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Stereoacuity of human infants

(binocular disparity/development)

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ABSTRACT Stereograms were presented in a two-choice preference procedure. The mean age at which stereopsis was first demonstrable was 16 weeks. By a mean age of 21 weeks, infants had achieved stereoacuity of 1 minute of arc or better. In comparison with the relatively slow development of visual acuity, the time course for the development of stereoacuity is extremely rapid.

The angle formed by rays of light diverging from a near object to enter the two eyes is larger than that formed by the rays from a more remote object. The disparity between these angles provides the stimulus cue for fine discrimination of the difference in distance between the objects. Sensitivity to this angular disparity, called "stereoacuity," is such that a disparity of only a few seconds of arc can be discriminated by adult observers (1, 2). Infants have been reported to respond to coarse disparities present in dynamic random-dot stereograms* by their fourth month of life (3–5). Applying a new procedure using line stereograms, we show that stereoacuity of 1° is measurable by the fourth month and that it rapidly improves to at least 1′ of arc by the fifth month. These data comprise a longitudinal study of the normal development of stereoacuity and provide a quantitative basis for assessing the losses of binocularity that have been inferred to accompany squint and other forms of binocular imbalance (6–8).

The observation that an infant prefers to look at a three-dimensional object over an otherwise equivalent two-dimensional representation (9) suggested the two-alternative, forced-choice preferential looking procedure which we employed (10). Stereograms were used in order to eliminate the parallax motion that is produced by movements of the head in relation to a real object. This relative motion can also serve as a cue to coarse differences in depth (1). The disparities of the stereograms were varied over a range sufficient to determine a threshold at which the preference approaches chance.

Sixteen infants, all within the normal range of refractive error and oculomotor status, were tested.† Each infant sat on its parent's lap at a distance of 60 cm from two rear-projection screens (11° diameter; 30° separation between centers). The two half-fields of each stereogram (one for each eye) were superimposed on one screen; two zero-disparity half-fields were superimposed on the second screen. The side of presentation of the disparate stimulus was randomized. The views of the two eyes were separated by means of crossed Polaroid filters mounted in a stereoprojector (Hawk MK VI) and in lightweight goggles worn by each infant. The Polaroid filters transmitted 11% of the light when uncrossed and 0.3% when crossed. The zero-disparity pattern was composed of two identical half-fields consisting of three 2°-wide vertical black bars spaced 2° apart. The stereogram consisted of one half-field of three 2°-wide bars spaced at 2° and one half-field in which the outside two bars were shifted laterally (in the same direction) to create the binocular disparity. The stimuli, as they would appear to a normal adult observer, are shown in Fig. 1. Eight disparities were tested; they subtended 58, 46, 34, 23, 10, 6, 1, and 0 minutes of arc. The infant sat in a darkened room; the only light visible to him came through the projection screens. Consequently, the primary cues for accommodation and convergence of the eyes were located at the plane of the screens.

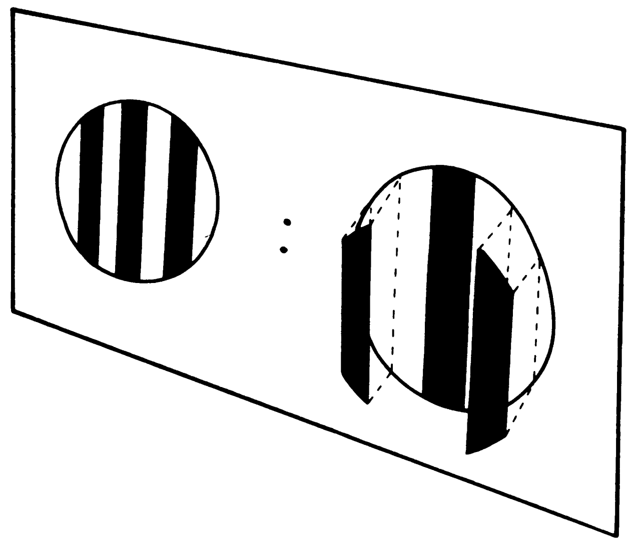

FIG. 1. A sample stimulus pair as it would appear to a normal adult observer. In this case, the stimulus to the left of the light-emitting diodes contains zero disparity and the stimulus to the right contains a large crossed disparity: the bars appear in front of the screen. In the experiment, uncrossed disparities, for which the bars appear behind the screen, were also used. The dashed lines are for construction. Note that the figure is not drawn to scale (see text for details).

On each trial, an observer centered the infant's gaze by flashing two red light-emitting diodes located midway between the two screens and by calling to the infant. The stimuli were

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* Although the random-dot technique has the advantage of eliminating monocular cues, it is not readily applied to the measurement of stereoacuity. In order to maintain the randomness of the stereogram, the disparate dot matrices can only be shifted with reference to each other by distances that are a multiple of the dot size with a minimum of one. Since stereoacuity can exceed the visual resolution of dots in the usual matrices by approximately 1 order of magnitude, the size of the dots required to permit disparities approaching stereo threshold is considerably below their visibility threshold. If, on the other hand, dot clusters of sufficient size constitute the displaced elements in the stereogram, they will be perceived monocularly and the advantage of the technique will be lost.

† The infants were examined by refraction at least monthly by the technique of near-retinoscopy (11). The average spherical error was +1.28 D and the average cylindrical error was −0.74 D. Five of the 16 infants showed significant astigmatism (>−1.00 D).

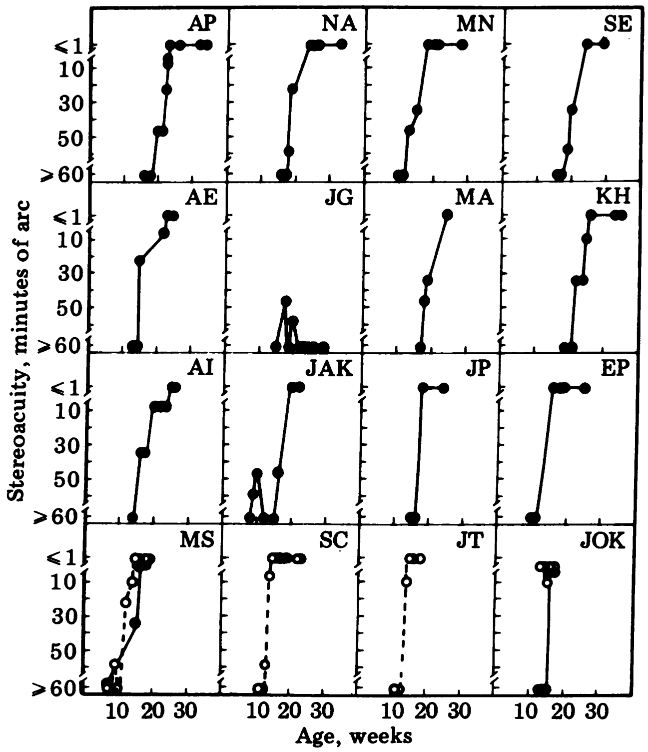

FIG. 2. Stereoacuity as a function of age for 16 infants. ●, Data obtained with uncrossed disparities; ○, data obtained with crossed disparities. Each data point represents the smallest disparity for which the infant showed a preference on at least 80% of the trials.

then presented. The observer, without knowledge of the position of the disparate stimulus, judged to which side, left or right, the infant was looking. Within a session (lasting approximately 15 min), 10 trials at each of four disparities were presented. Each trial lasted approximately 10 sec. All infants were tested with the 34′ disparity during each session. Any infant who failed to show at least 80% preference for the 34′ disparate stimulus was tested with the 58′, 46′, and 23′ stimuli. Infants who did show at least 80% preference for the 34′ disparate stimulus were tested with the 10′, 6′, and 1′ stimuli.‡ Stereoacuity was taken as the smallest disparity at which the infant showed at least 80% preference for the disparate stimulus.

Stereoacuities obtained for each of the infants are presented in Fig. 2. Twelve infants were tested with uncrossed disparities, two infants with crossed disparities, and two infants with both uncrossed and crossed disparities. All but one infant (JG) showed a rapid increase in stereoacuity with age. The mean age at which the infants first demonstrated a preference for the largest disparity available (58′) was 16 weeks (SD = 4 weeks). Because pilot studies showed that less than 50% of the infants tested discriminated disparities larger than 58′ at any age, this age probably represents the onset of stereopsis. Except for the one infant who never responded to uncrossed disparities smaller than 46′, the infants had achieved a stereoacuity of at least 1′ (the smallest disparity tested) by 20 weeks (SD = 4 weeks). The infants tested with crossed disparities had better stereoacuities relative to infants of the same age tested with uncrossed disparities. The mean age of first discrimination (58′) was 12 weeks for crossed disparity ($n = 3$) and 17 weeks for uncrossed disparity ($n = 13$). Furthermore, the mean age at which stereoacuity of 1′ was first demonstrated differed by 6 weeks (age 15 weeks for crossed disparities, age 21 weeks for uncrossed disparities). In spite of the small number of infants tested, these differences are statistically significant.§ Note that this difference also appears in the data of the infants who were tested with both types of disparity over the same period of time (MS and JOK).¶ A cross-sectional sample of infants ages 1–6 months ($n = 47$) confirmed the superiority of stereoacuity for crossed disparities. During the third, fourth, and fifth months of life, a significantly greater proportion of the infants tested with crossed stimuli reached criterion for each of the disparities than those tested with uncrossed stimuli.

In order to assess the preferential looking behavior of the infants for the patterns when the horizontal disparity cue to depth was removed, the bar patterns were rotated by 90° so as to make them horizontal and convert the disparity to the vertical. During a session in which at least 80% preference for 34′ horizontal disparity (vertical bars) over zero-disparity vertical bars was demonstrated, the infants were also tested with the vertical disparity stimulus pair: one screen contained zero-disparity horizontal bars and the second contained horizontal bars with 34′ vertical disparity. Adult observers perceive rivalry (alternation of the left and right eye views) under these conditions. Three of the infants preferred the zero-disparity stimulus to the vertical-disparity stimulus, and 13 demonstrated no preference. These data show that the response to vertically disparate bars, if present, is in a direction opposite to that for binocular horizontal disparities.

Of the 15 infants who showed an 80% preference for the 1′ horizontal disparity, 6 were tested on an additional control condition. Because of the incomplete polarization, the disparate stereogram, unlike the zero-disparity pattern, appears to have dim gray stripes interspersed between the black and white bars when viewed monocularly. In order to enhance this difference that could serve as a basis for discrimination, both half-fields were presented to the same eye by orienting both stereoprojector filters in the same direction. Whereas the mean percent preference for the disparate stimulus under stereoscopic viewing conditions was 80%, under this control condition the mean percent preference for the disparate stimulus fell to 48%. In order to assess preference based on differences in bar spacing in the monocular patterns, four infants viewed either the 1′ versus zero-disparity stimulus pair stereoscopically or, on other trials, viewed one half-field on each screen with both eyes: one screen contained the regularly spaced bars of a zero-disparity half-field and the other screen contained the irregularly spaced bars of the stereogram half-field (both polarized filters in the goggles had the same orientation). Mean percent preference for the disparate stimulus was 83% with stereoscopic viewing whereas, under the control condition, the mean percent preference was 51%. Because none of the three control conditions supports the preference behavior observed with stereoscopic viewing, we conclude that neither nonstereo binocular nor monocular differences are the basis of the discriminative behavior observed with the stereograms.

Although it is possible that the sudden appearance and rapid development of stereoacuity is related to the onset of precise and stable convergence, the differences we have observed be-

‡ All infants who demonstrated at least 80% preference for the 34′ horizontal disparity were also tested with a zero-disparity stimulus pair in order to assess the presence and magnitude of side preferences. None of the infants exceeded 70% preference for either side of the display.

§ The results of two-tailed t tests for differences between means show that both the age of first discrimination ($t_{14} = 4.9$, $P < 0.002$) and the age at which stereoacuity of 1′ is attained ($t_{14} = 5.9$; $P < 0.002$) are significantly different for the two groups (12).

¶ Richards has discussed the difference between crossed and uncrossed disparity discrimination and cases in which either one or the other is missing (13).

tween infants tested with crossed and uncrossed disparities argue against this interpretation. Inaccurate or unstable convergence should degrade both types of discriminative behavior equally. Furthermore, convergence is known to be fairly well developed by age 2 months (14). In fact, fine tuning of the convergence system may require a visual system sensitive to small binocular disparities rather than the reverse.

In comparison with the development of grating acuity (15–17), the time course for the development of stereoacuity is extremely rapid. Moreover, the rapid changes in stereoacuity occur at approximately the same age as the onset of susceptibility for strabismic amblyopia—the fourth month of life (18–20). Thus, there exists a suggestive parallel between the onset of the development of binocularity (as assessed by stereoacuity) and the beginning of the critical period for susceptibility to deficits that result from early binocular imbalance.

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