The Development of Binocular Summation in Human Infants

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The difference in pupil diameter between monocular and binocular viewing conditions was used as a measure of binocular luminance summation in 97 infants aged 0 to 12 months. No significant difference in pupil diameter under monocular versus binocular viewing conditions was found until the end of the fourth month of life. The age of onset was positively correlated with the age of onset for stereopsis as assessed by preferential looking. By the end of the 6th month, the difference in pupil diameter under the two viewing conditions was adult-like in magnitude. The procedure provides an objective measure of binocular function that is not affected by fixation error. The data suggest that the visual pathways by which signals from the two eyes converge are not functional until the 4th month of life. Invest Ophthalmol Vis Sci 24:1103-1107, 1983

Recent studies of the development of binocular vision in infancy, using both psychophysic and electrophysiologic techniques, indicate that the onset of stereopsis occurs during the 3rd to 5th months of life. These data suggest that the visual pathways through which signals from the two eyes converge for disparity processing are not developed at birth but, rather, require a period of maturation. In addition to disparity processing, successful performance on a test for stereopsis also depends upon the capacity for bifoveal fixation. Special conditions may bypass this requirement but, in general, a failure to demonstrate stereopsis may reflect immaturity either of disparity processing or of control of vergence.

Other measures of binocular function exist that do not confound maturity of vergence with maturity of the binocular visual pathways. Tests of binocular luminance summation, for example, assess the degree of convergence of the luminance signals from the two eyes. Full-field tests of luminance summation are not affected by fixation error and do not require processing of relative binocular positional information. The key finding obtained from adults is that when equal luminance stimuli are presented to each eye, binocular brightness exceeds monocular brightness. A recordable physiologic parallel to binocular luminance summation was first described by Bartley and later described in detail in a series of papers by ten Doesschate and Alpern. They found that, under steady state conditions, the pupil is smaller when both eyes are illuminated than when either eye is occluded. Moreover, with unequal illumination of the two eyes, a qualitative and quantitative parallel to the brightness summation data of Fechner and Levelt was obtained.

The present report describes results obtained with a procedure for assessing binocular luminance summation in the pupillary response of infants. Both the time course of development for binocular summation and the relation between binocular summation and stereopsis were determined.

Materials and Methods

Subjects

Ninety-seven infants, aged 0–12 post-term months, were recruited by letter through birth records available at the City Hall in Cambridge, Massachusetts. All infants who participated were healthy, orthophoric, and within the normal range of refractive error as assessed by near-retinoscopy. Twenty-three infants were tested monthly for binocular summation with the first visit at 0–3 months of age and the final visit at 6 months of age. Twelve infants were tested twice per month for both binocular summation and stereopsis during the 3rd–6th months of life. Sixty-
two infants, aged 0–12 months, participated in a cross-sectional sample. Ten normal adults, aged 20–50 years, were also tested.

Binocular Summation

All testing was conducted in a dark room. The infant was held over its parent's shoulder with its head at the entrance of a full-field, uniformly illuminated (1.92 cd/m²) white dome 35.5 cm diameter. The dome contained an 8° aperture through which a low light level video camera monitored the infant's right eye. The video camera was employed in conjunction with a telephoto lens (approx. 5X magnification), a videotape recorder, and a black and white display monitor.

The infant's left eye was occluded with an opaque black patch and the right eye was adapted to the background illumination of the sphere for 5 min. Dim red light-emitting diodes located next to the camera lens flashed alternately to help maintain the infant's attention. Since the infant was relatively free to move about during the taping, a minimum of 2 min of videotape of the infant's right eye was obtained with the left eye occluded (monocular viewing condition). Pilot work showed this to be the minimum duration within which at least ten frames that were clearly in focus and nearly straight ahead in viewing angle could be obtained. Actual recording time sometimes exceeded this and depended on the cooperation of the infant. The left eye was then unpatched and a break in videotaping of 60 sec was given since pilot work showed that up to 20–30 sec readaptation was necessary for pupil size to reach equilibrium after the patch was removed. At least 2 min of videotape was then obtained of the right eye with the left eye open (binocular viewing condition).

Pupil and iris diameters were measured from single frames displayed on the black and white monitor. Pupil diameter was converted to a percentage of iris diameter in order to eliminate variations associated with changes in head position during taping. Ten such measures of right eye pupil size were obtained for both the monocular and binocular viewing conditions. The measures were taken from the first 10 frames of the right eye that were clearly in focus, nearly straight ahead in viewing angle, and separated by at least 5 sec.

Stereopsis

Stimuli and apparatus previously described in detail² were employed. Briefly, stereograms were rear-projected onto two Polacoat Lenscreens (3M Company) that were 11.5° in diameter with 34° center-to-center separation. These screens were located to the left and right of two small light emitting diodes. Two half fields of a 45 min crossed disparity stereogram were superimposed on one screen; two identical half-fields of a zero-disparity stereogram were superimposed on the second screen. All patterns were composed of three 1.9° wide black bars spaced at 1.9°, except that in the stereogram the two outside bars were shifted laterally in one half field to create the disparity. The views of the two eyes were separated by means of linear polarizers (extinction ratio = 10⁻⁴) mounted in the stereoprojector (Hawk MK VI) and in lightweight goggles (Speedo) worn by the infant. The patterns had a mean luminance of 7.5 cd/m² and 92% contrast.

The infant was held on its parent's lap or over its parent's shoulder at a distance of 50 cm from the screens. The parent was asked to maintain the infant's head in an upright position and an observer, watching through a peephole between the screens, was able to monitor head position throughout the experiment. The room was dark so that the only light was provided by the screens. On each trial, the observer centered the infant's gaze by flashing the light-emitting diodes. The stimuli were then presented and the observer, without knowledge of the position of the disparate stimulus, made a forced choice judgment as to the side at which the infant preferred to look. The position of the disparate stimulus was randomized over trials. Within a session, lasting approximately 10 min, 20 trials were obtained. Presence of stereopsis was defined as 75% preference (p < 0.02) for disparate stimulus.

During some of the sessions in which the infants demonstrated at least 75% preference for 45 min crossed disparity over zero disparity, control trials were also included. Nine infants were each tested once with 45 min vertically disparate horizontal stripes paired with zero disparity horizontal stripes as a mean age of 17.9 weeks (SD = 4.2 weeks). These stimuli contain all of the same monocular cues and nonstereoscopic binocular cues as the stimuli used to assess stereopsis. However, unlike horizontal binocular disparity, vertical binocular disparity is not a cue for stereopsis. The mean % preference for 45 min horizontal disparity over zero disparity in these sessions was 78.3% (SD = 4.1%). In contrast, there was no significant preference for 45 min vertical disparity over zero disparity (mean = 49.4%; SD = 11.2%).

Eleven infants (mean age = 18.1 weeks; SD = 4.7 weeks) were each tested once with 80 min crossed disparity vs zero disparity. This horizontal binocular disparity is so large as to fall outside the range for stereopsis. Normal adults report rivalry in response to this stimulus. The mean % preference for 45 min
disparity over zero disparity in these sessions was 79.5% (SD = 5.4%) while the mean percent preference for 80 min disparity over zero disparity was 40.0% (SD = 18.7%).

In both of these control conditions, stimuli contained the same monocular and binocular cues as that in the test for stereopsis except for a binocular horizontal disparity cue within the range required for stereopsis. Without the disparity cue for stereopsis, the infants failed to demonstrate a significant visual preference. Thus, we conclude that the visual preference observed in the test for stereopsis is based on horizontal binocular disparity.

Results

Cross-sectional

Mean right eye pupil diameter as a percentage of iris diameter in the monocular viewing condition (filled triangles) and in the binocular viewing condition (open triangles) obtained with 62 infants aged 0–12 months is shown in Figure 1. Pupil diameter on the monocular viewing condition increases with age over months 1–6 (Pearson r = 0.94, \( p < 0.01 \)), but pupil diameter in the binocular viewing condition is not correlated with age over this same time period (Pearson r = 0.16, ns). A difference score was calculated for each infant and the mean difference in pupil diameter under the two viewing conditions is also shown in Figure 1. T-tests for paired comparisons confirm that there is no significant difference in right eye pupil diameter for monocular vs binocular viewing during months 1–4. However, right eye pupil diameter is significantly larger when the left eye is occluded during months 5–12 (\( p < 0.02 \)) and in adults (\( p < 0.05 \)).

Longitudinal

Longitudinal data from a representative infant are shown in Figure 2. Mean right eye pupil diameter as a percentage of iris diameter with the left eye occluded (filled triangles) and with the left eye open (open triangles) is shown in Figure 2A. The infant’s data are typical in that pupil diameter in the binocular viewing condition does not change significantly with age while pupil diameter in the monocular viewing condition increases with age. Figure 2B shows the differences computed from the data in Figure 2A by subtracting mean pupil diameter for binocular viewing from mean pupil diameter for monocular viewing at each age. It is not until the 14th week (4th month) that this infant shows a significant difference between the two test conditions.

Differences in pupil diameter under the two view-
ing conditions for the 23 infants who participated in the longitudinal study are shown in Figure 3. These difference values were calculated as described for Figure 2. The mean standard deviation of measurement for the group of infants is 2.10% of iris diameter, so that the minimum significant difference between test conditions in a t-test for paired comparisons is 4.75% of iris diameter \((p < 0.05)\). Using this criterion, the mean age at which a significant difference in right eye pupil diameter is found under the two viewing conditions is 15.83 wks \((SD = 3.64 \text{ wks})\). For these infants, the mean change in pupil diameter with monocular viewing is +11.05% of iris diameter \((SD = 4.91\%\) over the first 6 months of life. In comparison, pupil diameter with binocular viewing changes little over the same time period \((mean change = +1.00\% \text{ of iris diameter}; SD = 5.8\%)\).

Figure 4 presents data obtained from the 12 infants who were tested twice per month for both binocular summation and stereopsis over the 2nd through 6th months of life. An age of onset for each measure of binocularity was defined. For binocular summation, the age of onset was defined as post-term age at the test session during which the infant first showed a difference in pupil diameter with monocular versus binocular viewing of at least 4.75% of iris diameter. Age of onset for stereopsis was defined as post-term age at the first session in which the infant demonstrated 75% preference for the disparate stimulus over the nondisparate stimulus. Each data point in Figure 4 represents a single infant’s ages of onset for both tests. Five of the infants have exactly the same age of onset with both procedures, three show the pupil diameter difference earlier, and four show evidence of stereopsis earlier. Mean age of onset for binocular summation is 16.1 wks \((SD = 4.2 \text{ wks})\) and for stereopsis is 15.5 wks \((SD = 3.8 \text{ wks})\). These mean ages of onset are not significantly different \((mean difference = 0.33 \text{ wks or 0 sessions})\). The ages of onset obtained from the procedures are positively correlated \((Pearson r = 0.775; t_{10} = 3.878; p < 0.01)\).
Discussion

The results of this study demonstrate that binocular summation is measurable by the 4th month of life and is adult-like in magnitude by the 6th month of life. The onset age for binocular summation is highly correlated with the onset age for stereopsis. The correlation between binocular summation and stereopsis found in this study is consistent with the absence of binocular summation in the pupillary response of strabismic adults.14,16,17

The agreement between the onset ages for binocular summation in the pupillary response and for stereopsis provides additional evidence that development of bifoveal fixation is not the sole factor determining the onset of stereopsis. Rather, the visual pathways by which signals from the two eyes converge must undergo maturation. This hypothesis has already been advanced on the basis of data obtained both in a study of the onset ages of crossed versus uncrossed stereopsis2 and in a study using stereo stimuli specifically designed to minimize the effects of vergence inaccuracy on stereo testing.3 Taken together, these results indicate that binocular neural development occurs during the first few months of life.

The objective procedure for assessing binocular summation described here may be particularly suitable for use in testing strabismic infants. It requires a minimum of time and cooperation from the infant and can assess the integrity of binocular visual pathways even in the presence of large angle tropias.

Key words: binocular summation, infants, stereopsis, pupillary response

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References