceiving objects distributed across visual space, several visuomotor mechanisms must be engaged. The eve-movement systems are examples of such mechanisms. They direct the foveas, the retinal regions specialized for high resolution, toward single objects of interest at different elevations, azimuths, and distances. The visual accommodative system is another visuomotor mechanism needed to optimize resolution for objects at different distances. The eye, like any optical system, can only be sharply focused for one viewing distance at a time. At) object at another I distance gives rise to a defocused retinal image, the magnitude of defocus depending on the distance from the object to the plane for which the eve is in focus. The eye, however, can shift its plane of sharp focus (the focal plane) by changing the shape of the lens. For objects closer than the initial plane of sharp focus, the curvature of the surfaces of the lens is increased thereby increasing the lens's refractive power and moving the focal plane toward the eve. For more distant objects, the curvature of the lens is decreased, refractive power reduced, and the focal plane moves away from the eye. The term "visual accommodation" refers to these adjustments of the distance of the focal plane.

This paper will consider the development of visual accommodation during early infancy. Two types of measurements relevant to understanding infant accommodation have been discussed in the literature: (1) measurements of the focal plane of the eye when accommodation is paralyzed with cycloplegic drugs and (2) measurements of changes in the distance of the focal plane during active fixation of objects at various distances. This paper primarily concerns the second aspect of accommodation but, by way of introduction, the first will be discussed briefly here. Cycloplegic drugs can be used to temporarily, paralyze the ciliary muscle which controls the refractive state of the lens. It is assumed that the distance of the eye's focal plane then increases to the far point of accommodation, the most distant point to which the eye can accommodate accurately. This focal distance can then be measured during retinoscopy or other techniques.[1] Such measurements are used to diagnose how well an eye's optical system is adjusted for the perception of distant objects. Some

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[1] In retinoscopy, the experimenter slowly sweeps a streak or spot of light back and forth across the subject's pupil and views the image that is reflected from the subject's retina. The reflection generally appears to move in one of two directions. It appears to move in the opposite direction 6om the movement of the retinoscope when the subject's focal distance is nearer than the retinoscope (i.e., -when the distance to which the eye is accommodated is between the subject and the experimenter's retinoscope). This is called "against" motion. The reflected image appears to move in the same direction as the retinoscope when the subject's focal distance is more distant than the retinoscope. This is called "with" motion. In principle no motion is observed only when the subject's focal distance coincides with the distance of the retinoscope. The experimenter searches for this distance either by placing lenses of known power in front of the subject's eye to vary the optical distance or by simply varying the physical distance from subject to retinoscope.

eyes are not suitably adjusted and thus exhibit myopia (nearsightedness) or hyperopia (farsightedness). Others are well adjusted and exhibit emmetropia, the absence of refractive error. For the purposes of this paper, it is important to note that a person's accommodative capability will depend in part on whether he or she is myopic, hyperopic, or emmetropic. A myope, for example, is unable to accommodate accurately to distant objects. A hyperope, on the other band, has difficulty accommodating to near objects. A number of cycloplegic retinoscopy studies have suggested that the average human newborn is about 2 diopters hyperopic and that this hyperopic error gradually decreases during infancy and early childhood (reviewed by Banks 1980). However, due to a constant error inherent to retinoscopy in infants (Glickstein & Millodot 1970),[2] the newborn's and young infant's eye under cycloplegia may actually be nearly emmetropic. At any rate, it appears from these findings that the eye of the average young infant is not myopic under cycloplegia and, therefore, that the mechanical capability for accommodating to distant objects is present early in life.

Three experiments have investigated the development of the second aspect of accommodation, the ability to accommodate to targets at different distances (Braddick, Atkinson, French, & Howland 1979; Haynes, White, & Held 1965; White & Zolot, cited in White 1971). Naturally these experiments were conducted without accommodation-paralyzing cycloplegics. Haynes et al. and White and Zolot measured the distance of the focal plane during active fixation of a small target whose distance was varied from 8 to 100 cm. The results of the two experiments were generally similar. Haynes et al.'s data are displayed in figure 1. In each of the graphs, focal distance, the distance to which the eye appeared to be accommodated, is plotted as a function of stimulus distance. The units on the axes are diopters (D), the reciprocal of distance in meters. Perfect accommodation (i.e., precise correspondence between focal distance and stimulus distance across a wide range of distances) would be represented by a linear function with a slope of 1. The complete absence of accommodation (fixed focal distance regardless of stimulus distance) would be represented by a line with a slope of 0. The actual results are represented by a best-fitting line for each infant. Infants from a few days to 1 month of age exhibited no evidence of accommodation; each infant's focal distance appeared to be constant across stimulus distances. The median fixed focal distance was 19 cm. Considerable development was observed from 1 to 4 months; indeed, the accommodative functions for the 3- to 4-month group resemble adult functions. In summary, these findings suggest that accommodation is essentially nonfunctional from birth to 1 month but that it improves very rapidly from that age on. Recently, Braddick et al. (f979) have also studied infant visual accommodation using the photorefraction technique of Howland and Howland (1974). Their results showed the magnitude of accommodative error plus other optical errors and will be discussed in the general discussion section.

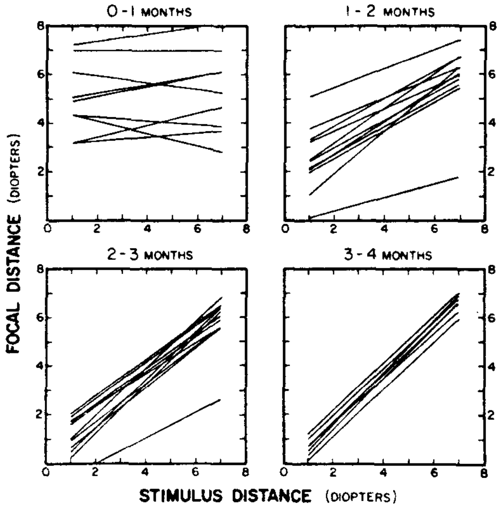

Fig. 1-The results of Haynes et al. (1965). The graphs summarize their measurements of accommodation at four different ages: 0-1 months, I2 months, 2-3 months, and 3-4 months. Each graph displays focal distance, the distance to which the eye appeared to be accommodated, as a function of the stimulus distance. The units on the axes are diopters, the reciprocal of distance in meters. Each infant's performance is represented by a best-fitting line.

Recent information concerning young infants' acuity and contrast sensitivity (Atkinson, Braddick, & Moar 1977; Banks & Salapatek 1978) led us to suspect that Haynes et al. actually underestimated accommodative ability during the first 3-4 months. Specifically, their visual stimulus may not have been an optimal stimulus for accommodation in such young subjects. The stimulus was a white, 11x 13-cm shield with a 4-cm red annulus and small black dots. The same target was used for all stimulus distances, so its angular subtense varied from 62° at 10 cm to 7° at 100 cm. Of course, the angular subtense of the annulus also varied (from 23° to 2° across those distances). Given the poor acuity and contrast sensitivity of young infants, one suspects that the salience of the target declined significantly with increasing target distance. Consequently, the younger infants may have had difficulty in picking up sufficient pattern information to enable accommodation to the more distant targets. In fact, Haynes et al. reported difficulty in sustaining stimulus fixation in infants less than I month of age (p. 529).

In the present paper the results of four experiments are reported. The first two experiments involved measurements of accommodative capability in 1-, 2-, and 3-month-old infants. The stimulus was constant in angular subtense for all three stimulus distances and contained large, high-contrast pattern elements. Thus we hoped it would be an optimal stimulus to accommodation for all of the age groups. The third experiment consisted of careful measurements of accommodation across a large number of stimulus distances. The subjects were

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[2] Glickstein and Millodot (1970) suggested that retinoscopy errs in the direction of hyperopia (farsightedness) due to the separation between the retinal receptor layer and the retinal laver from which the retinoscopic light is actually reflected. The error would cause underestimation of focal distance (expressed in diopters [D]). That is, a true focal distance of 50 cm (2 D) might appear, retinoscopically, to be 67 cm (1.5 D). The magnitude of this error is greater in small eyes, so its significance should decrease developmentally.

132-month-olds. The fourth experiment involved measurement of pupillary diameter in 1-, 2-, and 3-month-olds as they viewed the stimuli used in experiments 1 and 2. Finally, a model of accommodative development in infancy is proposed, and the data of these four experiments are used to test it. The model is based on the principle that accommodative ability is strongly dependent on depth of focus. We show that age-related changes in depth of focus due to the development of visual acuity and the pupil are sufficient to account for the observed development of accommodation. This model also explains the previously puzzling observation that visual acuity does not vary across stimulus distance in young infants.

Experiment 1

Subjects. —Infants were recruited by letter and phone from published announcements of births in the Austin area. The 20 infants who participated were all healthy. Fourteen of the 20 infants provided usable data. The others were eliminated due to sleepiness, fussiness, or failure to return for subsequent sessions.

Pilot work bad suggested that considerable accommodative development occurs between 1 and 2 months. Hence we decided to test infants longitudinally at weekly intervals from I to at least 2 months of age. Eight infants were tested in this manner. Six were full-term infants ranging from 31 to 75 days in age. The other two were monozygotic twins who were born 1 month prematurely. Their data, collected from 27 to 111 days postnatal, were treated separately from the full-term infants'. Six additional, full-term 3-month-olds (age 72-93 days) were tested in single sessions to supplement the 3month data.

Apparatus and procedure. —A schematic of the apparatus is shown in figure 2. The stimuli were projected onto a large Polacoat LS60 rear projection screen by a Kodak Carousel 650H projector. Stimulus luminance could be accurately adjusted with a rotating variable density filter mounted directly in front of the projection lens.

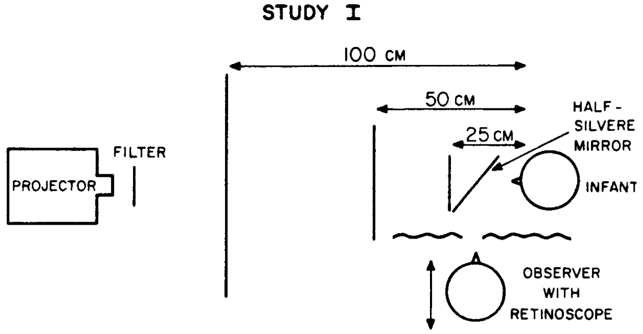

FIG. 2 - Schematic of the apparatus. The stimuli were projected onto a large, rear-projection screen. The infants viewed the stimuli through a half-reflecting mirror. The projection screen was moved to vary stimulus distance. The retinoscopist viewed the infant in the mirror from behind a curtain placed to the infant's side. For more detail, refer to text.

Three stimulus distances were presented: 25 cm (4 D), 50 cm (2 D), and 100 cm (I D). The stimuli were Karmel's (1969) random checkerboards subtending 30° x 30° (that is, 13.5 x 13.5 cm at the 25 cm distance, 27 x 27 cm at 50 cm, and 54 X 54 at 100 cm). The average size of the actual pattern elements was 2.1° with a standard deviation of 0.9°. Space-average luminance was 8 cd/m^2 (candelas per square meter), and contrast between adjacent light and dark pattern elements was 0.82. These stimuli were chosen because they have a relatively broad spatial-frequency spectrum (Banks & Salapatek, in press); that is, they contain considerable low, medium, and high spatial-frequency information. Thus, the acuity and contrast sensitivity limitations of young infants were at least minimized by using these targets.

Infants viewed the stimuli through a large, half-reflecting mirror while being held on their mothers' laps or over their mothers' shoulders. Because of the variety of holding positions, the height of the projected stimulus was adjusted for each infant. The experimenter performed retinoscopy and monitored the infants' behavioral state through a narrow break in a curtain placed to the infants' left. Data were recorded only if the infant's state was judged to be active and alert (state B) or quiet and alert (state C). Data were not recorded if they were fussy/crying (state A), drowsy (state D), or sleeping (state E). The importance of assessing behavioral state is illustrated by figure 3 (see figure caption for explanation). Another research assistant, positioned to the side of the screen, judged when the infant was fixating. When the infant was not fixating, data collection was halted and the research assistant attempted to reestablish fixation by dangling noisemaking toys in front of the screen. The toys were always removed from view before data collection began once again.

Retinoscopy was performed with an American Optical 11484B streak retinoscope with the streak fully diverged (Howland 1978) and oriented vertically. The measurements were always performed in the horizontal meridian of the infant's left eye. Because retinoscopy involves difficult subjective judgments, the experimenter generally used an ascending and descending staircase procedure in an attempt to minimize measurement error. The procedure began with the experimenter positioning himself on the infant's apparent line of sight as seen in the half-reflecting mirror. The initial retinoscope-infant distance was either quite short or quite long. The experimenter would then observe the reflected retinoscopic image with only two or four horizontal sweeps of the retinoscope. Depending on the image's apparent direction of motion (see n. 1 above), the experimenter would reposition himself considerably closer to or farther from the infant. The experimenter would continue to change the retinoscope-infant distance in large steps until he observed a clear reversal of the image's direction of motion. At that point, be would reverse his direction of movement with respect to the infant and repeat the procedure above with smaller step size until another clear reversal occurred. If the subject remained alert and maintained stimulus fixation, an additional sequence of observations with small step size was initiated. The distance at which the reversal point was observed during the last sequence was taken as the focal distance unless the point observed during the preceding sequence was noticeably different. In those cases, additional sequences were run until consistent values were obtained.

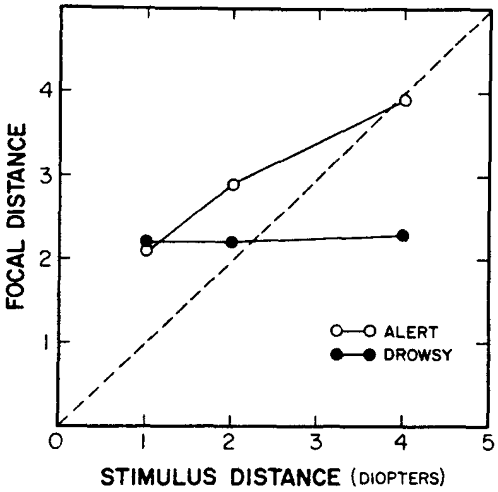

FIG. 3 - One 5-week-old's accommodation function in two different behavioral states. We had observed informally that a number of infants' accommodative performances were correlated with behavioral state. Infants who were active, alert (state B) or quiet, alert (state C) appeared to accommodate more accurately than those who were drowsy, (state D). In general, data were collected only when infants were in states B or C, but fig. 3 illustrates a case in which we measured accommodation functions for a 5-week-old in two behavioral states. The function represented by open circles was obtained while the infant's state was judged as active, alert (state B). The function represented by the closed circles was obtained while the infant was drowsy (state D). Accommodation was much more accurate in the first case.

An experimental session consisted of at least one focal-distance determination at each of the three stimulus distances. The order in which the distances were presented was randomized across subjects. Whenever possible the entire experiment was repeated within a session (with the order of stimulus distances reversed) to obtain a second set of retinoscopic measurements.

Results. —Accommodative data from an adult observer are shown in figure 4. Focal distance, the distance to which the eye appeared to be accommodated, is plotted as a function of stimulus distance. The units on the axes are diopters, the reciprocal of distance in meters. Obviously the adult observer accommodated quite accurately to the three stimulus distances; in fact, a straight line fit through these data points had a slope of 0.95 where 1.0 (broken line) represents perfect accommodation.

Longitudinal data from one infant are shown in figure 5. Noteworthy improvement in accommodation occurred from 5 to 9 weeks: The infant did not accurately match focal distance to stimulus distance at 5, 6, or 7 weeks of age; accurate matching was observed at 8 and 9 weeks. The other infants' accommodation functions exhibited similar developmental trends.

Figure 6 displays accommodation functions for all of the infants tested. To simplify the presentation of these results, we have replaced each measured accommodation function with a least-squares criterion, best-fitting straight line. We have also sorted the data into three age groups: 1-month-olds (3-5 weeks), 2-month-olds (7-9 weeks), and 3-month-olds (11-13 weeks). Infants who were tested longitudinally are represented by more than one line in each figure. The 6-week and 10-week data are not included in order to emphasize the age trends. Three aspects of these group data should be noted. First, the slopes of the accommodation functions appeared to increase with age. Second, the variability within groups appeared to decrease from 1 to 3 months. Third, accommodative error, the difference between ideal and observed focal distances for a given stimulus distance, appeared to decline with age. Unfortunately, due to constant measurement errors inherent to retinoscopy with infants, other interpretations of this apparent decrease in absolute accommodative error are possible.[3] Although these measurement errors affect the determination of focal distance at a given stimulus distance, they do not affect the slopes of accommodation functions because they are nearly constant in magnitude across various stimulus distances (see nn. 2 and 3). Consequently, we will emphasize slope data henceforth. Figure 7 summarizes the slopes of the accommodation functions across sessions and across infants. The slopes are those of the least-squares lines of figure 6. The average slopes were 0.51, 0.75, and 0.83 for 1-, 2-, and 3-month-olds, respectively. Since this experiment involved longitudinal and cross-sectional testing, separate statistical tests, some using age as a within-subjects factor and some using it as a between-subjects factor, were conducted on the slope data for each of three age comparisons. In the 1- and 2-month comparison, age was a within-subjects factor with two levels: 25-40 days (I month) and 51-66 days (2 months). The 2-month slopes were marginally significantly greater than the 1-month, $t(5) = 1.68$, $p = .078$, one-tailed.[4] To compare the 1- and 3-month slopes, age was treated as a between-subjects factor with two levels: 25-40 days (1 month) and 75-93 days (3 months). The 3-month slopes were also marginally significantly greater than the 1-month slopes, $t(11) = 1.49$, $p = .085$, one-tailed. To compare the 2- and 3-month slopes, age was again a between-subjects factor. The slopes did not differ significantly t(11) = 0.17, N.S. It is difficult to draw firm conclusions about age differences from these data because the differences between 1 and 2 months and between 1 and 3 months were only marginally significant. This is probably simply due to the small numbers of subjects whose data could be used in these analyses. The results of experiment 2, a cross-sectional study

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[3] In addition to the error described by Glickstein and Millodott (see n. 2 above), another measurement error, oblique astigmatism, may occur in retinoscopy. Oblique astigmatism is discussed in the results of experiment 2. It occurs when the optic axis of the eye being observed and the axis of the retinoscope do not coincide. The resulting measurement error is typically in the direction of myopia (nearsightedness), so it leads to overestimation of focal distance (expressed in diopters). Given the unstable fixation of young infants, the error is probably involved in many infant retinoscopic measurements. Furthermore, the magnitude of the error (for a given disparity between optic axis and retinoscopic axis) is greater in small eyes, so it should be greatest in young infants (Banks 1980). Thus, two measurement errors, opposite to one another in direction, may be involved in our measurements. Until the magnitudes of these errors are known for infants of various ages, determination of absolute focal distance will be problematic.

[4] We have stated one-tailed probabilities when directional predictions were made and only two age levels were involved in the statistical test.

with a larger number of subjects, showed significant age trends. Thus, experiments 1 and 2 indicate that accommodative accuracy increases noticeably from 1 to 2 months and then little if any from 2 to 3 months.

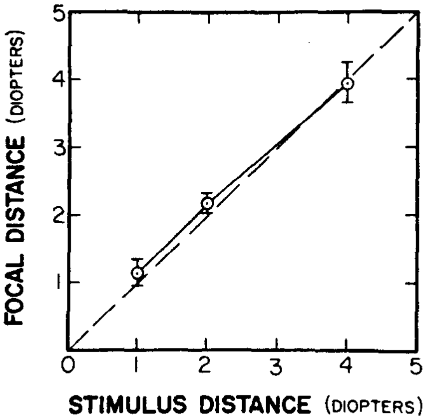

FIG. 4-Accommodation function for an adult observer. Focal distance is plotted as a function of stimulus distance. The brackets around each point represent the total range of four measurements. The function that would be obtained if accommodation were perfect is represented by the broken line. See text for further explanation.

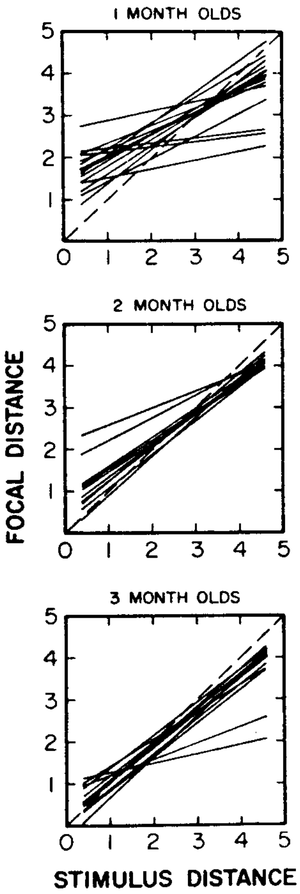

FIG. 5.-One infant's accommodation functions at different ages. Focal distance is plotted as a function of stimulus distance. Ages are indicated at the lower right.

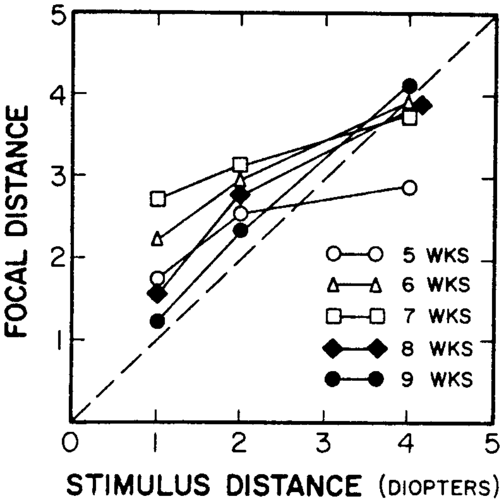

FIG. 6.-Summary of the results of experiment 1. Best-fitting lines were found for each infant's accommodation functions. Those lines are plotted here. The graphs display the lines for 1-month-olds (3-5 weeks), 2-month-olds (7-9 weeks), and 3-month-olds (11-13 weeks), respectively. Individual infants may be represented more than once in a particular age group. Data obtained at 6 and 10 weeks are not shown. The function that would be observed if accommodation were perfectly accurate is indicated by the broken lines.

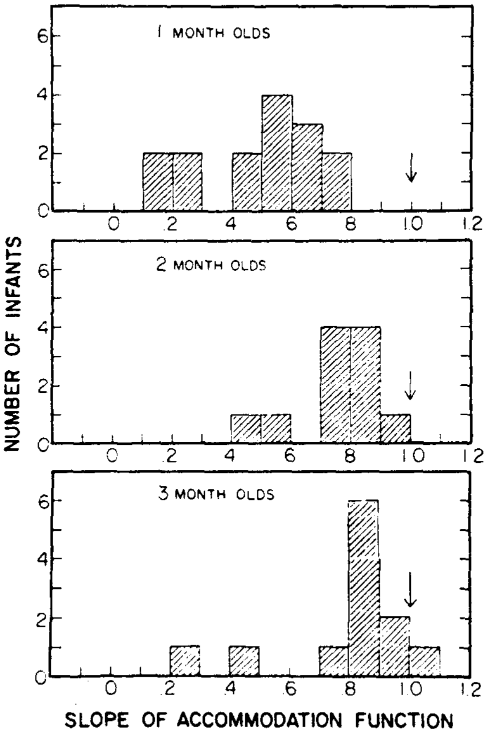

FIG. 7.-Summarv of the results of experiment 1. The heights of the bars represent the number of infants exhibiting particular slopes of the accommodation function at different ages: 1 month (3-5 weeks), 2 months (7-9 weeks), and 3 months (11-13 weeks). Individual infants who were tested longitudinally may be represented more than once in a particular age group. Data obtained at 6 weeks and 10 weeks are not shown. The slope of the function that would be observed if accommodation were perfectly accurate is indicated by the arrows.

These results are somewhat different from those of Haynes et al. (1965). They presented their data using different age groupings than ours (see fig. 1), but Haynes (Note 1) provided a more useful summary of the same data. The average slopes of the accommodation functions he reported were 0.06 from 2 to 6 weeks (1 month), 0.50 from 6 to 10 weeks (2 months), and 0.76 from 10 to 14 weeks (3 months). Our results (0.51, 0.75, and 0.83 at 1, 2, and 3 months, respectively) indicate better accommodation at the younger ages.

We also tested two premature, monozygotic twins. The twins were born 36 weeks after the mother's last reported menstrual period and, consequently, were judged to be 4 weeks premature. Data from one of the twins are shown in figure 8. The other twin's data were remarkably similar, although no useful data were collected at 7 weeks due to excessive fussiness. The slopes of both twins' accommodation functions, although showing increases with age, were lower than full-term infants' of similar postnatal age. Figure 9A plots accommodative slopes for these two infants at the various postnatal ages tested. The average slopes for all of the full-term infants are also shown for comparison. Interestingly, the premature twins' data were more similar to the full-term infants' if slopes were compared at similar postmenstrual ages as in figure 9B. Note the close agreement between the preterm and full-term data (at least at the ages where comparison is possible). This finding, which is similar to the results of other work comparing preterm and full-term infants (e.g., Fantz, Fagan, & Miranda 1975), suggests the importance of maturational factors in early accommodative development.

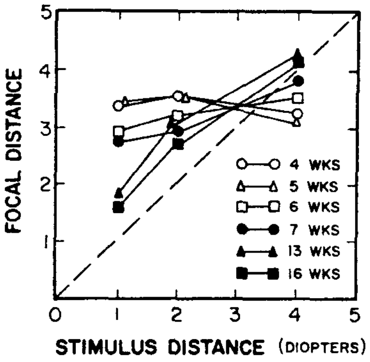

FIG. 8. -Accommodation functions for a preterm infant. Focal distance is plotted as a function of stimulus distance. Postnatal ages are indicated at the lower right,

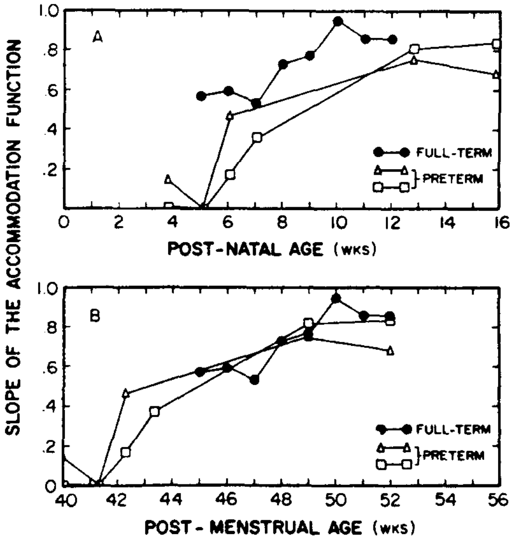

FIG. 9-Comparison of the accommodation function slopes of full-term and preterm infants. The full-term data (solid symbols) are the average slopes obtained at various ages. The preterm data (open symbols) are the slopes obtained for two different infants at various ages. A, Comparison of full-term and preterm slopes when plotted as a function of postnatal age. B, Comparison of full-term and preterm slopes when plotted as a function of postmenstrual age.

Experiment 2

Although the results of experiment 1 appeared to be reliable, we were concerned that two aspects of the measurement technique may have distorted infants' true accommodative capability. First, the retinoscopist always knew which stimulus distance was being presented on a given trial. Since retinoscopy requires a difficult subjective judgment, it is possible that experimenter bias may have influenced the measurements. Second, since the retinoscopic light was swept horizontally across the infants' line of sight, it may have distracted the infants and adversely affected accommodative accuracy. Experiment 2 was designed to eliminate these two concerns. The retinoscopist was "blind" to his optical distance from the infant to eliminate any influence of experimenter bias. The retinoscopist was also positioned 30° horizontally from the infant's line of sight to minimize distraction due to the retinoscopic light.

Subjects.—Infants were again recruited by letter and phone. The 45 infants who participated were full-term and healthy. Infants were tested cross-sectionally at 1, 2, and 3 months of age. Twelve 1-month-olds (22-35 days), eight 2-month-olds (55-63 days), and eight 3month-olds (77-94 days) provided usable data, the others being eliminated due to excessive fussiness or sleepiness.

Apparatus and procedure.—The apparatus was very similar to that of experiment 1. The projection system, stimuli, and stimulus distances were identical to those of experiment I (see fig. 2). The infants viewed the stimuli directly, however, rather than through the half-reflecting mirror of experiment 1. The variable density filter was adjusted to maintain an average stimulus luminance of 8 cd/m^2.

The retinoscopist positioned himself 67 cm from the infants' left eye and 30º to the left of the center of the checkerboard stimulus. To check his position, he occasionally measured the infant-retinoscope distance with a cloth tape measure. The retinoscopist also monitored the infants' state; again data were collected only if the infants appeared to be in state B or C. A research assistant positioned to the infant's right monitored the stimulus distance. Another research assistant, positioned to the side of and behind the projection screen, judged when the infant was fixating.

Retinoscopy was performed in a manner similar to experiment 1 except that the physical distance between the infants' left eye and the retinoscope was constant at 67 cm throughout the experiment. The optical distance between infant and retinoscope was varied by briefly placing ophthalmic lenses of varying power directly in front of the infants' left eye. The lenses were chosen and held in position by the research assistant positioned to the infants' right.[5] For each lens power the retinoscopist simply reported whether be observed "with" or “against” motion of the reflected retinoscopic image. The research assistant used this information and an ascending and descending staircase procedure to determine the next lens power to be tested. Step size was typically 1 D during the initial series of the staircase and ½ D for subsequent series. The procedure continued until the assistant had bracketed the lens power for which neither with nor against motion was observed with at least one ascending and one descending series. When an infant was sufficiently cooperative, three series were conducted. The research assistant interpolated between two lens powers when no single lens yielded a neutral (nonmoving) image. To determine the infants' apparent focal distance, we added 1.5 D, the dioptric value of the 67-cm observation distance, to the dioptric value of the neutralizing lens. This is a standard retinoscopic procedure (Borish 1970).

Results and discussion.—We used the off-axis retinoscopy procedure of experiment 2 to determine the accommodation function of an adult observer. This function is shown in figure 10. Clearly it differed from the one obtained with the same observer in experiment I (fig. 4). First, the apparent focal distance was generally 1-2 D greater than it was in experiment 1. Second, the slope of the accommodation function exceeded the slope of the function obtained in experiment 1; indeed, it actually exceeded 1.0, the slope of a perfect accommodation function. Both of these deviations from experiment I were due to a measurement error associated with off-axis retinoscopy.[6] Fortunately, one can use basic principles in geometric optics to estimate the change in accommodation-function slope one should observe for off-axis retinoscopy (Bennett & Francis 1962). Assuming that the refractive surfaces of the eye can be approximated by a single refracting surface (a practice often employed to model retinal image formation; see Emsley [19531), one can show that the accommodation-function slope for a perfectly accommodating eye should be 1.29 (rather than 1.0) when retinoscopy is performed 30° from the optic axis. The dotted line in figure 10 illustrates this prediction. Note that the slope of the adult's function (1.20) is closer to the dashed line (1.29) than to the dotted line (1.0). Therefore, one should reduce the slopes obtained in experiment 2 by a factor of 1.29 before comparing them to the slopes of experiment 1. Doing so for the function in figure 10 yields an adjusted slope of 1.20/ 1.29 or 0.93 which is quite similar to the 0.95 slope of figure 4. Given the effects of measurement error in off-axis retinoscopy, the adjusted slopes of the infant accommodation functions provide the most meaningful index of accommodative ability.

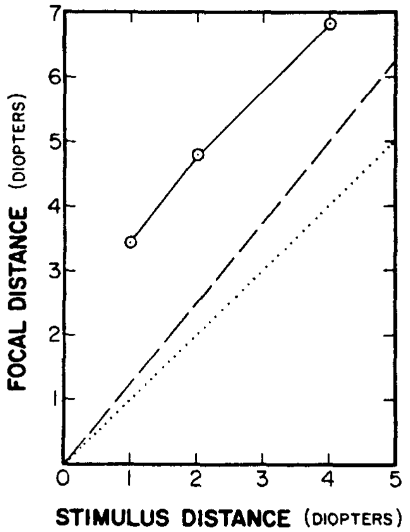

FIG. 10.-An adult observer's accommodation function measured using the procedure of experiment 2. Focal distance is again plotted as a function of stimulus distance. The dotted line represents the function obtained

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[5] We were concerned that some subjects might adjust their accommodation upon introduction of the ophthalmic lens in an attempt to minimize the resulting monocular defocus. In pilot work adults generally did not accommodate to the lens for brief lens presentations (less than 5 see), perhaps because to do so would have caused defocus in the other eye. Nonetheless, we were cautious in the infant experiments to look for evidence of any attempts to accommodate to the ophthalmic lens. Such attempts would have led to difficulty in neutralizing the retinoscopic reflex by introducing different lens powers.

[6] To understand this error, consider the following example. A number of point sources of light are placed at various locations but equidistant from an eye. One of the sources is presented on the eye's optic axis and the others at various angular separations from the axis. The eye is accommodated to the source on the optic axis and, therefore, the image of that Source is coincident with the eye's retina. Now consider image formation for one of the peripheral point sources. For the large majority of adult eyes, the image of a peripheral source would lie in front of the retina (Ferree, Rand, & Hardy 1931). In other words, even though the eye is accommodated to the point source on the optic axis, the eye would be noticeably overaccommodated for an equidistant, peripheral source. The magnitude of this effect depends on the curvature of the retina and other ocular parameters, so nonnegligible individual differences among adults are observed (Ferree et al. 1931; Leibowitz, Johnson, & Isabelle 1972). Nonetheless, this property of peripheral-image formation undoubtedly led to the 1-2 D increase in responses shown in figure 10. This effect also accounts for the observed increase in the slope of the accommodation function because its magnitude increases with increases in the eye's refractive power.

with perfect accommodation when on-axis retinoscopy is used. The dashed line represents the same function once its slope is corrected for 30* off-axis retinoscopy. See text for further explanation.

Figure 11 displays the unadjusted slopes of 1-, 2-, and 3-month functions. As in experiment 1, slope appeared to increase significantly between 1 and 2 months, and between-subjects variability appeared to decrease somewhat from 1 to 3 months. The slope of a perfect accommodation function, 1.29, is indicated by arrows. The average infant slopes, once adjusted by the factor 1/1.29, were 0.41 for 1-month-olds, 0.80 for 2-month-olds, and 0.78 for 3-month-olds. An analysis of variance was performed on the adjusted slope data with age as a between-subjects factor. The age factor was significant, $F(2,24) = 7.93$, $p = .002$. Planned comparisons between the three age groups revealed that 3-month slopes were significantly greater than 1-month, $t(14) = 3.44$, 1) < .605, one-tailed, but not significantly greater than 2-month, $t(18) = -.002$, N.S.; and 2-month slopes were significantly greater than 1-month, $t(18) = 3.55$, 1) < .00, one-tailed.

Comparison of figures 7 and 11 shows that the results of experiments 1 and 2 were equivalent once the slope data of experiment 2 were adjusted for off-axis measurement error. This indicates that neither experimenter bias nor distraction due to the retinoscopic light influenced the measurement of accommodative capability.

Experiment 3

The results of experiments 1 and 2 revealed considerable accommodative develop. merit during the first 3 months of life; slopes of the accommodation functions improved from about 0.50 at 1 month to about 0.80 at 3 months. We were concerned, however, that the 1-month slopes may not accurately reflect their accommodative ability because they were determined by data at only three stimulus distances: 25, 50, and 100 cm. It is possible that some 1-month-olds were able to accommodate quite accurately across a particular range of stimulus distances (e.g., 25-40 cm) but were not able to accommodate accurately across another range of distances (e.g., 40-100 cm). Our three-distance procedure may not have detected such a situation. In experiment 3 we carefully measured 6-week-olds' accommodation to seven different stimulus distances in order to determine better the shape of young infants' accommodation functions. Six-week-olds were chosen for two reasons: (1) infants at this age had been quite cooperative in general and (2) 6-week-old accommodation functions in experiment I were generally low enough in slope for shape differences in the accommodation function to have been a significant factor.

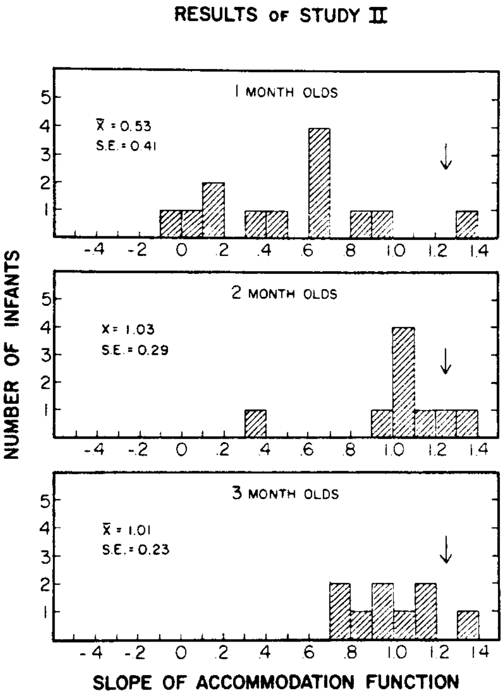

Fig. 11.-Summary of the results of experiment 2. The number of infants exhibiting particular slopes of the accommodation function is shown for three different ages: 1, 2, and 3 months. Best-fitting lines were fit to individual accommodation functions to obtain these slopes. These values have not been adjusted to compensate for the effect of oblique astigmatism. The slope of the functions that would be observed if accommodation were perfectly accurate is indicated by the arrows. Means and standard errors are shown on the left.

Subjects.— Once again infants were recruited by letter and phone. Six healthy, full-term infants ranging in age from 42 to 51 days participated. Five of them provided useful data. The collection of a complete set of data generally required two 45-min sessions.

Apparatus and procedure.—The apparatus and procedure were identical to those of experiment 1 except that seven stimulus distances were employed: 25.0 cm (4 D), 28.5 cm (3.5 D), 33 cm (3 D), 40 cm (2.5 D), 50 cm (2 D), 67 cm (1.5 D), and 100 cm (1 D).

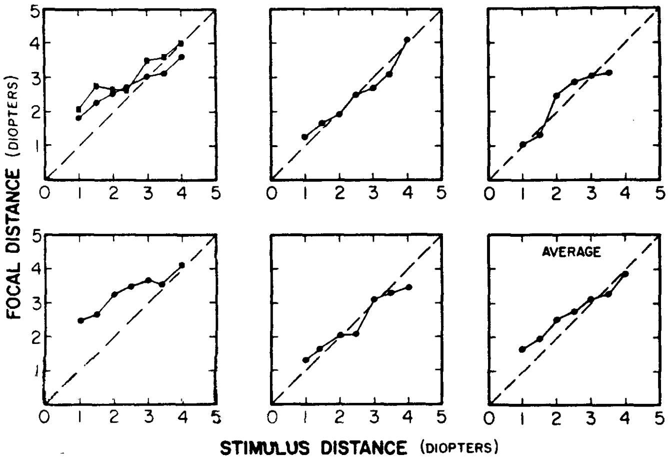

FIG. 12.- Individual infants' accommodation functions in experiment 3. Focal distance is plotted for seven different stimulus distances. Five panels show each of the infants' responses individually. Two complete functions were obtained for one of the infants. The data point at 1 D was lost for another of the infants. The panel at the lower right displays the average accommodation function for the five infants.

Results.—Figure 12 displays the infants' accommodative responses to the seven stimulus distances. Each panel shows one infant's responses; note that we obtained two complete functions for one of the infants. The slopes of these functions were comparable to those observed for 6-week-olds in experiment 1.

An analysis of variance was performed on these data with stimulus distance (in diopters) as a within-subjects factor. The main effect of distance was highly significant, $F(6,24) = 29.5, p < .001$. To determine the shapes of the accommodation functions, trend analyses were performed. The linear trend was highly significant, $F(1,24) = 174.37$, $p < .001$, but neither the cubic, $F(1,24) = 0.55$, N.S., nor quadratic, $F(1,24) = 0.26$, N.S., trends were. Thus the slopes of the accommodation functions were approximately constant across the range of stimulus distances used in our experiments. This implies that the slope values reported in experiments 1 and 2 were reasonable indices of young infants' accommodative performance across the range of distances tested. It remains possible, however, that nonlinear accommodation functions would have been observed if we had tested infants younger than 6 weeks in experiment 3.

Experiment 4

In the general discussion section, a model of accommodative development is proposed. The model states simply that age-related changes in depth of focus determine development in accommodation. Depth of focus is strongly dependent on pupil diameter, however, s~ to test the model, pupil diameters of young infants must be known. Rather than depend on existing developmental data, we ran another experiment to measure pupil diameters in 1-, 2-, and 3-month-olds while they fixated the stimuli used in experiments 1, 2, and 3.

Subjects.—Forty-two healthy, full-term infants were tested cross-sectionally at 1, 2, and 3 months of age. Six 1-month-olds (21-41 days old), six 2-montb-olds (51-61 days), and six 3-montb-olds (84-94 days) provided usable data. The others were eliminated due to excessive fussiness or sleepiness or because of poor photographic records in one or more of the experimental conditions.

Apparatus and procedure.—The projection system, stimuli, and stimulus distances were identical to those of experiments 1 and 2. The infants viewed the stimuli directly as in experiment 2 rather than through the half-reflecting mirror used in experiment 1.

Infrared photographs of the infants' faces were taken as they viewed the stimuli. The faces were illuminated by the stimulus and by an infrared light source (a 15-watt tungsten bull) filtered by Kodak Wratten filter no. 87C). The light source was invisible to adults and did not influence pupil diameters. Photographs were taken with a standard, 35-mm camera with a 200-mm telephoto lens and 3-D close-up lens attachment. The camera and light source were placed about 60 cm from the infant and 30° horizontally from the infant's line of sight. This allowed ~s to separate the corneal reflections of the stimulus and the " source which was useful in later assessment of eye position. High-speed infrared film (Kodak HIE 135-20) sensitive to the long-wavelength light of the light source was used throughout the experiment. A small cardboard ruler was taped to the bridge of the infant's nose. The photographs included the ruler and both eyes to facilitate calibration.

The experimenter operated the camera. A research assistant positioned to the side of and behind the projection screen judged when the infant was fixating the stimulus. Once the light source and camera were properly positioned and the infant seemed to be fixating, three to six photographs were taken at each of the three stimulus distances.

To measure pupil diameter the negative was projected onto a smooth surface. If the negative was of sufficient quality, the following procedure was assumed. First, the experimenter checked the relative positions of the pupil and the corneal reflection of the stimulus to determine if the infant had been fixating. If the corneal reflection was not positioned properly, the photograph was not measured. If the reflection was positioned correctly, the distance between two calibration points on the ruler was measured and recorded. This information allowed us to avoid measurement errors due to changes in the distance of the camera from the infant. Finally, the distance between the upper and lower pupillary margins of the left eye was measured. Only the upper and lower margins were used to avoid parallax errors in measurement. The measurements represent apparent pupil diameters because we did not correct for magnification due to the cornea.

Results and discussion.—The average pupil diameters, averaged across distances, were 4.2, 4.6, 4.6, and 5.2 min for 1-, 2-, and 3montb-olds and adults, respectively. The average diameters, averaging across ages, were 4.6, 4 -~. and 4.8 mm for 25, 50, and 100 cm respectively. An analysis of variance with stimulus distance as a within-subjects factor and age as a between -subjects factor was conducted. The distance main effect was significant, $F(2,52) = 4.02$, $p = .024$.[7] The age main

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[7] Although it is tangential to the purpose of this article, the main effect of stimulus distance warrants some discussion. if an adult fixates a

effect, $F(3,26) = 1.85$, $p = .164$ and the age X distance interaction, $F(6,52) = 1.11$, $p = .367$, were not significant.

The failure to observe a large increase in pupil diameter with age was somewhat surprising in light of the findings of Salapatek, Bechtold, and Bergman (Note 2). They measured pupil diameters for 1-month-olds, 2-month-olds, and adults at a variety of stimulus luminances. At 6.6 cd/m^2, the luminance level closest to that of our experiments, they observed average diameters of 4.9 and 5.0 min for 2-month-olds and adults, respectively, which is very similar to our results. However, Salapatek et al. (Note 2) observed average diameters of only 2.8 min for 1-month-olds, a value notably lower than ours. A look at their experimental procedure may reveal the source of this disagreement. Salapatek et al. always presented the 6.6 cd/m^2 stimulus after 10 min of dark adaptation and 2 min of other, dimmer stimuli. No assessments of behavioral state were recorded, so many of their younger infants may have been drowsy by that point. Adults' pupils constrict as they become drowsy (Lowenstein & Loewenfeld 1950), and we have informally observed a similar phenomenon in young infants. Thus Salapatek et al. may have underestimated 1-month pupillary diameter. The younger infants in our experiment were probably more alert than theirs because our procedure was much shorter in duration, and noise-making toys were used to maintain attentiveness. Consequently, our results are probably more representative of alert 1-month-olds.

General Discussion

Experiments 1 and 2 yielded very similar estimates of developing accommodative ability using two different procedures. These results were, however, somewhat disparate from those of Haynes et al. (1965). Specifically, we observed more accurate accommodation among the younger infants than Havnes et al. did. There are innumerable potential causes of the disagreement, but two seem most feasible. First, as we noted in the introduction, their stimulus may not have been an adequate stimulus for accommodation, particularly at the greater distances. Our stimulus, on the other hand, was high in contrast and large (subtending 30° X 30° at all three stimulus distances), so it may have provided a greater inducement for accommodation. Second, differences in the two subject populations could have contributed to the discrepancy. Haynes et al, conducted their investigation on institutionalized infants. All of their subjects appeared to be normal, but institutionalized infants frequently exhibit delayed development in comparison to noninstitutionalized infants (e.g., Fantz et al. 1975).

Recently, Braddick et al. (1979) studied infant visual accommodation using the photorefraction technique of Howland and Howland (1974). They tested infants ranging in age from 1 day to 12 months at two stimulus distances, 75 and 150 cm. Photorefraction does not allow one to determine directly the magnitude of a focusing error because it does not separate the effects of such an error from those of other optical factors such as scattering. Consequently Braddick et al. presented their findings as the percentage of infants exhibiting in-focus accommodative responses. "In-focus" responses were defined as those in which the apparent focal distance (focusing error plus other optical aberrations) fell between 75 and 40 cm for the 75cm target distance and between 270 and 80 cm, for the 150-cm distance. The younger infants, particularly 1- to 9-day-olds, exhibited more accurate accommodation to the 75-cm, target than to the 150-cm target; 85% were "in-focus" for at least some of the 75 cm trials but only 28% were for the 150-cm trials. In contrast, nearly all of the older infants consistently met the in-focus criterion for both target distances.

Unfortunately, it is difficult, for two reasons, to compare the Braddick et al. results with those of Haynes et al. and the present study. First, retinoscopy and photorefraction measure different aspects of defocus. Retinoscopy yields an estimate of the difference between the eye's focal distance and the stimulus distance; in other words, it yields an estimate of the accommodative error. Photorefraction, on the other hand, yields an estimate of the magnitude of all optical errors of which accommodative error is just one. Second, the data were reported in very different ways. The present study and Haynes et al. reported the magnitude of accommodative error at a variety of stimulus distances, whereas Braddick et al. reported the proportion of infants who met their in-focus criterion at two different distances. Nonetheless, Braddick's results support our conclusion that Haynes et al. underestimated the accommodative ability of very young infants. Most of Braddick's 1-week-olds exhibited a focal distance between 40 and 75 cm for the 75-cm target distance, whereas all of Haynes' 1-week-olds exhibited focal distances between 12 and 25 cm for all target distances.

The next question to consider is, What mechanisms underlie accommodative development? Visual accommodation is commonly viewed as a control system with two primary components: (1) a sensory component which evaluates the clarity or sharpness of the retinal image in order to determine whether an accommodative change is required and (2) a motor component which implements the changes in lens shape needed to maximize image sharpness. Given this viewpoint, two general hypotheses of the mechanism of accommodative development seem reasonable. The first hypothesis, which we will call the "motor hypothesis," states that development in the motor

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slowly approaching, constant luminance target, the pupil constricts. This is the well-known pupillary near response which is apparently linked to accommodation and convergence (Marg & Morgan *1949)*. The adult results were consistent with this trend, but the magnitude of the near response was somewhat less than that observed by others (Alpern, Mason, & Jardinicu *1961;* Marg & Morgan *1949);* that is to say, the decrease in diameter from 100 to 25 cm was not as large as expected. To our knowledge, there is no information in the literature concerning the development of the pupillary near response. Our infant data, with the exception of the 2-month-olds, did not exhibit the pattern typical of the adult pupillary near response. This suggests that the near response is not as evident in young infants as it is in adults, but another explanation is possible. *Although the* space-average luminance of each of our stimuli was 8 cd/M2, there were measurable regional variations in the luminance of each of the stimuli. The projection system and projection screen produced unavoidable "hot spots." The area and magnitude of the "hot spots" varied from stimulus to stimulus, the 50-cm stimulus having the brightest yet smallest "spot." It is possible that that this slight imperfection in the stimuli could have artifactually influenced the pupil measurements across stimulus distance and obscured the presence of a pupillary near response.

component of the accommodative control system accounts for the observed developmental changes. In other words, the early inability to accommodate accurately might be due to some deficit in the programming and/or execution of accommodative responses. The second hypothesis, which we will call the "sensory hypothesis," notes that the programming of accurate accommodative responses is dependent on the detection of the consequences of inaccurate accommodation. Thus the sensory hypothesis holds that accommodative development results from development in the ability to detect the image blurring resulting from a focusing error.

It is difficult to test the motor hypothesis empirically, but some evidence weighs against it. Santonastaso (1930) and others have observed that the refractive state of newborns' and 1-montb-olds' eyes changes dramatically when accommodation-paralyzing, cycloplegic drugs are introduced. Moreover, Havnes et al. (1965) observed large differences between newborns' refractive states when they were asleep compared with when they were awake. Thus the young infant's lens and the associated musculature are flexible enough to allow large changes in focal distance under some conditions. Our data indicate, however, that these changes are not well correlated with stimulus distance.

Evaluation of the sensory hypothesis involves the concept of "depth of focus." This concept is best defined by considering an eve whose accommodative state is fixed. In that case, "depth of focus" refers to the range of stimulus distances across which no detectable change in retinal image blurring occurs. It seems intuitively reasonable that eves with large depths of focus would be unable to accommodate accurately over some range of stimulus distances because small errors of focus would not produce detectable increases in blur. In contrast, eyes with small depths of focus would readily detect such blurring and, thus, would be capable of more accurate accommodation. The sensory hypothesis follows this line of reasoning to state that age-related changes in depth of focus might account for the observed accommodative development. To evaluate the hypothesis, the depth of focus of young infants' eyes was calculated and then used to predict accommodative performance as a function of age.

Green, Powers, and Banks (in press) recently developed a means of calculating depth of focus in a variety of eyes. Using geometric optics and linear systems analysis, they showed that

$$\Delta D = \frac{15.7\sqrt{1-M}}{p \bullet w} \quad (1)$$

where ΔD = depth of focus in diopters, p = pupil diameter in millimeters, w = visual acuity in stripes/degree, and $1 - M$ = a criterion-dependent value. For simplicity, they assumed that $1 - M$ remains constant at 0.2 across age. This means that a 20% reduction in contrast at spatial frequency w is required to detect defocus. Substituting 0.2 for $1 - M$ in equation (1) yields

$$\Delta D = \frac{7.03}{p \bullet w} \quad (2)$$

These equations do not include the effects of some optical aberrations of the human eye: diffraction, spherical aberration, and chromatic aberration. When one incorporates these aberrations into the calculations, the estimated depth of focus is increased (see, e.g., Charman & Whitefoot 1977; Green et al., in press). Fortunately, the effect of these aberrations is not significant in eyes with low visual acuity (Green et al, in press), so equations (1) and (2) should be reasonably accurate for the human infant eye. In summary, the equations show that depth of focus is Inversely proportional to both pupil diameter and visual acuity. (The dependence on pupil diameter is well known by photographers who increase the depth of focus in a photograph by decreasing the size of the camera's aperture.)

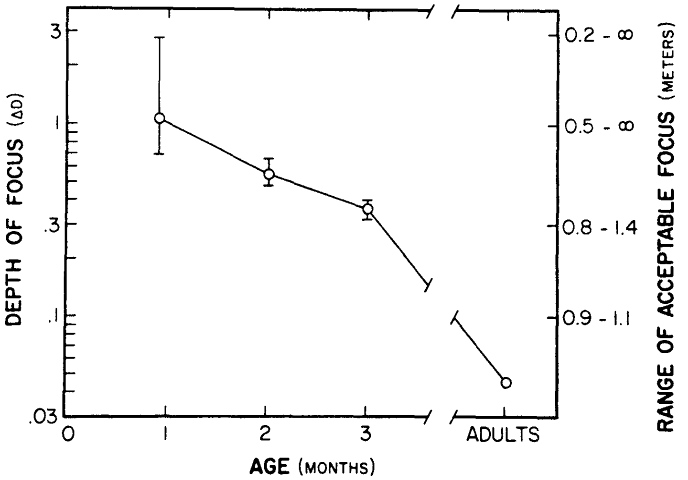

FIG. 13 - Estimated depth of focus for 1-, 2-, and 3-month-olds and adults. The vertical axis on the left represents depth of focus in diopters. The data points and brackets were obtained from eq. (2). The data points represent the average depths of focus calculated using acuity values from Atkinson et al. (1977), Banks and Salapatek (1978), and Allen (Note 3). The brackets represent the total range of depths of focus calculated using those acuity values. The vertical axis on the Tight shows, for different values of Z~ D, the range of stimulus distances which would be in acceptable focus if the eye were accommodated to I m.

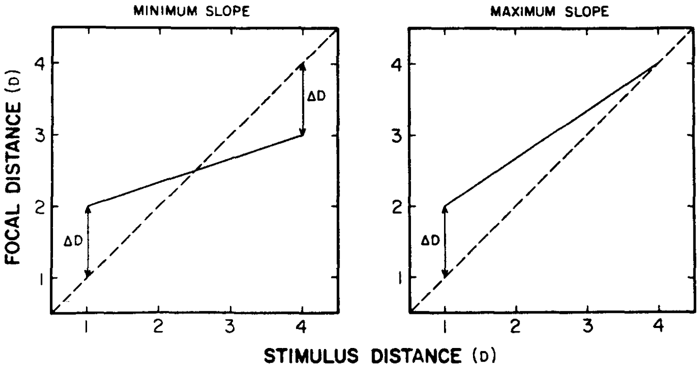

FIG. 14 - Illustration of the method for estimating minimum and maximum accommodation function slopes from the depth-of-focus values of fig. 13. See text for further explanation.

Figure 13 shows the depths of focus estimated from equation (2) for 1-, 2-, and 3-month-olds and adults. The values for p were obtained from experiment 4. The values for *w* were obtained from three experiments: Atkinson et al. (1977), Banks and Salapatek (1978), and Allen (Note 3). Each of these experiments measured visual acuity in 1-, 2-, and 3-month-olds with stimuli of about the same luminance as the stimuli used in our experiments 1-4. The brackets plotted at each age represent the range of depths of focus predicted by the different acuity values.

The depth-of-focus values can be used to predict accommodative performance at a given age if we assume, as the sensory hypothesis does, that the magnitude of accommodative error does not exceed depth of focus at that age. Figure 14 illustrates how these predictions are made. We do not know the various age groups, resting points of accommodation (the natural focal distance assumed in the absence of a stimulus to accommodation; Leibowitz & Owens [19781), so we can only define a range of predicted accommodative performance rather than make exact predictions. If an infant's resting point of accommodation lay halfway between 100 cm (1 D) and 25 cm (4 D), the range of stimulus distances tested, we would expect the accommodative error to be approximately equal to the depth of focus at both ends of the accommodation function (1 and 4 D). This situation is illustrated in the left side of figure 14 and yields the accommodation-function slopes labeled "minimum slope" in figure 15. If an infant's resting point of accommodation lay at one of the extremes of the accommodation function, an accommodative error approximately equal to the depth of focus would be predicted for the other extreme. This situation is illustrated in the right side of figure 14 and yields the predictions labeled "maximum slope" in figure 15. Thus the range of predicted accommodative slopes is delimited by the predicted maximum and minimum slopes.[8]

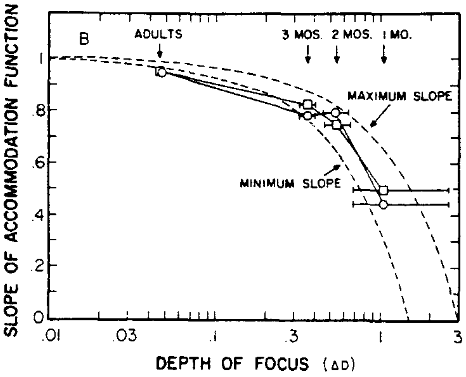

FIG. 15.-Observed and predicted accommodation function slopes for 1-, 2-, and 3-month-olds and adults. Slopes of the accommodation function are plotted as a function of estimated depth of focus. The broken lines represent the minimum and maximum predicted slopes. The data points represent the actual slopes obtained in experiment 1 (open squares) and experiment 2 (open circles). Each point is positioned horizontally according to the depth of focus estimated for that age (see fig. 13). The brackets represent the range of estimated depths of focus (see fig. 13) (adapted from Green et al. [in press]).

Figure 15 also displays the average accommodative slopes we observed in experiments 1 and 2 for each age group. The agreement between the observed and predicted infant slopes is clearly quite good. (The adult prediction is somewhat off, presumably because eq. [2] underestimates depth of focus for eyes with high visual acuity.) Since the predicted slopes are based entirely on estimated depths of focus, this result supports the sensory hypothesis; that is, early accommodative development results in large part from age-related decreases in depth of focus.[9] The result is consistent with earlier suggestions by Owens and Held (1978) and Salapatek, Bechtold, and Bushnell (1976).

This finding clarifies why young infants do not exhibit differences in acuity across target distances (Atkinson et al. 1977, Fantz, Ordy, & Udelf 1962; Salapatek et al. 1976) even though their accommodative ability is relatively poor. Infants accommodate only as accurately as needed to maintain reasonably constant image sharpness. Since their depth of focus is so large, considerable accommodative errors can occur without a noticeable decline in visual acuity. To illustrate this point, consider the findings of Atkinson et al. (1977). They measured the visual acuity of 1-, 2-, and 3-month-olds at target distances of 30 and 60 cm. Their stimuli were sine-wave gratings with an average luminance of 30 cd/M2. They found that visual acuity did not vary with target distance for any of the age groups (see table 1). To show that this result can be predicted by

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[8] This analysis assumes that infants' resting point of accommodation typically lies somewhere between 25 and 100 cm. If it were significantly closer than 25 cm or significantly farther than 100 cm, the analysis would predict an accommodative slope of 1.0. Although we have no direct data on the position of the resting point, the fact that most of our infants' accommodation functions exhibited minimum accommodative errors between 25 and 50 cm (see figs. 3, 5, 6, and 8) suggests that the resting point is probably not beyond the 25-100-cm interval.

[9] It is interesting to note that if the sensory hypothesis were extended to accommodative control in adults, it would (at least qualitatively) predict the accommodative capability of adults with amblyopia. "Amblyopia" is defined as the low visual acuity of one eye for which no obvious cause can be detected by physical examination. Wood and Tomlinson (1975) observed poorer accommodation in their subjects' amblyopic eyes than in their normal eyes. The amblyopic eve's depth of focus should be large due to its low acuity, and thus the sensory hypothesis predicts poorer accommodation. The sensory hypothesis is consistent with other findings in the adult accommodation literature. Hennessy, Iida, Shiina, and Leibowitz (1976) measured adults' accommodation while manipulating pupil diameter with an artificial pupil (in one condition retinal illuminance was held constant). Decreasing pupil diameter resulted in decreased accommodative accuracy. Since depth of focus is inversely proportional to pupil diameter (eq. [11), this would be predicted by the sensory hypothesis. Charman and Tucker (1977) and Heath (1956) demonstrated that accommodative accuracy is strongly dependent on the spatial-frequency content of the visual stimulus, Heath presented optically degraded stimuli at a number of distances and found that accommodative accuracy declined with increases in optical degradation (which is equivalent to attenuating the higher spatial frequencies in the stimulus). Charman and Tucker presented sine-wave gratings with different spatial-frequencies. Accommodative accuracy declined notably for low spatial frequencies (less than 3 cy/deg [cycles/degree]). Both of these results would be predicted by, the sensory hypothesis since depth of focus is inversely proportional to w, the highest detectable spatial frequency in the stimulus (eq. [1]).

our hypothesis, we have roughly estimated depths of focus and accommodative errors in their age groups. The pupil diameters of the infants in their experimental situation were not reported, so in calculating depth of focus we assumed they were similar to those of our experiment 4. This is a conservative assumption because their stimuli were more intense than ours, which would lead to smaller pupil diameters and, consequently, to larger depth-of-focus estimates. Using our estimates of pupil diameter and their estimates of acuity, the depth-of-focus values in table I were obtained from equation (2). We next estimated the accommodative errors that would be expected at 30 and 60 cm from the results of our experiment 1. To do this, we calculated the average accommodative responses at 25, 50, and 100 cm for each age group and estimated accommodative errors at 30. and 60 cm by interpolation. Except for a slight discrepancy for 2-month-olds at 60 cm, the expected accommodative error was always less than depth of focus. Consequently, on~ predicts no difference in visual acuity between 30 and 60 cm.

These findings contradict a common interpretation of the fact that newborns and 1-month-olds accommodate very poorly if at all. Several research publications and textbooks have mentioned the Haynes et al. (1965) finding that newborn to 1-month-infants exhibited a fixed focal distance of 19 cm (7% inches). Many of these concluded that such infants must see objects more clearly at that distance than at any other. For example, one textbook states, "Because the ciliary muscles of the newborn's eye are too immature to accommodate images at all distances, new babies see best at a distance of about 7½ inches" (Papalia & Olds 1975, p. 111). In light of our findings, this interpretation appears to be false for two reasons. First, the sensory component of the accommodative system, not the motor component, seems to be primarily responsible for any early accommodative deficit. Second, the clarity of young infants' vision does not seem to vary across a considerable range of distances. Therefore, instead of stating that young infants see relatively clearly at one distance and not others, it is more accurate to say that they see equally unclearly across a wide range of distances.

TABLE 1

Analysis of Atkinson, Braddick, and Moar (1977)

Age of Infant	Average Acuity (cy/deg)		Depth of Focus (D)	Accommodative Error (D)	
	30 cm	60 cm		30 cm	60 cm
1 month	.6	.6	±2.8	+.1	+1.0
2 month	2.9	3.2	± .5	+.3	+ .7
3 month	1.7	1.9	± .8	+.1	+ .3

Our hypothesis has some interesting theoretical implications concerning visuomotor development. We have proposed that the accommodative system at any age is an integral part of a feedback system: The eye's optics form a retinal image; the retina and central visual system evaluate the image's sharpness in some manner; and, through the accommodative system, any necessary adjustments of the eye's optics are programmed. It is important to consider which of the constituents of the feedback system is (are) the primary limitation (s) on early accommodative control. The motor component of the accommodative system has, of course, already been ruled out tentatively. The primary limitation, we have argued, is due to the large depth of focus of the young eye. One can now ask which of the system's constituents is (are) most responsible for the age-related changes in depth of focus. Pupil size must be involved to some extent because depth of focus is inversely proportional to pupil diameter (eq. [1]). But pupil size did not change significantly with age (experiment 4). Acuity, on the other hand, grows from about 1 stripe/deg (degree) at I month to 45 stripes/deg in adults. Thus, acuity, development must be a much more significant factor than pupillary growth in the age-related changes in depth 4 focus. One can now ask which constituents of the developing visual system are primarily responsible for the development of visual acuity. Dobson and Teller (1978) and Salapatek and Banks (1978) have pointed out that the optical quality of the young infant's eye probably exceeds the resolution capability of the visual system as a whole (for details see Salapatek & Banks [1978], pp. 85-86). Consequently, the retina and central visual system are probably the most significant constraints on visual acuity. This implies, in turn, that development in the accommodative feedback system is primarily, dependent on the growth of high-resolution neural processing. (By "high-resolution neural processing" we mean the aspect of visual acuity that is neurally, not optically, determined.)

Interestingly, a large body of experimental evidence suggests that the converse is also true; that is, acuity growth may be strongly dependent on accommodative development. Much of the evidence for this comes from research with kittens and infant monkeys. For example, kittens who experience only degraded visual input in infancy (due to paralysis of the accommodative mechanism or suturing of the translucent eyelids closed) do not develop normal acuity in the deprived eye(s) (Giffin & Mitchell 1978; Ikeda & Tremain 1978). Some psychophysical and clinical evidence points to a similar relation in humans. Patients with a history of cataracts early in life do not typically attain normal acuity even after removal of the cataract and full optical correction (National Advisory Council 1976).[10] Furthermore, adults with myopic (near-sighted) refractive errors do not exhibit normal acuity even if the error has been corrected for years (Fiorentini & Maffei 1976). These findings indicate that acuity development depends on the sharpness of images transmitted to the retina early in life. Since sharp retinal images are only attained by accurate accommodation, these findings

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[10] Enoch and Rabinowicz (1976) reported the case history of an infant whose unilateral cataract was surgically removed 4 days after birth. Reasonably accurate optical correction of that (aphakic) eye was first instituted at 25 days. Interestingly, the visual acuity of the aphakic eye improved after optical correction but was still notably poorer than the normal eye throughout the age range tested (9-129 days). Some of the aphakic eye's acuity deficit could have been due to uncorrected refractive error during testing, but the finding still suggests that defocused visual experience early, in life impedes acuity growth.

also imply that normal visual acuity would not develop in the absence of an accurate accommodative system. Therefore, a reciprocal dependency between accommodative development and acuity development seems to exist.

It is enlightening to consider bow various models of development might account for such a reciprocal dependency. In this discussion we consider four general models which are distinguished by the roles they assign to experience. (This treatment is very similar to Gottlieb's [1976].) The first model maintains that experience plays *no role* in the development of the particular behavior under study. Development of that behavior is genetically programmed and unaffected by experience. The second model states that experience maintains development of the behavior. Experience preserves a genetically programmed developmental state present in the newborn organism. The absence of appropriate, maintaining experiences leads to regression from that state. The third model states that experience *facilitates* development of the behavior under study. In this case experience assists in the achievement of particular developmental states. The fourth model states that experience *induces* development of that behavior. Experience plays an essential role in determining the course of development. The developmental state ultimately achieved reflects the content of the inducing experience.

It is easy to show that two of these models cannot adequately explain the reciprocal dependency in the development of accommodative control and acuity. The first model (no role for visual experience) can be rejected because it cannot account for the proven effects of visual experience on the development of visual acuity (Enoch & Rabinowicz 1976; Giffin & Mitchell 1978; Ikeda & Tremain 1978). The second model (maintaining role for visual experience) can also be discounted because it is inconsistent with the observation that visual acuity and accommodation are both functionally deficient neonatally.

It is particularly interesting to consider how the two remaining models might account for the reciprocal dependency. Simple versions of the fourth model (inducing role for visual experience) may not be able to easily explain how such a system can improve. Specifically, induction models would claim that the retina and central nervous system develop functional capabilities which reflect the content of the experience received during infancy. The neonate's eyes are not generally accommodated appropriately to the visual stimuli they are fixating, so most of the visual experience received must be quite defocused.[11] Consequently, an inductively determined visual system should develop low resolution capabilities. It is unclear, then, bow acuity would ever achieve higher values to allow the accommodative system to develop greater accuracy. We should note that with some very special assumptions, an induction model might be able to "bootstrap" to higher performance levels.

Some versions of the third model (facilitating role for visual experience) also seem workable a priori given certain assumptions. One acceptable version would hold that particular elements in the retina and central visual system are predisposed to develop medium resolution capabilities once some percentage of moderately blurred experience (as opposed to grossly blurred experience) is received and that other elements are predisposed to develop high resolution capabilities once some percentage of slightly blurred experience (as opposed to grossly and moderately blurred) is received. The moderately blurred experience would in fact be encountered by neonates when, by chance, they fixated a visual stimulus whose distance was relatively close to the eye's momentary focal distance. Once some facilitation of this neural development occurred, accommodation would improve correspondingly, thereby increasing the probability of the infant receiving some reasonably focused visual experience. This in turn would facilitate the development of high resolution elements. For the model to be consistent with other findings, however, the percentage of appropriately unblurred experience required for facilitation should be reasonably high. Otherwise it could not account for the failure of humans with myopia or anisometropia (different refractive errors in the two eyes) or kittens reared with paralyzed accommodation (Ikeda & Tremain 1978) to develop normal acuity in the deficient eye(s); in those cases the deficient eye(s) still would have received some small percentage of sharply focused visual experience during development.

In summary, we have argued that the development of at least one visuomotor mechanism, visual accommodation, involves a reciprocal dependency between two different processes and, furthermore, that development in this reciprocally dependent system might be explained by particular versions of facilitation and induction models. It would be important to determine whether other sensorimotor systems, such as convergence and visually guided reaching, involve analogous reciprocal dependencies and, if so, whether they, too, are best explained by facilitation and induction models.

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[11] Accommodation is not the only way by which an organism can adjust its eye to receive sharply focused retinal images; one can choose to fixate objects whose distance coincides with the eye's current focal distance. Note, however, that young infants could not employ such a strategy to ensure habitual fixation of objects at the appropriate distance. Because of their large depth of focus they would be unable to detect the decrease in blur associated with fixating objects at the focal distance.

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