Four-Month-Old Infants' Sensitivity to Binocular and Kinetic Information for Three-Dimensional-Object Shape

Articles

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YONAS, ALBERT, ARTERBERRY, MARTHA E , and GRANRUD, CARL E *Four-Month-Old Infants' Sensitivity to Binocular and Kinetic Information for Three-Dimensional-Object Shape* CHILD DEVELOPMENT, 1987, 58, 910–917 4-month-old infants were tested for sensitivity to kinetic and binocular information for 3-dimensional-object shape The study included 2 tests a test for sensitivity to binocular disparity and a shape perception test The disparity sensitivity test used a preferential looking procedure developed by Held, Birch, and Gwiazda On the basis of the results of this test, infants were assigned to disparity-sensitive and disparity-insensitive groups In the shape perception test, a "transfer-across-depth-cues" method was employed Infants were habituated to a rotating object whose shape was specified by kinetic information and were then presented with stationary stereograms specifying the same object and a novel-shaped object The disparity-sensitive infants looked significantly longer at the novel object than at the familiar object, whereas the disparity-insensitive infants showed no difference in looking time to the novel and the familiar objects The results indicate that disparity-sensitive 4-month-old infants can perceive 3-dimensional-object shape from kinetic and binocular depth information

Infancy researchers face a problem when they attempt to infer that infants can perceive a three-dimensional property of the environment such as depth or three-dimensional-object shape The most widely used methods in infant perception research (habituation and preferential looking) allow us to infer that infants can discriminate two stimuli, but discrimination of two stimuli rarely provides sufficient evidence to conclude that infants perceive a three-dimensional property of the stimuli For example, a finding that infants can discriminate two objects that differ in three-dimensional shape would not warrant the conclusion that infants can perceive three-dimensional shape because infants could potentially discriminate these objects by detecting proximal stimulus features that are correlated with shape without perceiving shape per se Before concluding that infants can perceive a three-dimensional property such as shape, we must rule out the possibility that infants might respond to a proximal stimulus feature that is correlated with the three-dimensional property without actually perceiving the three-dimensional property

One strategy for distinguishing responses to the three-dimensional environment from responses to proximal stimulation is to seek evidence of externally oriented, depth-specific behavior such as avoiding the deep side of a "visual cliff" (Gibson & Walk, 1960) or reaching to the three-dimensional location of a target object (Yonas & Granrud, 1985) Although these methods have been useful for studying depth perception in infants 5 months of age and older, they appear to be of limited usefulness for studying younger infants due to the immaturity of reaching and locomotion during the first months of life

Yonas and Pick (1975) proposed a potentially more useful strategy for studying depth perception in younger infants the "transfer-across-depth-cues" procedure They noted that an environment's spatial layout or an object's three-dimensional shape can be specified by many different depth cues In the transfer procedure, infants are habituated to a particular spatial layout specified by one depth cue Following habituation, they are shown the same spatial layout and a different

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spatial layout, both specified by a single new depth cue. The proximal stimulus properties of the habituation display that make possible the perception of its spatial layout are different from those that allow discrimination of the test displays. If infants perceive and respond to the spatial layout, they should recognize the familiar layout despite the change in the proximal stimulus cue and remain habituated, whereas they should dishabituate to the novel layout. Conversely, if they respond to the proximal stimulus and not to the distal layout, they should find both displays novel.

The present study used this transfer-across-depth-cues procedure to investigate 4-month-old infants' perception of three-dimensional-object shape from binocular and kinetic depth information. Infants were habituated to a shape specified by kinetic information and were then shown the same shape and a novel shape on successive trials, both specified by binocular information in static stereograms. If the infants look longer at the novel shape than the familiar shape despite the shift in the type of information specifying the shape, it will indicate that they can perceive three-dimensional shape from both binocular and kinetic depth information.

Several previous studies have reported that 4-month-old infants can perceive three-dimensional-object shape from kinetic depth information (Kellman, 1984; Kellman & Short, 1985; Owsley, 1983). The present study sought to corroborate the findings of these studies. In addition, it sought to fill an important gap in the existing data on infant stereopsis. While several studies have found that 4-month-old infants can detect binocular disparity—the stimulus information for stereoscopic depth perception (Birch, Gwiazda, & Held, 1982; Fox, Aslin, Shea, & Dumais, 1980; Held, Birch, & Gwiazda, 1980; Petrig, Julesz, Kropfl, Baumgartner, & Anliker, 1981)—they do not demonstrate that infants can perceive depth or three-dimensional shape from disparity. It may be possible that infants are able to detect disparity before they are able to perceive depth or object shape from disparity. It is also possible that, although young infants can detect disparity, they must learn the relation between a given level of disparity and a given distance. In light of these possibilities, we cannot infer that infants have stereopsis (perceive depth from binocular disparity) from the finding that they can detect binocular disparity. This study sought more direct evidence of stereopsis in 4-month-old infants by investigating whether 4-month-olds can perceive three-dimensional shape from binocular depth information.

Shaw, Roder, and Bushnell (1985) attempted a study similar in design to the proposed one. They found that, while 6-month-old infants appeared to transfer three-dimensional-object shape specified by kinetic information to binocular information, 4-month-old infants did not. Since the median age for the onset of sensitivity to binocular disparity is 16 weeks of age (Held et al., 1980), it is possible that the 4-month-olds in the Shaw et al. study perceived the stimulus objects' shapes from kinetic information in the habituation trials but, as a group, were insensitive to the binocular information available in the test trials and were unable to discriminate the novel object from the familiar object. Therefore, in addition to the shape perception test described above, this study included a test for sensitivity to binocular disparity.

The disparity sensitivity test, which followed the preferential looking procedure developed by Held et al. (1980), was conducted to identify disparity-sensitive and disparity-insensitive 4-month-olds. Because disparity detection is necessary for shape perception from disparity, only disparity-sensitive infants could be expected to recognize the familiar object in the test trials of the shape perception test. Disparity-insensitive infants will serve as a control for the possibility that monocular cues, differentiating the two objects, are the basis of transfer from the kinetic habituation period to the static test presentations.

Method

Subjects.—Seventy-three full-term 4-month-old infants (35 males, 38 females, mean age = 114.5 days, range = 106–124 days) constituted the sample for this study. An additional 34 infants were tested but not included in the sample due to failure to complete both tests (30) or experimenter and/or equipment error (four).

Materials and apparatus.—This experiment was comprised of two tests: a three-dimensional-shape perception test and a disparity-sensitivity test. Different screen configurations were used in each test and will be described separately below. The apparatus used in the three-dimensional-shape perception test is illustrated in Figure 1. The infant sat on the parent's lap approximately 40 cm from a 27 × 27-cm rear-projection screen (Raven Screen Corp., type-R black rear-screen material) mounted in a 91 × 175.5-cm back-

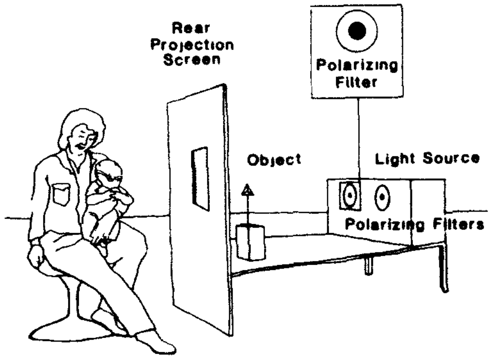

FIG 1 —Experimental setup used in the shape perception test.

ground surface The shadow of a stimulus object was cast onto the screen by either one or two 100-watt point-source lamps positioned 11 cm apart and located 119 cm from the screen Electronic shutters in front of the lamps controlled whether the stimulus object was illuminated by one or two lamps Light from the lamps passed through differently oriented polarizing filters (Melles Griot, product no 03FPG005) The infants wore eyeglasses containing another set of polarizing filters that corresponded in orientation to those on the lamps

There were two stimulus objects a flat triangle with three internal lines that met at the center of the figure and a three-dimensional tetrahedron (see Fig. 2) Each object was made of 0 3 cm diameter black wire Translucent sheets of red plastic were affixed to each triangular side of the tetrahedron The interior of the triangle was filled with two sheets of translucent red plastic so that the interior areas of the triangle and tetrahedron had approximately equal luminances Both objects measured 14 5 cm across the base and 12 cm in height The vertex of the tetrahedron protruded 7 cm Each object was mounted on a 14 7-cm stem attached to a motorized base 8 cm from the rear-projection screen From the infant's viewpoint, the shadow cast by each object subtended 16 7° of visual angle vertically and 19 9° horizontally

During habituation trials, the stimulus object rotated continuously in a counterclockwise direction at 15 rpm and was illuminated by only one lamp Due to the polarizing filters, the object's shadow was visible to the infant's right eye only This display created a kinetic depth effect (Wallach & O'Connell, 1953) in which the stimulus object's three-dimensional shape, specified by kinetic information isolated from other cues for shape, was unambiguously perceived by adults viewing the display The sequence of drawings in Figure 2 illustrates the perspective transformations undergone by each stimulus object as it rotated During the test phase of the experiment, the stimulus objects were stationary and were illuminated by two lamps separated by 11 cm The base of the triangle and the tetrahedron were parallel to the screen This positioning made the monocular projections of the two displays as similar as possible The positions of the projection lamps were chosen to simulate approximately the appropriate right- and left-eye views that the subject would get from a real object actually located at the position of the viewing screen The display created a stereogram in which binocular disparity specified the object's shape (for a detailed description of this type of stereogram, see Gordon & Yonas, 1976) Figure 3 shows the left- and right-eye views of the test dis-

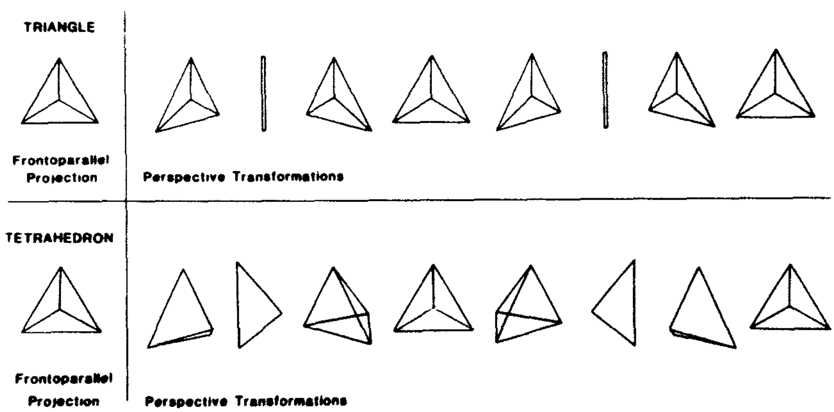

FIG 2 —Schematic diagram of the views of the triangle and tetrahedron displays undergoing one continuous 360° rotation Subjects were habituated to either the rotating triangle or the tetrahedron for the shape perception test.

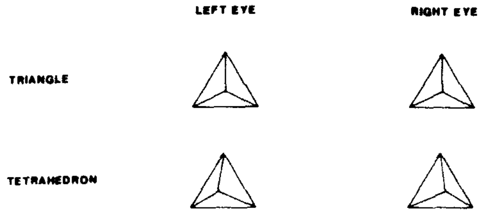

FIG. 3.—Schematic drawing of the left- and right-eye views of the test displays in the shape perception test. The shift of the central vertex in the tetrahedron has been exaggerated.

plays. In the tetrahedron, the horizontal position of the central vertex was shifted approximately 2 mm to the left in the left-eye view and 2 mm to the right in the right-eye view relative to the location of the center of the projection of the triangle. The maximum amount of disparity was approximately 5°. To adults with normal stereopsis, the tetrahedron appeared to be three dimensional with its vertex protruding toward the screen, while the triangle appeared to be a flat plane. Both objects were perceived to be located a small distance in front of the screen.

An experimenter observed the infant through an aperture in the background surface. The experimenter pressed a button that was connected to a laboratory microcomputer whenever the infant fixated the display and released the button when the infant looked away from the display. The computer recorded the infant's total fixation time in each trial, initiated and terminated trials by opening and closing the shutters on the lamps, determined when the infant became habituated, and signaled a second experimenter to change the stimulus object between test trials.

The experimental room was dark except for light from the rear-projection screen and from a 15-watt lamp illuminating the infant. A small music box played "Talk to the Animals" to keep the infant calm.

In the disparity-sensitivity test, the infant sat in the parent's lap approximately 60 cm from the two circular black rear-projection screens, which were each 10 cm in diameter, separated by 12 cm, and mounted in a 111 × 76-cm gray background. Thirty cm above the rear-projection screens in the background were a centrally located aperture that was 4.5 cm in diameter and through which an observer viewed the infant and a red light that flashed at the beginning of each trial to draw the infant's attention toward the screens. Slides were projected onto the screens by two carousel projectors, one mounted on top of the other. Each slide contained two sets of bars. One set was projected onto the left screen and the other onto the right screen. Light from the two projectors passed through differently oriented polarizing filters. As in the shape perception test, the infant wore eyeglasses containing polarizing filters that corresponded in orientation to those on the projectors. As a result, only the image from a single projector was visible to each eye.

The display in one screen was a stereogram consisting of three regularly spaced vertical black bars that were 1.25 cm wide and spaced 1.25 cm apart (projected by the bottom projector) and a second pattern of three bars (projected by the top projector) superimposed on the first pattern. The center bars in the two patterns were aligned, but the two outside bars in the second pattern were shifted .53 cm in the same direction relative to the first pattern to create 30 min of uncrossed binocular disparity, which was calculated using the standard formula reported in Cormack and Fox (1985), assuming an interpupillary distance of 4 cm. To the right eye, the outside bars were shifted to the left; there was no shift in the bars to the left eye. The display in the other screen was similar to the stereogram but contained no binocular disparity. This zero-disparity display consisted of two identical patterns (one projected by each projector) of three regularly spaced vertical bars, each 1.25 cm wide, spaced 1.25 cm apart and superimposed directly on top of each other. The bars in both displays were presented on a colored background of red, blue, or green; every three trials, the background color was changed to maintain the infant's attention. The displays had luminances of 6.05, 7.04, and 8.54 cd/m^2 for the red, blue, and green displays, respectively. From the infant's viewpoint, the screens subtended 9.5° of visual angle and the bars 1.2°.

The 30-min uncrossed disparity value was chosen on the basis of findings by Birch et al. (1982), suggesting that 30–60 min is the amount of disparity to which the maximum number of 4-month-olds are sensitive. Because sensitivity to uncrossed disparity appears to develop later than does sensitivity to crossed disparity (Birch et al., 1982; Held et al., 1980), uncrossed disparity was used to increase the likelihood that infants assigned to the disparity-sensitive group were sensitive to both types of disparity.

To adult observers with normal stereopsis, the stereogram appeared to be a three-dimensional arrangement of bars with the outside bars located several cm behind the center bar The zero-disparity display appeared to be a flat array of three bars The disparity-sensitivity test was conducted in the dark, the light in the experimental room was provided by the slide projectors

We should note that these displays contained several cues other than binocular disparity that could potentially be used to discriminate the disparity and zero-disparity displays For example, due to incomplete polarization the stereogram contained light gray stripes between the black bars Results from three control conditions in the Held et al (1980) study, however, indicated that infants' discrimination of two displays similar to those used in the present study was based on binocular disparity only and not on monocular or nonstereoscopic binocular cues The apparatus used in the present study was designed to match as closely as possible the apparatus used by Held et al to ensure that infants could discriminate the stereogram and zero-disparity displays on the basis of only binocular disparity

Procedure —The experiment included two tests a shape perception test and a disparity-sensitivity test The shape perception test was conducted first for all infants This order of testing was chosen because pilot testing suggested that the shape perception test was less interesting for the infants than was the disparity-sensitivity test The shape perception test was, therefore, conducted at the beginning of the experiment while the infants were typically alert and not fussy Before the shape perception test began, the polarizing glasses were placed on the infant and secured with an adjustable elastic strap The infant was then seated on the parent's lap facing the rear-projection screen

Prior to the beginning of each trial, the screen was dark The shutter on one lamp was opened to present the display and initiate a trial The habituation trials followed an infant-control procedure (Horowitz, Paden, Bhana, & Self, 1972), continuing until the infant looked away from the display for 2 continuous sec or until 60 sec had elapsed The shutter was then closed to terminate the trial After a 5-sec interval, another trial was initiated This procedure continued until the infant met the criterion for habituation Habituation was defined as two consecutive trials with fixation times less than 50% of the mean fixation time from the first two trials If the mean fixation time for the first two trials was less than 12 sec, however, the first two trials with a mean fixation time of 12 sec or more were used to determine the habituation criterion

When the habituation criterion was reached, four test trials were conducted Each trial lasted 15 sec from the infant's first fixation of the display The infant viewed the two stimulus objects, one at a time, on alternating trials The objects remained stationary in the test trials and were illuminated by both lamps The object, novel or familiar, seen on the first trial was chosen randomly An infant had to complete at least two test trials (i e , one presentation of each stimulus object) to be included in the sample If an infant completed four test trials, the mean looking times from the two novel object trials and the two familiar object trials were used in the data analysis If an infant completed three test trials, only the first two trials were included in the data analysis

Two experimenters conducted the shape perception test. One observed the infant and recorded fixation times This experimenter did not know which stimulus object was being presented on a given trial The other experimenter controlled the motor that rotated the stimulus objects and changed the objects between test trials In addition, a third experimenter recorded the fixation times of 24 infants to obtain a measure of interjudge reliability The mean correlation between the fixation times scored by the two observers was $r = 94$

The infant was given a break of at least 5 min after the shape perception test was completed The infant was then tested for sensitivity to binocular disparity Two experimenters conducted the disparity-sensitivity test. One observed the infant through the aperture and judged and recorded the infant's looking preferences The other controlled the slide projectors and the flashing light.

Infants' looking preferences were determined using a modified forced-choice preferential looking (FPL) procedure At the beginning of each trial, the screens were dark and the flashing light turned on to center the infant's gaze If the light did not attract the infant's attention, the observer also called to the infant. When the infant looked toward the screens, the flashing light was extinguished and the displays presented A trial lasted until the observer felt a judgment could be made on which side the infant preferred to fixate, the observer was required to make a side judgment on each trial When the observer made a judgment, the trial was terminated and the projector lenses covered to occlude the displays Trials averaged about 10–15 sec in length After a brief interval, another trial began The observer was unaware of the stereogram's position on each trial, and the left-right positions of the displays were randomly varied Unlike traditional FPL procedures (Teller, 1979), the observer received no feedback regarding the stereogram's location In addition, the observer's task was to identify the side of the preferred stimulus and not to guess the side of a target stimulus These changes from the usual FPL procedure were made to ensure that auditory cues from the slide projectors could not reveal the stereogram's position

The infant was given a break from the disparity sensitivity test at the first sign of boredom or fussiness If the infant remained attentive, 15 trials were given It was not possible to conduct a large number of trials in the disparity-sensitivity test Since the infants had already completed the shape perception test, they typically became inattentive and fussy after a small number of trials in the disparity-sensitivity test. The test was stopped after 15 trials to avoid trials in which the infants were inattentive The infant had to complete at least 10 trials to be included in the sample Infants who looked preferentially at one of the displays on at least 70% of the trials were assigned to the disparity-sensitive group Infants who did not meet this criterion were assigned to the disparity-insensitive group

Results

Disparity-sensitivity test —Twenty-five infants met the criterion of a 70% looking preference and were assigned to the disparity-sensitive group This group consisted of 15 females and 10 males with a mean age of 115 days (range 106–124 days) The infants in this group completed a mean of 10 3 (SD = 0 94) trials and exhibited a mean looking preference of 74 3% (SD = 7 04) Seven of these infants looked preferentially at the zero-disparity display

Forty-eight infants did not meet the disparity sensitivity criterion and were assigned to the disparity-insensitive group This group consisted of 24 females and 24 males with a mean age of 114 days (range 106–124 days) These infants completed a mean of 11 6 (SD = 2 47) trials and exhibited a mean looking preference of 51 1% (SD = 7 5)

Shape perception test —Of the 25 infants in the disparity-sensitive group, 19 looked longer at the novel than at the familiar object. This number is significantly greater than chance, $p < 01$, by a sign test In contrast, only 27 of the 48 disparity-insensitive infants looked longer at the novel object

The results from the shape perception test are summarized in Table 1 The infants' test trial looking times were analyzed in a 2 × 2 × 2 × 2 mixed-design analysis of variance with sex (male and female), group (disparity-sensitive and disparity-insensitive), and habituation object (triangle and tetrahedron) as between-subject factors and test object (novel vs familiar) as a within-subjects factor The analysis revealed a significant main effect for test object, $F(1,65) = 11\ 19$, $p < 001$, and a significant group × test object interaction, $F(1,65) = 4\ 38$, $p < 05$ No other main effects or interactions were significant.

The main effect for test object indicates that, when the data from both groups are combined, the infants looked significantly longer at the novel object than at the familiar object. In light of the significant group × test object interaction, however, this main effect is uninformative The group × test object interaction indicates that the difference in looking times to the novel and the familiar objects was significantly greater for the disparity-sensitive

TABLE 1

MEANS AND STANDARD DEVIATIONS OF LOOKING TIMES (in Seconds) DURING HABITUATION AND TEST TRIALS AND MEAN NUMBER OF HABITUATION TRIALS COMPLETED

Group Mean	No of Trials	First Two Trials	Last Two Trials	Novel Object	Familiar Object
Disparity-sensitive group					
Mean	6 0	25 4	5 7	8 3	5 6
	(2 0)	(16 50)	(3 5)	(3 5)	(2 8)
Disparity-insensitive group					
Mean	7 1	27 8	5 7	7 3	6 3
	(2 9)	(17 1)	(4 1)	(3 5)	(3 7)

NOTE —Standard deviations are in parentheses infants than for the disparity-insensitive infants

Planned comparisons, using Tukey's Honestly Significant Difference test, were performed to analyze the data from each group separately The disparity-sensitive infants looked significantly longer at the novel object than at the familiar object ($p < 05$) regardless of whether the triangle or tetrahedron had been seen during habituation This finding indicates that the disparity-sensitive infants perceived the stimulus objects' three-dimensional shapes specified by kinetic and binocular information The infants' absence of longer looking time to the familiar object indicates that they perceived some similarity between the habituation object and the familiar test object In contrast to the disparity-sensitive infants, the disparity-insensitive infants showed no significant difference in their looking times to the novel and familiar objects ($p > 05$) These infants, therefore, showed no evidence that they perceived the stimulus objects' three-dimensional shapes

Because infants were habituated to moving displays and tested for transfer to static displays, analysis of recovery from habituation is problematic Previous studies have found that moving displays engage infants' attention more effectively than static displays (e g , Kaufmann-Havoz, Kaufmann, & Stucki, 1986), therefore, we did not expect to observe recovery from habituation during the test trials Of primary interest was the comparison between the infants' looking times for the novel and familiar shapes in the test trials

Discussion

Three primary conclusions can be drawn from the results of this study First, the results indicate that 4-month-old infants who can detect binocular disparity can also perceive three-dimensional-object shape from binocular depth information This finding supports earlier reports that stereopsis emerges at about 3–4 months of age in human infants (Birch et al , 1982, Fox et al , 1980, Held et al , 1980) It further suggests that the ability to perceive shape from binocular information and the ability to detect binocular disparity appear concurrently However, we do not know which aspect of binocular information the disparity-sensitive infants were using As Aslin and Dumais (1980) have pointed out, shadow-cast stereograms, such as those used in this study, do not isolate binocular disparity from vergence It is possible that the disparity-sensitive infants used binocular convergence rather than binocular disparity to perceive the objects' shapes in the stereograms This issue could be investigated by using random-dot stereograms (Julesz, 1971), which isolate disparity from vergence information in a transfer study similar to the present one

It is possible that the disparity-sensitive infants discriminated the two objects on the basis of subtle monocular differences present during the test trials (e g , position of the vertex or slight luminance differences due to the plastic coverings) Since adults viewing the two displays monocularly were unable to detect these differences, and since the disparity-insensitive infants did not show a preference for the novel object, it is unlikely that the disparity-sensitive infants were responding to the available monocular differences The group × test interaction supports our conclusion that the disparity-sensitive infants were responding to the binocular information specifying three-dimensional-object shape

The second conclusion that can be drawn from the results is that 4-month-old infants can perceive three-dimensional-object shape from kinetic depth information This study corroborates earlier findings by Kellman (1984), Kellman and Short (1985), and Owsley (1983) that 4-month-old infants are sensitive to kinetic information for three-dimensional shape

Third, the results indicate that habituation occurred at the level at which three-dimensional-object shape is represented This suggests that binocular and kinetic information activate a common representation of shape Therefore, as early as 4 months of age, the mechanisms that detect binocular and kinetic information appear to function not as isolated modules but instead as parts of a unified spatial perception system

A methodological implication of this study is that the transfer-across-depth-cues method is an effective way to explore spatial perception in young infants Studies have typically used spatially specific responses such as reaching (Yonas & Granrud, 1985) and avoiding a drop-off (Gibson & Walk, 1960) to investigate infant spatial perception Because reaching and crawling do not appear until about 5 and 7 months of age, respectively, it has been difficult to investigate spatial perception in young infants The transfer-across-depth-cues method may be useful for studying many aspects of spatial perception in young infants

Recent findings indicate that infants as young as 3 months of age can achieve at least some degree of shape constancy (Caron, Caron, & Carlson, 1979, Cook & Birch, 1984) It remains unknown which visual information infants use to perceive shape before 4 months of age Since most infants appear to be insensitive to binocular disparity before about 4 months of age (Birch et al, 1982), it seems unlikely that 3-month-old or younger infants can use stereopsis to perceive three-dimensional shape Although 7-month-old infants can perceive shape from shading information, this ability may not appear until after 5 months of age (Granrud, Yonas, & Opland, 1985) In addition, infants younger than 5 months of age may be insensitive to several other pictorial depth cues that could potentially be used in shape perception (Yonas, Granrud, Arterberry, & Hanson, 1986) Therefore, it seems likely that kinetic information plays a central role in three-dimensional-shape perception before about 4 months of age Unfortunately, the method used in the present study does not allow us to explore infants' sensitivity to kinetic information prior to the onset of binocular sensitivity An important goal for future research is to create a method that will allow us to assess sensitivity to kinetic information for depth and shape in infants who do not yet possess stereoscopic vision

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