explained by fertilization of a polar body and ovum, and because fewer embryologic processes are involved in this method, it may be that most chimeras are conceived by this mechanism.

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## Stereopsis in Human Infants

Abstract. *Stereoscopic depth perception was tested in human infants by a new method based on attracting the infant's attention through movement of a stereoscopic contour formed from a dynamic random-element stereogram. The results reveal that stereopsis emerges at 3 1/2 to 6 months of age, an outcome consistent with evidence for rapid postnatal development of the visual system.*

Although stereoscopic depth perception is typically present in adults, little is known about its ontogenetic development. Despite great interest, efforts to investigate stereopsis in infants have encountered formidable difficulties posed by labile attention and limited response repertoire. As a consequence, the results have been inconclusive (*1*). We now report an investigation of stereopsis in infants based on a new method that involves engaging an infant's attention through the apparent motion in visual space of a stereoscopic form contained within a random-element stereogram.

Random-element stereograms, unlike conventional ones, contain no discrete contours or other monocular cues. Only viewers with stereopsis can perceive stereoscopic contours—without stereopsis only a random distribution of minute dots or elements is perceived (*2*). The stereogram display we used consists of a large array of red and green dots generated on a projection-type color television receiver. The red and green dots stimulate separate eyes when the array is viewed through red and green filters; this is the well-established anaglyph method of stereoscopic presentation. All stereogram dots are replaced randomly 60 times per second, which produces apparent random motion of individual dots but does not impair perceptibility of the stereoscopic form, at least for normal adults; however, it does camouflage local changes in dots that, under static conditions, might serve as a nonstereoscopic cue to changes in position of the stereoscopic form (*3*).

We used the capability of the stereogram generation system to produce moving stereoscopic forms in order to exploit the tendency of infants to track moving objects visually. Visual tracking of a random-element stereoscopic form would be compelling evidence of the possession of stereopsis, since stereopsis is a precondition for the perception of such a form. In the testing procedure, each infant was held by a parent approximately 130 cm in front of a large rear-projection screen upon which the stereogram was displayed. A spectacle frame containing one red and one green filter (Wratten 29 and 58) was placed on the infant's face. The stereoscopic form, a 10° by 15° vertically oriented rectangle, was positioned in the center of the screen at the beginning of each stereoscopic test trial (*4*). Whenever the infant's attention appeared to be directed toward the center of the screen, a concealed observer signaled the operator of the stereogram generator. The operator then moved the form laterally, left or right, in accord with a random schedule unknown to the observer. After 2 seconds, the operator returned the form to screen center and signaled the observer to make a forced-choice judgment as to the direction of form movement, a judgment based solely on the infant's visual behavior (*5*). To minimize bias, the observer received no feedback from the operator about the direction of movement, the operator received no feedback about the observer's judgment, and the parent could not detect the location of the stereoscopic form.

Before starting the stereoscopic test trials, the attentive state of each infant was assessed by a series of trials in which a physical analog of the stereoscopic form was the stimulus (*6*). If the observer could correctly detect direction of movement of the physical form at least 75 percent of the time, the infant was deemed suitable for stereoscopic testing. For stereoscopic trials the infants were tested for 40 trials, or fewer if they became uncooperative. Infants were excluded from the data analysis if they were not attentive for at least the first ten stereoscopic trials (*7*).

In experiment 1, infants were recruited to form three age groups—2 1/2, 3 1/2, and 4 1/2 months (*8*) (Fig. 1A). Performance of the 2 1/2-month group did not differ from chance [$t$ (14) = 1.79, $P > .10$]. Performance was greater than chance for both the 3 1/2-month group [$t$ (14) = 5.02, $P < .001$] and the 4 1/2-month group [$t$ (9) = 11.61, $P < .001$]. The age trend across groups was significant [$F$ (2, 37) = 8.37, $P < .0013$].

The performance of the older infants strongly suggests that they possess stereopsis, since the random-element stereogram prevents the use of nonstereoscopic cues. It is logically possible, however, that the lateral position of the form was detected even though it was not perceived in depth. To check on this we ran a second experiment with five disparity values, including two very large values that exceed adult fusional limits and do not induce stereopsis. Seventeen infants were tested (seven at 3 1/2 months and ten at 4 1/2 months); ten infants had served in experiment 1 (Fig. 2). The above-chance performance on the two intermediate disparities, 45 minutes [$t$ (13) = 3.12, $P < .01$] and 134 minutes [$t$ (15) = 7.21, $P < .001$], and the chance performance on the two largest disparities, 313 and 447 minutes [combined $t$ (7) = −2.34, $P > .05$], suggest that performance is related to the stereoscopic depth position of the form, a result con-


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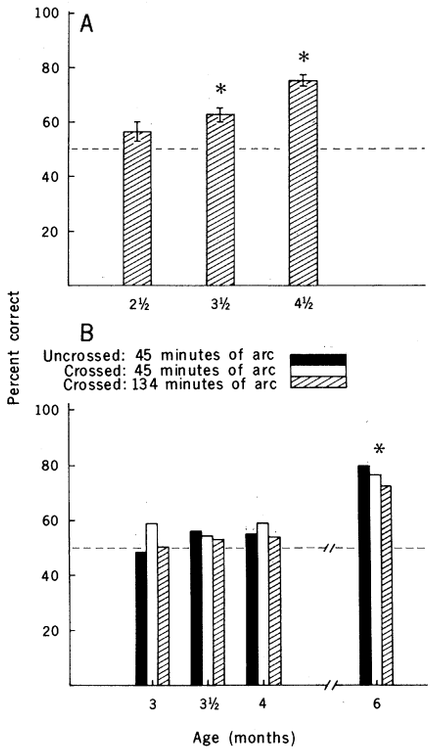


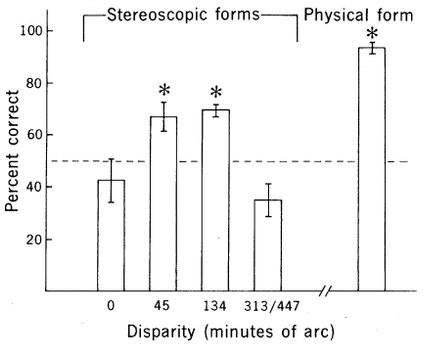


Fig. 1 (left). (A) Correct discriminations (mean ± standard error) by each of three age groups. Chance discrimination is 50 percent. Groups that differed significantly from chance are indicated by asterisks. (B) Correct discriminations plotted for the same group of infants tested periodically from 3 to 4 months and again at 6 months. Crossed and uncrossed refer to the direction and magnitude of disparities used in each testing session. Fig. 2 (right). Correct discriminations plotted for varying disparities of the stereoscopic form and for the physical counterpart of the form (*4*).

sistent with the hypothesis that these infants have stereopsis.

To examine more closely the relationship between age and emergence of stereopsis, we recruited eight 3-month-old infants and tested them periodically until 6 months of age. This third experiment was similar to the first except for an additional crossed disparity (45 minutes) and an uncrossed disparity (45 minutes), in which the stereoscopic form appears to lie in depth behind the plane of the projection screen. To accommodate these two new conditions we made no more than 15 observations for any one condition, and we interspersed physical-form trials between conditions in an effort to maintain interest. The infants were tested weekly until $4\frac{1}{2}$ months of age; holidays and academic conflicts prevented further testing until 6 months of age. Although the performance of three infants was above chance by $4\frac{1}{2}$ months (*9*), the group performance (Fig. 1B) did not exceed chance until testing resumed at 6 months.

These data, which are consistent with our earlier results, raise the question, What is responsible for the chance performance of the younger infants? Two possible explanations are reduced acuity and inadequate attention. Both are unlikely. The dot size of the stereogram (45 minutes) exceeds the acuity threshold of 2-month infants (*10*). And their satisfactory performance on the physical-form trials rules out a simple failure of attention. Two more likely and not incompatible explanations are the inability of younger infants to maintain consistent binocular fusion and the incomplete neural development of the binocular visual system (*11, 12*). On the latter point (*12*), physiological evidence from animals suggests that, while basic structures for vision are present at birth, there remains a postnatal period during which neural connections undergo substantial growth and elaboration.

It should be possible, through the method described here, to investigate behavioral milestones corresponding to this early period of neural development. Further, the presence or absence of stereopsis in children $2\frac{1}{2}$ years and older is well established as a good predictor of binocular integrity (*13*). The method may lend itself to even earlier detection of anomalies of binocular vision suffered by human infants.

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4. Retinal disparity was calculated according to the standard formula for geometric disparity of discrete contours [W. L. Gulick and R. B. Lawson, *Human Stereopsis: A Psychophysical Analysis* (Oxford Univ. Press, London, 1976)]. With a viewing distance of 130 cm and an interpupillary distance of 4 cm, the disparity of the stereoscopic form was 134 minutes; it resulted in a form that appeared to lie in a depth plane in front of the screen.
5. Our observational procedure was a variant of the forced-choice preferential looking technique [D. R. Peeples and D. Y. Teller, *Science* **189**, 1102 (1975); D. Y. Teller, *Infant Behavior and Development*, in press]. This technique capitalizes on research [R. L. Fantz, *Ann. N. Y. Acad. Sci.* **118**, 793 (1965)] that demonstrated that infants prefer to fixate stimuli composed of contours. The technique can also be used to measure detection of other stimulus parameters (such as brightness, hue, movement).
6. The physical form consisted of a red and black 10° by 15° random-element rectangle on a black background.
7. A total of 51 infants were tested; five failed to meet the 75 percent criterion for physical-form trials, and six did not provide data for ten stereoscopic-form trials.
8. The age groups had the following characteristics: $2\frac{1}{2}$ months: $N = 15$, range 72 to 81 days; $3\frac{1}{2}$ months: $N = 15$, range 97 to 108 days; and $4\frac{1}{2}$ months: $N = 10$, range 120 to 157 days.
9. The differences among the disparity conditions were never significant ($F = 1.7$). At 6 months, performance averaged across disparities was significantly different from chance [$t$ (7) = 8.08, $P < .001$]. The appearance of stereopsis in the longitudinal study was delayed relative to that in the cross-sectional studies. The reasons for this difference are not readily apparent. Differences in number of trials per condition is not a likely factor, since these proved to be quite comparable for all studies. We suspect that the more extended and repeated testing of the longitudinal group produced cumulative effects that depressed infant performance. Further, the possibility of sampling variation cannot be discounted.
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