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Binocular Vision and Spatial Perception in 4- and 5-Month-Old Infants

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Four experiments investigated the relation between the development of binocular vision and infant spatial perception. Experiments 1 and 2 compared monocular and binocular depth perception in 4- and 5-month-old infants. Infants in both age groups reached more consistently for the nearer of two objects under binocular viewing conditions than under monocular viewing conditions. Experiments 3 and 4 investigated whether the superiority of binocular depth perception in 4-month-olds is related to the development of sensitivity to binocular disparity. Under binocular viewing conditions in Experiment 3, infants identified as disparity-sensitive reached more consistently for the nearer object than did infants identified as disparity-insensitive. The two groups' performances did not differ under monocular viewing conditions. These results suggest that, binocularly, the disparity-sensitive infants perceived the objects' distances more accurately than did the disparity-insensitive infants. In Experiment 4, infants were habituated to an object, then presented with the same object and a novel object that differed only in size. Disparity-sensitive infants showed size constancy by recovering from habituation when viewing the novel object. Disparity-insensitive infants did not show clear evidence of size constancy. These findings suggest that the development of sensitivity to binocular disparity is accompanied by a substantial increase in the accuracy of infant spatial perception.

The adult human visual system uses many sources of optical information to perceive the three-dimensional spatial layout of the environment. We can perceive objects' locations, sizes, and shapes from kinetic information produced by motion in the light reaching the eyes (Gibson, 1966; Johansson, 1978), from binocular disparity (Julesz, 1971), and from "pictorial" depth cues such as interposition, shading, and texture gradients (Gibson, 1950; Hochberg, 1971). Unlike adults, newborn infants appear to be incapable of using many sources of information in spatial perception. Recent research suggests that infants become sensitive to binocular disparity between 3 and 4 months of age (Birch, Gwiazda, & Held, 1982, 1983; Birch, Shimojo, & Held, 1985; Fox, Aslin, Shea, & Dumais, 1980; Held, Birch, & Gwiazda, 1980; Petrig, Julesz, Kropfl, Baumgartner, & Anliker, 1981) and that sensitivity to pictorial depth cues first appears between 5 and 7 months of age (Granrud, Haake, & Yonas, 1985; Granrud & Yonas, 1984; Granrud, Yonas, & Opland, 1985; Kaufmann, Maland, & Yonas, 1981; Yonas, Cleaves, & Pettersen, 1978; Yonas, Granrud, & Pettersen, 1985; Yonas, Pettersen, & Granrud, 1982). During the first 4 months, infants may perceive the environment's spatial layout from kinetic depth information (Kellman, 1984; Owsley, 1983; Yonas, 1981; Yonas & Granrud, 1985). This staggered development of sensitivity to different sources of spatial information suggests that at least three distinct mechanisms function in mature spatial perception: one sensitive to kinetic information, one sensitive to binocular information, and one sensitive to pictorial information (Yonas & Granrud, 1985). From an evolutionary perspective, the existence of several spatial perception mechanisms, each responsive to a different class of spatial information, suggests that each mechanism provides a significant selective advantage. The gradual development of these mechanisms further suggests that there may be important limitations in the young infant's spatial perception abilities before all three mechanisms are functioning, and marked improvements in spatial perception as each mechanism begins to function.

We do not yet know how the development of sensitivity to a wider range of spatial information affects the infant's ability to perceive the three-dimensional environment. Although newborn infants appear to lack stereopsis and sensitivity to pictorial depth cues, they may achieve veridical spatial perception by detecting kinetic depth information. This seems plausible in light of findings that kinetic information can specify spatial layout unambiguously for adult observers (Braunstein, 1976; Gibson, 1966; Johansson, 1978; Lee, 1980; Rogers & Graham, 1979; Wallach & O'Connell, 1953), that 3- to 5-month-old infants can perceive distance and three-dimensional object shape from at least some types of kinetic depth information (Granrud, Yonas, Smith, Arterberry, Glicksman, & Sorknes, 1984; Kellman, 1984; Kellman, Hofsten, & Soares, 1985; Owsley, 1983; Kellman & Short, 1985; Walker-Andrews & Lennon, 1985; Yonas, 1981), and that kinetic information plays a central role in young infants' object perception (Kellman & Spelke, 1983; Spelke, 1982). If kinetic information is sufficient for veridical perception, the development of stereopsis and sensitivity to pictorial depth cues may add little

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or nothing to infants' spatial perception abilities (at least in situations in which kinetic information is available). On the other hand, because stereopsis greatly complicates the anatomical and physiological processes of the visual system, requiring fine motor coordination of the two eyes and a highly complex neural substrate (Ogle, 1962), we might infer that stereopsis must confer a considerable perceptual advantage to offset its apparently considerable biological cost. If so, the development of stereopsis may substantially increase the accuracy of infants' spatial perception.

It remains unknown when stereopsis first develops. However, recent findings, indicating that sensitivity to binocular disparity appears at about 3 to 4 months of age (Birch et al., 1982; Fox et al., 1980; Held et al., 1980; Petrig et al., 1981), suggest that stereopsis emerges between 3 and 4 months. In the present study we asked how the development of sensitivity to binocular disparity affects infant spatial perception. The study included four experiments. Experiment 1 compared monocular and binocular depth perception in 5-month-old infants. At this age, most infants can detect binocular disparity (Birch et al., 1982) and can perceive depth from binocular information (Gordon & Yonas, 1976; Yonas, Oberg, & Norcia, 1978). We reasoned that if the development of sensitivity to binocular disparity increases the accuracy of infant depth perception, binocular depth perception should be superior to monocular depth perception at 5 months of age. Conversely, a finding of no difference between monocular and binocular depth perception might indicate that the development of sensitivity to disparity has no significant effect on infant depth perception. Experiment 2 had two goals. The first was to compare monocular and binocular depth perception at 4 months, the average age at which infants can first detect binocular disparity (Birch et al., 1982; Held et al., 1980). The second was to determine whether reaching is a valid measure of depth perception in 4-month-old infants. The findings of Experiments 1 and 2 suggested that binocular depth perception is more accurate than monocular depth perception in 5- and 4-month-old infants. Following these findings, in Experiments 3 and 4 we asked whether the superiority of binocular depth perception is related to the development of sensitivity to binocular disparity. Four-month-old infants were tested for sensitivity to binocular disparity using a method developed by Held et al. (1980). The spatial perception abilities of disparity-sensitive infants and disparity-insensitive infants were then compared. If the development of sensitivity to binocular disparity results in improved spatial perception, spatial perception should be more accurate in disparity-sensitive infants than in disparity-insensitive infants.

Experiment 1

A recent study by Granrud, Yonas, and Pettersen (1984) suggested that binocular depth perception is considerably more accurate than monocular depth perception in 5- and 7-month-old infants. In this study, infants viewed a pair of different-sized objects presented side by side. The smaller object was within reach and the larger object was just beyond reach; the objects subtended equal visual angles at the infants' observation point. Infants in both age groups showed a remarkably consistent reaching preference when viewing the objects binocularly: They reached for the nearer object on nearly every trial. When viewing the objects monocularly, however, the infants' reaching preference for the nearer object was only slightly greater than chance. These results suggest that for infants in both age groups, binocular vision was superior to monocular vision for perceiving the objects' relative distances.

However, the Granrud et al. (1984) study may not have made an ecologically valid comparison of monocular and binocular depth perception. There are two reasons to believe that the information available in the monocular condition was not representative of the monocular information typically available in real-world settings. First, the objects were stationary. Although the infants' heads were unrestrained, they may not have moved enough to generate sufficient motion parallax (probably the primary monocular cue available in this situation) to specify the objects' distances. Second, the objects were suspended in front of a vertical gray surface. When objects are resting on a textured surface, rather than floating in midair, much more spatial information is available to the monocular viewer, such as gradients of motion parallax, texture size, and texture density (Gibson, 1950). In sum, the Granrud et al. (1984) study may show only that binocular depth perception is superior to monocular depth perception when little monocular information is available; it does not demonstrate that binocular vision facilitates depth perception in natural situations in which adequate monocular information may be available.

Experiment 1 represents a more rigorous test of the Granrud et al. (1984) hypothesis that for 5-month-olds binocular depth perception is superior to monocular depth perception. As in the Granrud et al. study, infants in this experiment viewed, monocularly and binocularly, two objects subtending equal visual angles presented side by side at different distances. In addition, steps were taken to provide infants with more monocular depth information than was available in the Granrud et al. (1984) study. The objects rested on a textured surface that moved back and forth, perpendicular to the infant's line of sight, to generate motion parallax specifying the objects' distances. As a result, the monocular information available in this experiment should be similar to the monocular information typically available in real-world situations, in which an infant moves or is moved about the environment and views objects resting on textured surfaces. Thus, Experiment 1 should provide a more ecologically valid comparison of monocular and binocular depth perception in 5-month-old infants.

If infants reach preferentially for the nearer object, it will indicate that they perceive the objects' relative distances. If their reaching preference is more consistent in the binocular condition than in the monocular condition, it will suggest that binocular depth perception is more accurate than monocular depth perception. Conversely, if monocular and binocular depth perception are equally accurate, we should find no difference between the infants' performances in the two conditions.

Method

Sixteen infants participated in Experiment 1. Fifteen infants were included in the sample: 7 female and 8 male infants with a mean age of 147.7 days (4.8 months) and an age range of 140–153 days. One infant was tested but excluded from the sample because of failure to meet the criterion number of reaches (four) in each condition.

Apparatus. The infant sat in a semireclining infant seat facing the stimulus objects. The stimulus objects were two yellow and white teddy bears that differed only in size. The large and small bears, which measured 18 × 15 × 9 cm and 12 × 10 × 6 cm, respectively, were presented side by side 5 cm apart and were affixed by Velcro to a white surface, 75 × 50 cm. The surface was slanted 20° from the horizontal plane so that it was parallel to the infant's line of sight, and it was patterned with squares made from 2-cm wide lines regularly spaced 4 cm apart. The front of the large bear was 7 cm from the edge of the surface nearest the infant; the front of the small bear was even with the surface's nearest edge. In order to ensure that the nearer object was within reach, the distance between the infant and the objects was adjusted slightly for each infant, averaging approximately 13 cm to the nearer object and 20 cm to the farther object. The visual angles subtended by both objects were approximately 42° vertically and 37° horizontally from the average observation point.

The surface was mounted on a carriage that rode on a track located beneath the surface. The surface and the objects were moved back and forth along the track, perpendicular to the infant's line of sight, by means of a handle attached to one corner of the surface. During each trial, an experimenter moved the surface continuously at a velocity of approximately 8 cm per second through an 8-cm range of movement.

Each experimental session was recorded on videotape from two cameras, one mounted in the ceiling directly above the infant and the other mounted on a tripod directly to the infant's left. A special effects generator produced a split-screen image with both the top and side views of the infant. The split-screen image made it possible to measure, from the video record, the three-dimensional locations of the stimulus objects and the infant's hands at any point in the experimental session.

Procedure. There were two conditions in the experiment: a monocular viewing condition and a binocular viewing condition. Each infant was given trials in both conditions. For the monocular condition, an adhesive eye patch was placed over one eye (randomly chosen). The initial viewing condition was chosen randomly; 10 trials were presented in this condition. When these trials were completed, the infant was removed from the infant seat and given a break for several minutes. Ten trials were then presented in the other viewing condition. Infants who became fussy or inattentive during the experiment were removed from the infant seat and given a short break before testing resumed.

Prior to the beginning of each trial, the objects were occluded by a screen held by an experimenter. A trial was initiated by raising the screen and revealing the display. The trial was terminated, and the display occluded, after the infant's first reach toward one or both of the objects. A reach was defined as the infant's either touching the nearer object or moving a hand beyond the front edge of the surface toward the farther object (these judgments, made by an experimenter during the experiment, were used only to terminate trials; they were neither recorded nor included in the data from the experiment). If 30 s elapsed without the occurrence of a reach, the trial was terminated. Between trials, while the display was occluded, the left–right positions of the two objects were changed. Another trial was then initiated. The objects' initial left–right positions were chosen randomly. Left–right positions were then alternated on successive trials.

Two experimenters conducted the experiment. One experimenter stood to the infant's left, behind a curtain out of sight from the infant, and moved the surface back and forth. This experimenter timed the trials with a hand-held stopwatch and signaled the second experimenter when 30 s had elapsed. The second experimenter stood behind the infant. This experimenter judged when a reach had occurred, occluded the display at the end of a trial, changed the objects' positions between trials, and removed the occluding screen to initiate a new trial. The infant's parent was seated out of sight from the infant and was asked not to distract the infant during the experiment.

Infants' reaches were scored from the videotape record. Three criteria had to be met simultaneously for a reach to be scored: (a) the infant's hand, or hands, had to cross a line drawn on the video monitor that corresponded to the front edge of the supporting surface (as viewed from the top-view camera); (b) the hand had to be within, or pass through, the region directly in front of an object, that is, not to the left or right of the object (as determined from the top view); and (c) the hand had to be lower than the top of the nearer object and higher than the surface (as determined from the side view). Only the first reach occurring in a trial was scored. After the first reach, the trial was considered to be terminated.[1] Reaches were scored in three categories: for the nearer object, for the farther object, and for both objects if the infant reached for both objects simultaneously with two hands. When the data were tabulated, reaches for both objects simultaneously were scored as one reach for each object. No reach was scored for a trial if the above three criteria were not met during the trial. Trials in which no reach occurred were not included in the data. Only infants who reached on at least four trials in each condition were included in the sample.

The videotapes were scored independently by two research assistants, one of whom was unfamiliar with the hypotheses of the experiment. Interjudge reliability, computed using the kappa (κ) statistic (Bartko & Carpenter, 1976),[2] was .92. This high level of agreement suggests that scoring was objective and uninfluenced by experimenter bias.

Results and Discussion

The top half of Table 1 presents the mean number of reaches scored and the mean percentage of reaches scored to the nearer object in each viewing condition. The infants' preferences to reach for the nearer object were analyzed in a 2 × 2 mixed-design analysis of variance (ANOVA) with sex (male and female) as a between-subjects factor and viewing condition (monocular and binocular) as a within-subjects factor. The dependent variable was the percentage of reaches scored to the nearer object. This analysis revealed a significant main effect for viewing condition, $F(1, 13) = 30.00$, $p < .01$, no main effect for sex, and no Sex × Viewing Condition interaction. The main effect for viewing condition indicates that the infants' preference to reach for the nearer object was significantly greater in the binocular condition than in the monocular condition.

In the monocular condition, the infants' preference to reach for the nearer object was significantly greater than chance ($p < .01$), by the least significant difference (LSD) test (Kirk, 1982). This finding replicates the monocular condition results from the Granrud, Yonas, and Pettersen (1984) study, and it indicates that for 5-month-old infants monocular information is sufficient for perceiving objects' relative distances. However, the only moderately consistent reaching preference found in the monocular condition suggests that perception of the objects' distances was often equivocal. In contrast, the reaching preference found in the binocular condition was remarkably consistent: The infants

[1] This was done to minimize the influence of tactile reinforcement on the infants' reaches. The first reach in a trial is likely to be guided by visual information, but subsequent reaches may be influenced by tactile reinforcement resulting from the first reach (touching the nearer object or failing to touch the farther object).

[2] Kappa is a percent agreement measure corrected for agreements expected by chance. Kappa is typically more suitable than Pearson's product–moment correlation coefficient (r) as a measure of interjudge reliability, because kappa measures actual trial-by-trial agreement, whereas r measures only "pattern" agreement and is not reduced by large actual disagreements so long as raters covary consistently. Kappa is also preferable to a simple percent agreement measure, because percent agreement does not take into account the percentage of trials on which raters would be expected to agree by chance alone (see Bartko & Carpenter, 1976).

Table 1
Mean Number of Reaches and Mean Percentage of Reaches to Nearer Object in Experiments 1 and 2

Viewing condition	No. of reaches	% of reaches
	Experiment 1	
Binocular		
M	8.5	94.2
SD	2.7	7.5
Monocular		
M	8.1	70.6
SD	3.3	12.3
	Experiment 2	
Binocular		
M	7.8	68.1
SD	2.8	16.1
Monocular		
M	8.5	59.1
SD	3.7	19.5

reached for the nearer object on almost every trial. This suggests that, binocularly, perception of the objects' relative distances was unequivocal.

These results corroborate and extend the findings of Granrud, Yonas, and Pettersen (1984). For 5-month-old infants, binocular depth perception appears to be significantly more accurate than monocular depth perception, even when a considerable amount of monocular information is available. It remains possible, of course, that in some situations binocular and monocular depth perception would be equally accurate. We should note that some types of monocular depth information were not available in this experiment, such as interposition (Granrud & Yonas, 1984) and accretion and deletion of texture (Granrud, Yonas, Smith, Arterberry, Glicksman, & Sorknes, 1984). Moreover, motion parallax generated by self-movement may provide more effective depth information than motion parallax generated by external movement (Rogers & Graham, 1979). Additional research is needed to determine whether the advantage of binocular depth perception would be diminished if more, or more effective, monocular depth information were available.

The use of the eyepatch in the monocular condition but not in the binocular condition introduces the possibility of an alternative interpretation of the results. It is possible that in the monocular condition the eyepatch itself, rather than less accurate depth perception, was responsible for the infants' reduced reaching preference. Although the eyepatch did not cause the infants to reach for the object on the side of the unpatched eye (approximately 55% of the infants' reaches in the monocular condition were for the object on the right, regardless of which eye was patched), irritation caused by the eyepatch may have reduced infants' attention to the objects' distances or caused their reaching to be more random. Although the plausibility of this interpretation is diminished by the equal number of reaches observed in the two viewing conditions, we cannot yet rule out the possibility that the less consistent reaching preference found in the monocular condition may be directly attributable to the eyepatch. This issue is addressed in Experiment 3.

Experiment 2

Experiment 2 had two goals. The first was to compare monocular and binocular depth perception in 4-month-old infants using the same method as in Experiment 1. Recent research suggests that 4 months is the mean age at which infants can first detect binocular disparity (Birch et al., 1982; Fox et al., 1980; Held et al., 1980; Petrig et al., 1981). This experiment, therefore, sought to determine whether binocular depth perception is more accurate than monocular depth perception at the age at which infants are first developing the ability to detect binocular depth information.

The second goal was to discover whether 4-month-old infants' reaching is influenced by object distance and whether reaching is a valid measure of spatial perception in infants at this age. Although several studies have investigated the effect of object distance on young infants' reaching, none has found unambiguous evidence of spatially adapted reaching in infants younger than 5 months of age. Cruikshank (1941) reported that infants as young as 10 weeks of age (2½ months) make more "approach movements" with the hands toward a near object (25 cm away) than toward a more distant object (75 cm) that has a retinal image size equal to that of the nearer object. Although this finding suggests that object distance influences young infants' reaching, we must be cautious in drawing this conclusion. Because Cruikshank did not clearly define approach movements, we do not know precisely what behaviors constituted these movements. Thus, Cruikshank's results are difficult to interpret. Bower (1972) conducted a study similar to Cruikshank's in which 7- to 15-day-old infants were tested. He reported that these infants made more attempts to reach for an object just within reach than for an object beyond reach. Like Cruikshank (1941), however, Bower, reported no objective criterion for scoring reaches. Furthermore, Dodwell, Muir, and DiFranco (1976) and Rader and Stern (1982) failed to replicate aspects of Bower's findings.

Field (1976), using an objective measure to score infants' arm extensions, found that infants as young as 15 weeks of age (3½ months) made significantly more arm extensions when viewing an object 13 cm away than when viewing an object 52 cm away. Although Field's findings suggest that reaching is adjusted to object distance by 15 weeks, this conclusion must be accompanied by a caveat. We cannot be certain that the greater frequency of arm extensions observed in the 13-cm condition relative to the 52-cm condition was based on perception of the objects' distances, nor that the 15-week-olds actually reached for the stimulus objects. It is possible that the infants exhibited excited arm thrashing, rather than directed reaching for the objects (cf. White, Castle, & Held, 1964), and that differential arm thrashing in the presence of the nearer and farther objects was elicited by proximal stimulus correlates of distance, rather than the objects' perceived distances. For example, head movements generate more rapid retinal motion when a nearby object is viewed than when a more distant object is viewed; this proximal stimulus cue may have evoked more arm movement in the 13-cm condition independent of perception of the objects' distances.

Experiment 2 sought firmer evidence of spatially adapted reaching in 4-month-old infants. In this experiment, as in Experiment 1, infants viewed two objects presented side by side at different distances. A significant reaching preference for the nearer object, despite variations in its right–left position, would provide clear evidence of directed reaching for the nearer object; and directed reaching, unlike random arm thrashing, would be difficult to account for in terms of responses to proximal stimulus cues.

Method

Subjects. Twenty-seven infants participated in Experiment 2. Twenty-four infants were included in the sample: 12 female and 12 male infants with a mean age of 111.5 days (3.7 months) and an age range of 106–119 days. Three infants were tested but excluded from the sample because of failure to meet the criterion number of reaches (three) in each condition.

Apparatus. The apparatus was the same as that used in Experiment 1.

Procedure. One change was made in the procedure from Experiment 1: The criterion number of reaches in each condition required for inclusion in the sample was reduced to three. This change was made because we anticipated that 4-month-olds would reach less frequently than would 5-month-olds.

Infants' reaches were scored using the same method as in Experiment 1. Two observers independently scored every infant's experimental session; one observer was unfamiliar with the hypotheses of the experiment. Interjudge reliability was κ = .89.

Results and Discussion

The lower half of Table 1 presents the mean number of reaches scored and the mean percentage of reaches to the nearer object in each viewing condition. The infants' preferences to reach for the nearer object were analyzed in a 2 × 2 mixed-design ANOVA with sex as a between-subjects factor and viewing condition (monocular and binocular) as a within-subjects factor. The dependent variable was the percentage of reaches scored to the nearer object. This analysis revealed a significant main effect for viewing condition, $F(1, 22) = 5.15$, $p < .05$, no main effect for sex, and no Sex × Viewing Condition interaction. The main effect for viewing condition indicates that the infants' preference to reach for the nearer object was significantly greater in the binocular condition than in the monocular condition. This finding suggests that the infants perceived the objects' relative distances more accurately in the binocular condition than in the monocular condition.

As in Experiment 1, the infants' preference to reach for the nearer object in the monocular condition was significantly greater than chance (by LSD test, $p < .05$). This finding indicates that 4-month-olds are sensitive to monocular depth information and that, for these infants, monocular vision is sufficient for perceiving objects' relative distances.

The data were examined to determine whether the eyepatch introduced a bias to reach for the object on the side of the unpatched eye. As in Experiment 1, the eyepatch did not cause a side bias (approximately 58% of the infants' reaches in the monocular condition were for the object on the right regardless of which eye was patched). Furthermore, the infants reached for the objects equally often in the two viewing conditions, suggesting that the eyepatch did not cause significant irritation. However, interpretation of the results should be tempered with respect to the possibility that the eyepatch itself, rather than less accurate depth perception, caused the reduced reaching preference in the monocular condition. Once again, this issue is addressed in Experiment 3.

It is interesting to note that a significantly smaller proportion of the infants showed a binocular advantage in Experiment 2 than in Experiment 1: 13 out of 24 infants in Experiment 2, compared to 14 out of 15 in Experiment 1 ($\chi^2 = 6.60$, $p < .05$). This finding suggests the hypothesis that the superiority of binocular depth perception results from the development of sensitivity to binocular disparity. Findings by Held et al. (1980) and Birch et al. (1982) suggest that only 50% to 60% of normal infants are sensitive to binocular disparity at 4 months of age (16 weeks), whereas 80% to 90% are sensitive to disparity at 5 months of age (20 weeks). If the superiority of binocular depth perception results from the development of sensitivity to binocular disparity, we would expect binocular depth perception to be superior to monocular depth perception in nearly all 5-month-olds but in only about 50% to 60% of 4-month-olds. This expectation was confirmed in Experiments 1 and 2. We might also expect disparity-sensitive 4-month-olds to be capable of accurate binocular depth perception and disparity-insensitive 4-month-olds to be capable of only moderately accurate depth perception both binocularly and monocularly. Experiment 3 was designed to test this hypothesis.

In addition to suggesting that binocular depth perception is superior to monocular depth perception in 4-month-old infants, the results from Experiment 2 provide evidence that 4-month-old infants' reaching is spatially adapted. Although previous studies by Cruikshank (1941) and Field (1976) suggested that 4-month-olds' reaching may be guided by object distance, it is not clear that infants in these studies exhibited directed reaching for the stimulus objects, rather than random arm thrashing evoked by proximal stimulus cues. The results of Experiment 2, however, cannot be accounted for plausibly in terms of infants responding to proximal stimulus cues.[3] The finding that 4-month-old infants' reaching is influenced by object distance is interesting with regard to the development of reaching and also has an important methodological implication. It indicates that reaching can be a valid index of perceived distance in 4-month-old infants.[4] The limited response repertoire of young infants has been a serious obstacle for the investigation of spatial perception in infants younger than about 5 months of age. The finding that 4-month-old infants

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[3] The following alternative account of the results was considered but ruled out. It is possible that random arm thrashing by the infants resulted in fortuitous hand contacts with the nearer object but never with the more distant object, and that proximal stimulus cues related to the nearer object became associated with tactile reinforcement. This association could result in a reaching preference for the nearer object even if infants could not perceive the objects' relative distances. To test for this possibility, each infant's reaching preference for the nearer object was computed for the first half and second half of the trials completed in each viewing condition. We reasoned that if preferential reaching were based on an association between proximal stimulus cues and tactile reinforcement, infants' reaching preferences for the nearer object should increase during the experiment as this association is learned. The tendency to reach for the nearer object did not increase during either viewing condition, suggesting that the infants did not form an association between proximal stimulus cues and tactile reinforcement. Instead, the infants' reaching appears to have been guided by perception of the objects' distances.

[4] We should note that additional research would be useful to test the hypothesis that 4-month-olds may reach preferentially for the physically smaller of two objects, rather than for the nearer object.

reach preferentially for the nearer of two objects gives us a potentially useful tool for studying many aspects of spatial perception in infants at this age.

Experiment 3

Experiment 3 was conducted to explore the relation between the development of sensitivity to binocular disparity and the accuracy of infant spatial perception. Specifically, it asked whether 4-month-old infants who are sensitive to binocular disparity can perceive objects' relative distances more accurately than can 4-month-old infants who show no evidence of sensitivity to disparity.

Infants' sensitivity to binocular disparity was assessed using a procedure developed by Held et al. (1980). Infants viewed a stereogram containing 30 min of uncrossed binocular disparity paired with a similar display containing no disparity. To adults with normal stereopsis, the stereogram appeared to be a three-dimensional arrangement of three vertical black bars, whereas the zero-disparity display appeared to be a flat arrangement of three bars. The finding by Fantz (1961) that infants look preferentially at a three-dimensional display when it is paired with a similar flat display suggests that infants with stereopsis should look preferentially at the stereogram. Infants who cannot detect binocular disparity should be unable to differentiate the two displays and, therefore, should show no looking preference. 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 only on the basis of binocular disparity.

Infants' looking preferences were scored using a modified two-alternative forced-choice preferential looking procedure. An observer viewed the infant through a peephole between the stimulus displays and, without knowing the position of the stereogram, judged the side to which the infant preferred to look on each trial. It was assumed that an infant was able to detect binocular disparity if the infant looked preferentially at one of the displays on at least 75% of the trials. Infants who met this criterion were assigned to the disparity-sensitive group. Infants not meeting this criterion were assigned to the disparity-insensitive group.[5]

The disparity-sensitive and disparity-insensitive groups' abilities to perceive two objects' relative distances were compared using the depth perception test from Experiments 1 and 2. If the superior accuracy of binocular depth perception in 4- and 5-month-old infants results from the development of sensitivity to binocular disparity, we should find an advantage of binocular depth perception over monocular depth perception only for the disparity-sensitive group; the disparity-insensitive group's performances should be similar in the two viewing conditions. Moreover, in the binocular condition, the disparity-sensitive infants should show more accurate depth perception than the disparity-insensitive infants.

The monocular viewing condition served as a control for the possibility that the two groups differed along dimensions other than sensitivity to binocular disparity. It is possible that 4-month-old infants who are sensitive to binocular disparity are more advanced than disparity-insensitive 4-month-olds in a number of visual and motor abilities. For example, disparity-sensitive infants may have better visual acuity and/or more accurate reaching abilities than disparity-insensitive infants. Disparity-sensitive infants may also have more accurate monocular depth perception than disparity-insensitive infants; it is conceivable that the ability to achieve accurate depth perception (from either monocular or binocular depth information) depends on reaching a particular level of cortical maturity, which is correlated with the appearance of sensitivity to binocular disparity. If the two groups differ on any dimension other than binocular sensitivity and if these differences have significant effects on infants' performances in this experiment, the effects of these differences should be observed in the monocular condition.

Method

Subjects. Fifty-one infants participated in Experiment 3. Forty-two infants were included in the sample: 18 female and 24 male infants with a mean age of 111.7 days (3.7 months) and an age range of 106–120 days. Nine infants were excluded from the sample because of failure to complete both parts of the experiment.

Apparatus. The same apparatus used in Experiment 2 was used in the depth perception test in Experiment 3.

In the disparity-sensitivity test, the infant sat on the parent's lap facing two circular rear-projection screens (type R, black rear-screen material, Raven Screen Corp.), each 10 cm in diameter, separated by 12 cm, mounted in a 111 × 76-cm gray background. Centered in the background above the rear-projection screens were an aperture, 4.5 cm in diameter 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. The stimulus displays were projected onto the screens by two carousel projectors, one mounted on top of the other. Each projector projected half of the display in each screen. Light from the two projectors passed through differently oriented polarizing filters (Melles Griot, product No. 03FPG005).[6] The infant wore infant-sized eyeglasses containing polarizing filters corresponding in orientation to those on the projectors. As a result, images projected by the bottom projector were visible only to the infant's left eye, whereas images projected by the top projector were visible only to the infant's right eye. During the disparity-sensitivity test, the only light in the room was emitted by the slide projectors.

The display in one screen was a stereogram consisting of three regularly spaced 1.25-cm wide vertical black bars spaced 1.25 cm apart (projected by the bottom projector) and a second pattern of three 1.25-cm wide vertical black bars (projected by the top projector) superimposed on the first pattern. The center bars of the two patterns were aligned. The two outside bars in the second pattern were shifted 0.53 cm in the same

[5] It is important to note that failure to meet the disparity-sensitive criterion does not necessarily imply that an infant cannot detect binocular disparity. The term *disparity-insensitive*, as used in this experiment, implies only that infants assigned to this group showed no evidence of sensitivity to binocular disparity.

[6] The type of rear-projection screen material and polarizing filters is important. Pilot testing indicated that gray polacoat screen material and standard plastic polarizing filters may be inadequate.

direction, relative to the outside bars in the first pattern, to create 30 min of uncrossed binocular disparity.[7] This disparity value was chosen based on 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 maximize the likelihood that infants assigned to the disparity-sensitive group were sensitive to both types of disparity.

The display in the second screen was similar to the stereogram but contained no binocular disparity.[8] 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, superimposed directly on top of each other.

The bars in both displays were presented on red backgrounds. The infant sat approximately 60 cm from the rear-projection screens. From 60 cm, the screens subtended 9.5° of visual angle, and the bars subtended 1.2° of visual angle. Each display had a luminance of 7 cd/m^2. To adult observers with normal stereopsis, the stereogram appeared to consist of a three-dimensional arrangement of bars, with the two outside bars located several centimeters behind the center bar. The zero-disparity display appeared to be a flat array of three bars located at the plane of the screen.

The top projector's carousel held two slides, in which the regular and irregular bar patterns were in opposite left–right positions. The stimulus displays' left–right positions were changed by advancing or reversing this projector. The bottom projector contained only one slide and projected identical regularly spaced bar patterns to the two screens on every trial.

Procedure. Experiment 3 had two parts: a disparity-sensitivity test and a depth perception test. The disparity-sensitivity test was always conducted first. This was done because pilot testing suggested that the disparity-sensitivity test was less interesting for the infants than was the depth perception test. In order to minimize subject attrition, the disparity-sensitivity test was administered at the beginning of the experiment while infants typically were attentive and in a calm state.

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 projector 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 was 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 were presented. A trial lasted until the observer felt she could judge 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 displays were extinguished. Trials averaged about 10–15 s 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 the standard FPL procedure (Teller, 1979), the observer's task in this experiment was to identify the side that was fixated preferentially, not to guess the side of a target stimulus. In addition, the observer did not receive feedback regarding the stereogram's position. These changes from the standard FPL procedure were made to ensure that auditory cues from the slide projectors could not reveal the stereogram's position and to ensure that the experimenters were unaware of the disparity-sensitivity test results while conducting the depth perception test.

The infant was given a break from the disparity-sensitivity test at the first sign of boredom or fussiness. If the infant remained attentive, 20 trials were given. 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 75% of the trials were assigned to the disparity-sensitive group. Infants who did not meet this criterion were assigned to the disparity-insensitive group. To ensure that the depth perception test could be conducted without any experimenter bias, the infant's looking preference data were not analyzed until the infant had completed the depth perception test. Thus, during the depth perception test, neither experimenter was aware of the group to which an infant belonged.

The infant was given a short break between the disparity-sensitivity and depth perception tests. The depth perception test used the same procedure as in Experiment 2. In addition, the same criterion was set for inclusion in the sample: three reaches in each viewing condition. Infants' reaches were scored from the videotape record of the experiment using the same method as in Experiments 1 and 2. Two observers independently scored each infant's experimental session. To ensure that there was no experimenter bias in scoring, the observers were unaware of the group (disparity-sensitive or disparity-insensitive) to which each infant had been assigned. In addition, one observer was unaware of the hypotheses of the study. Interjudge reliability was $\kappa = .88$.

Results and Discussion

Disparity-sensitivity test. Eighteen infants met the 75% looking preference criterion in the disparity-sensitivity test and were assigned to the disparity-sensitive group. The disparity-sensitive group consisted of 10 female and 8 male infants with a mean age of 111.2 days (3.6 months) and an age range of 108–117 days. These infants completed a mean of 13.9 trials (SD = 4.5) and looked preferentially at the stereogram on a mean of 78.5% (SD = 4.0) of these trials. Twenty-four infants did not meet the disparity-sensitivity criterion and were assigned to the disparity-insensitive group. This group consisted of 8 female and 16 male infants with a mean age of 112.2 days (3.7 months) and an age range of 106–120 days. The disparity-insensitive infants completed a mean of 13.3 trials (SD = 3.0) and looked preferentially at the stereogram on a mean of 51.6% (SD = 8.4) of these trials.

About 43% of the infants met the 75% looking preference criterion for inclusion in the disparity-sensitive group. This figure is consistent with the Birch et al. (1982) finding that 51% of 4-month-olds can detect 30 min of uncrossed disparity. These similar results suggest that the displays used in the present study contained no monocular or nonstereoscopic binocular cues distinguishing the stereogram and zero-disparity displays that were not available in the Birch et al. (1982) and Held et al. (1980) studies. Because infants did not discriminate the stereogram and zero-disparity displays from nonstereoscopic cues in the Held et

[7] Disparity was calculated using the standard formula reported by Cormack and Fox (in press), assuming symmetrical convergence and an interpupillary distance of 4 cm (Krieg, 1978).

[8] Because the stimulus displays were created by stacked projectors, perfect alignment of the bar patterns projected by the two projectors was not possible. Disparity increased slightly from the top to the bottom of each display. The stereogram contained approximately 30.30 min of uncrossed disparity at the top of the outside bars and 30.39 min at the bottom of the bars. In addition, although there was no disparity at the top of the stereogram's center bar, there was approximately 0.10 min (6 s) of uncrossed binocular disparity at the bottom of the center bar. The zero-disparity display also contained a small amount of uncrossed disparity. Although there was no disparity at the top of the bars, the display contained about 6 s of disparity at the bottom of the center bar and 5.4 s of disparity at the bottoms of the outside bars. These amounts of disparity approach the adult human threshold for stereoacuity (Westheimer, 1979) and, in light of findings by Birch et al. (1982), are likely to be undetectable by 4-month-old infants.

al. (1980) study, it is likely that in the present study the disparity-sensitive infants discriminated the stereogram and zero-disparity displays based on binocular disparity only.

Depth perception test. The results from the depth perception test are summarized in Table 2. The infants' preferences to reach for the nearer object were analyzed in a 2 × 2 × 2 mixed-design ANOVA with sex and group (disparity-sensitive and disparity-insensitive) as between-subjects factors and viewing condition (monocular and binocular) as a within-subjects factor. The dependent variable was the percentage of reaches scored to the nearer object. The analysis revealed a significant main effect for viewing condition, $F(1, 38) = 8.11$, $p < .01$, and a significant Group × Viewing Condition interaction, $F(1, 38) = 6.69$, $p < .05$. No other effects reached statistical significance.

The main effect for viewing condition corroborates the results of Experiment 2, indicating that overall the 4-month-olds' preference to reach for the nearer object was significantly greater in the binocular condition than in the monocular condition. More important for the hypotheses of the study, the significant Group × Viewing Condition interaction indicates that the binocular advantage shown by the disparity-sensitive group was significantly greater than that shown by the disparity-insensitive group. A set of planned comparisons, using the LSD procedure, was performed to analyze the data further. Both groups of infants showed significant reaching preferences for the nearer object in both the binocular and monocular viewing conditions ($p < .01$). In the binocular condition, the disparity-sensitive infants reached significantly more consistently for the nearer object than did the disparity-insensitive infants ($p < .01$). In the monocular condition, the two groups' reaching preferences did not differ significantly ($p > .05$). In addition, the disparity-sensitive infants' binocular reaching preference was significantly greater than was their monocular reaching preference ($p < .01$), whereas the disparity-insensitive infants' reaching preferences did not differ in the two viewing conditions ($p > .05$).

Four important conclusions can be drawn from the results of the monocular viewing condition. First, the equivalent monocular performances of the disparity-sensitive and disparity-insensitive groups suggest that the results of the binocular condition cannot be attributed to nonbinocular differences between the groups, such as differences in visual acuity or in sensitivity to monocular depth information. Thus, the disparity-sensitive infants' more consistent reaching preference in the binocular condition appears to have resulted from more accurate binocular depth perception in these infants. Second, the two groups' equivalent monocular performances suggest that the disparity-sensitive infants' superior binocular performance cannot be attributed to more mature and accurate reaching by these infants. In the monocular condition, the disparity-sensitive infants' reaching was no more accurate (in terms of reaching to the nearer object) than was the disparity-insensitive infants' reaching. It seems implausible that the disparity-sensitive infants' superior reaching accuracy would reveal itself only in the binocular condition, unless this superior reaching accuracy were based on superior spatial perception. Third, the two groups' equivalent reaching preferences in the monocular condition suggest that the groups did not differ in attentiveness or in motivation to reach for the nearer object. Fourth, the disparity-insensitive infants' equivalent performances in the monocular and binocular conditions indicate that wearing an eyepatch did not measurably influence performance on the depth perception test, except insofar as it removed stereoscopic depth information. Had the eyepatch influenced the results, the disparity-insensitive infants' performance while wearing the eyepatch should have differed from their binocular performance, but it did not. Thus, the disparity-sensitive infants' less consistent reaching preference in the monocular condition compared to the binocular condition appears to have resulted from less accurate depth perception and not from extraneous variables introduced by the patch itself. This finding further suggests that the results of Experiments 1 and 2 cannot be accounted for by effects caused by the eyepatch, other than the reduced accuracy of monocular compared to binocular depth perception. In sum, although we cannot be certain that the two groups had equivalent reaching skills, visual acuity, or monocular depth perception abilities, the results of this experiment cannot be attributed to these or other nonbinocular differences between the groups.

Table 2
Mean Number of Reaches and Mean Percentage of Reaches to Nearer Object in Experiment 3

Group	Binocular condition		Monocular condition	
	No. of reaches	% of reaches	No. of reaches	% of reaches
Disparity-sensitive				
M	8.9	75.4	8.9	59.2
SD	3.8	16.3	3.5	9.4
Disparity-insensitive				
M	7.6	64.7	7.9	61.4
SD	3.2	16.4	3.3	16.1

At present, there is no obvious alternative to the conclusion that in the binocular viewing condition the disparity-sensitive infants perceived the objects' relative distances more accurately than did the disparity-insensitive infants. We cannot be certain that the disparity-insensitive infants were actually insensitive to binocular disparity, because failure to show a looking preference in the disparity-sensitivity test does not necessarily imply inability to discriminate the stereogram and zero-disparity displays. In fact, given the small number of trials administered in the disparity-sensitivity test, it seems likely that some disparity-sensitive infants were misclassified as disparity-insensitive. However, the converging results of the disparity-sensitivity and depth perception tests suggest that the disparity-sensitive and disparity-insensitive groups differed in sensitivity to binocular disparity. The most plausible explanation for the results is that the disparity-sensitive infants' looking preference in the disparity-sensitivity test was based on detecting disparity in the stereogram and that their superior binocular depth perception was based on detecting and using disparity to facilitate their perception of the objects' relative distances; in contrast, the disparity-insensitive infants, as a group, could not detect disparity in stereogram and could not use disparity for perceiving the objects' distances; thus, they showed no difference in their monocular and binocular performances. This explanation's plausibility stems from its parsimony. Only one construct, a difference between the groups in sensitivity to disparity, accounts for the results of both tests. There is no obvious alternative that provides a similarly parsimonious interpretation of the results. For example, although a difference in attentiveness could account for the groups' different performances in the disparity-sensitivity test, it cannot account for the depth perception test results (for the reasons cited above). The results of this experiment, therefore, suggest that the development of sensitivity to binocular disparity is accompanied by a substantial increase in the accuracy of infant depth perception.

Experiment 4

Experiment 4 investigated whether spatial perception is generally more accurate in disparity-sensitive 4-month-old infants than in disparity-insensitive 4-month-olds or whether the perceptual advantage associated with sensitivity to binocular disparity is confined to guiding reaching or perceiving objects' relative distances. As in Experiment 3, sensitivity to binocular disparity was assessed in a preferential looking test and, based on the results of this test, infants were assigned to disparity-sensitive and disparity-insensitive groups. A size-constancy test was then conducted to compare spatial perception in the two groups. A second, related goal of Experiment 4 was to seek additional evidence that the results of Experiment 3 were not caused by extraneous variables. The size-constancy test in Experiment 4 used a habituation–dishabituation of looking procedure. Thus, differences between the disparity-sensitive and disparity-insensitive infants' performances in this experiment could not be attributed to differences in reaching skill. This procedure also provided direct measures of infants' attentiveness: looking time and trials required to reach habituation.

Size constancy refers to the ability to perceive an object's constant physical size despite changes in its retinal image size. According to the traditionally predominant theory of size perception, the visual system registers an object's retinal image size and then takes into account information for the object's distance to compute its physical size (e.g., Boring, 1950; Helmholtz, 1910/1962; Kaufman, 1974; Rock, 1975, 1977, 1983). Although alternative accounts of size constancy have been proposed (e.g., Gibson, 1950), generating considerable controversy (see Epstein, 1977; Hochberg, 1971), the best evidence currently available suggests that accurate size perception depends on accurate distance perception (Rock, 1977). We might, therefore, expect that infants can achieve size constancy to the extent that they can perceive objects' distances. If distance perception is more accurate in infants with sensitivity to binocular disparity than in infants without sensitivity to binocular disparity, size perception should also be more accurate in disparity-sensitive infants. Experiment 4 tested this hypothesis.

Recent studies by McKenzie, Tootell, and Day (1980) and Day and McKenzie (1981) suggested that at least some degree of size constancy is present by 4½ months of age (18 weeks). The size-constancy test in Experiment 4 used Day and McKenzie's (1981) method (with slight modifications). Infants were habituated to an object that continuously approached and receded. This object subtended a wide range of visual angles during habituation. Object distance and visual angle were varied during habituation to "desensitize" the infants to changes in these variables in order that infants' responses to a change in object size could be assessed independently of their responses to changes in object distance and visual angle. After a habituation criterion was reached, infants viewed, one at a time, the same moving object and a novel moving object that differed from the familiar object in size only. During these test trials, both the familiar and novel objects subtended visual angles that fell within the range of those seen during habituation. Thus, infants should not discriminate the familiar and novel objects based on their retinal image sizes, because both objects had familiar retinal image sizes. Discrimination of the two objects, as evidenced by significant recovery from habituation when viewing the novel object, would therefore suggest perception of the objects' physical sizes.

Method

Subjects. Fifty-seven infants participated in Experiment 4. Forty-seven infants were included in the sample: 22 female and 25 male infants with a mean age of 114.4 days (3.8 months) and an age range of 103–125 days. Ten infants were tested but excluded from the sample: 8 because of failure to complete both parts of the experiment and 2 because of experimenter error.

Apparatus. The apparatus for the disparity-sensitivity test was the same as that used in Experiment 3. In the size-constancy test, the infant sat in an infant seat facing the experimental display. There were three stimulus objects. During habituation and test trials, the infant viewed a pair of teddy bears that differed in size but were otherwise identical. The large and small bears measured 28 × 23 × 14 cm and 21.5 × 17.5 × 11 cm, respectively. The bears were medium brown with gold ribbons tied around their necks. The third stimulus object, a yellow and black soccer ball 20 cm in diameter, was presented at the end of the experiment to obtain a measure of the infant's attentiveness.

The objects were moved along a white surface, 190 cm long and 55 cm wide, patterned with gray lines 2 cm wide and regularly spaced 7.75 cm apart. A 2.5-cm-wide slot bisected the surface. A rod extending down from the bottom of each stimulus object fit into a carriage, which rode on a metal track parallel to the slot beneath the surface. An experimenter moved the carriage and object along the track by means of a handle, attached to the carriage, that extended out from beneath the surface. The rod supported the object about 1 cm above the surface.

The apparatus was enclosed in plain white walls. Only the experimental apparatus and a plain gray wall at the end of the surface were visible to the infant. Observers viewed the infant through narrow gaps in the walls located about 20 cm in front of the infant on each side of the apparatus. The stimulus objects were not visible to the observers. Each observer held a button, connected to a microcomputer, that was depressed when the infant fixated the stimulus object and released when the infant looked away. The computer recorded fixation times, calculated the habituation criterion, and signaled an experimenter with a blinking light when trials were finished and when habituation had occurred. Between trials, the surface and stimulus objects were occluded from the infant by a colorfully patterned screen that slid through one of the gaps in the walls.

Procedure. Experiment 4 had two parts: a disparity-sensitivity test and a size-constancy test. The disparity-sensitivity test was always conducted first. This test followed the same procedure as the disparity-sensitivity test in Experiment 3. Once again, infants who completed at least 10 trials and showed a looking preference for one of the displays on at least 75% of the trials were assigned to the disparity-sensitive group; infants who completed at least 10 trials but who did not meet the 75% criterion were assigned to the disparity-insensitive group. Unlike Experiment 3, in Experiment 4, infants were assigned to either the disparity-sensitive or disparity-insensitive group immediately upon completion of the disparity-sensitivity test. This immediate assignment was necessary to ensure that size of habituation object (large and small) was counterbalanced within each group. Day and McKenzie's (1981) results suggested that this is an important variable to counterbalance. They found that dishabituation to the novel object was greater in infants habituated to the smaller object than in infants habituated to the larger object.

The infant was given a short break between the disparity-sensitivity and size-constancy tests. In the size-constancy test, the infant was habituated to one teddy bear that continuously approached and receded. Half of the infants were habituated to the small bear and half to the large bear. Habituation object was counterbalanced within each group. Infants were habituated using an infant-control procedure (Horowitz, Paden, Bhana, & Self, 1972). Looking time was measured from the infant's first fixation of the object, and the total amount of looking time within each trial was recorded. Fixation of the object was determined by the infant's direction of gaze. A trial lasted until the infant looked away from the object for 2 continuous seconds (calculated by the computer) or until 120 s of total looking time had accumulated in that trial before the infant looked away for 2 continuous seconds. The object was then occluded and, after a brief interval, another trial began. This procedure was continued until the infant became habituated. The habituation criterion was two consecutive trials with a mean looking time of less than 50% of the mean of the first two trials. After the last habituation trial, two test trials were administered. The test trials also followed the infant-control procedure; each trial lasted until the infant looked away from the object for 2 continuous seconds, or until 120 s of total looking time had accumulated. In one test trial, the infant viewed the familiar teddy bear; in the other, the infant viewed the different-sized bear. Order was counterbalanced. After the test trials, the soccer ball was presented to measure the infant's attentiveness.

Prior to each habituation trial, the stimulus object was occluded. Trials were initiated by removing the occluder to present the moving object. The habituation object had four different starting points: 80, 105, 130, and 155 cm from the infant. The starting points were randomly ordered, without replacement, in blocks of four trials. The object first approached the infant, moving forward 50 cm, then moved back to the starting point. An experimenter moved the object at a constant velocity of about 30 cm per second. The range of visual angles subtended by the small bear (measured vertically) during habituation trials was 7.9° to 35.6°. The range of visual angles subtended by the large bear (measured vertically) was 10.2° to 43.0°. During test trials, both objects started moving from 105 cm. The ranges of visual angles subtended by the large and small bears during test trials were 14.9° to 27.0° and 11.6° to 21.4°, respectively. Thus, the visual angles subtended by the objects in the test trials fell within the range of visual angles seen during the habituation trials for both habituation objects. The ball's starting point and range of motion were the same as the bears' during the test trials.

Two experimenters conducted the experiment. One observed the infant, recorded fixation time, and put the occluder in place between trials. This experimenter was unaware of the group to which the infant had been assigned and the object that was presented on a given trial. The other experimenter moved the object during the trials, positioned the object between trials, and changed the objects between test trials. This experimenter could not see the infant. A third experimenter observed 23 randomly selected infants (9 from the disparity-sensitive group and 14 from the disparity-insensitive group). Fixation times recorded by this experimenter were used only to calculate reliability and had no control over the experiment. The correlation between the two observers' scores was computed for each infant. The mean correlation was .997 (SD = .005), which indicated an exceptionally high level of interjudge reliability.

Results and Discussion

Disparity-sensitivity test. Twenty infants met the disparity-sensitivity criterion of a 75% looking preference and were assigned to the disparity-sensitive group. This group consisted of 10 female and 10 male infants with a mean age of 113.7 days (3.7 months) and an age range of 103–123 days. The infants in this group completed a mean of 12.6 (SD = 3.1) trials and looked preferentially at the stereogram on a mean of 78.6% (SD = 4.0) of these trials. Twenty-seven infants did not meet the disparity-sensitivity criterion and were assigned to the disparity-insensitive group. This group consisted of 12 female and 15 male infants with a mean age of 114.9 days (3.8 months) and an age range of 106–125 days. These infants completed a mean of 14.3 (SD = 2.9) trials and looked preferentially at the stereogram on a mean of 48.3% (SD = 10.3) of these trials.

Size-constancy test. The results from the size-constancy test are summarized in Table 3. The infants' test trial looking times were analyzed in a 2 × 2 × 2 × 2 mixed-design ANOVA with sex, group (disparity-sensitive and disparity-insensitive), and habituation object (large and small) as between-subjects factors and test object (novel and familiar) as a within-subjects factor. The analysis revealed a significant main effect for test object, $F(1, 39) = 15.67$, $p < .01$, and a significant Group × Test Object interaction, $F(1, 39) = 4.37$, $p < .05$. No other effects were statistically significant.

The main effect for test object indicates that, as a group, the 4-month-olds looked significantly longer at the novel object than at the familiar object during the test trials. This finding suggests that 4-month-olds have at least some degree of size constancy. It, therefore, replicates the findings of Day and McKenzie (1981) and extends them to a slightly younger age. More important for the hypotheses of the study, the significant Group × Test Object interaction indicates that infants in the disparity-sensitive group showed significantly greater recovery from habituation when viewing the novel object than did infants in the disparity-insensitive group. Two planned comparisons, using Tukey's HSD test (Kirk, 1982), were performed to analyze the data further. In the test trials, infants in the disparity-sensitive group fixated the novel object significantly longer than the familiar object ($p < .01$). This result provides evidence of size constancy in disparity-sensitive 4-month-olds. These infants apparently perceived the constant physical sizes of the objects, despite continuous change in their retinal sizes, and dishabituated based on the different physical size of the novel object. Infants in the disparity-insensitive group showed only a nonsignificant tendency to fixate the novel object longer than the familiar object ($.05 < p < .10$). The results, therefore, are unclear regarding size constancy in 4-month-olds who have not yet developed sensitivity to disparity. It is important to note that the disparity-insensitive infants looked significantly longer at the ball than at the familiar object, $t(26) = 4.23$, $p < .01$, indicating that their failure to dishabituate significantly to the novel object was not due to inattention or fatigue. Moreover, the two groups exhibited approximately equal fixation times on the first two habituation trials, took equal numbers of trials to reach the habituation criterion, and exhibited approximately equal fixation times when viewing the soccer ball at the end of the experiment. These results suggest that the difference between the groups' performances cannot be accounted for by differences in attention. The results, therefore, indicate that the disparity-sensitive infants perceived the objects' sizes more accurately than did the disparity-insensitive infants.

We do not mean to imply that infants are unable to perceive objects' sizes prior to the onset of disparity sensitivity. Perhaps a more sensitive experiment would reveal size constancy in disparity-insensitive infants. Moreover, the disparity-insensitive infants showed some evidence of size constancy in this experiment,

Table 3
Means and Standard Deviations of Looking Times (in seconds) During Habituation and Test Trials and Mean Number of Habituation Trials Completed in Experiment 4

	Habituation			Test		
Group	No. of trials	First 2 trials	Last 2 trials	Familiar object	Novel object	Ball
Disparity-sensitive						
M	5.7	60.0	13.1	12.0	34.6	32.7
SD	2.9	27.8	10.7	11.3	35.1	29.8
Disparity-insensitive						
M	6.1	56.4	8.3	10.6	19.5	29.1
SD	2.4	30.1	5.6	10.0	27.3	28.6

because the difference between their fixation times for the novel and familiar objects approached significance. It is not clear, however, that every infant in the disparity-insensitive group was actually insensitive to binocular disparity. Because infants' behavior tends to be highly variable, a large number of trials is typically required to achieve a reliable measure of an individual infant's abilities. In the present study, infants visited the lab only once, and it was necessary to complete both the disparity-sensitivity and depth perception tests during this single visit. Consequently, only a limited number of trials could be conducted in the disparity-sensitivity test. In light of the small number of trials completed by the infants in the disparity-sensitivity test and the Birch et al. (1982) finding that 51% of 4-month-olds can detect uncrossed binocular disparity (compared to about 43% classified as disparity-sensitive in this study), it seems likely that several disparity-sensitive infants were misclassified as disparity-insensitive. Thus, misclassified disparity-sensitive infants may have contributed to the disparity-insensitive group's apparent dishabituation to the novel object. Given this possibility, these findings do not allow us to draw a conclusion regarding the presence or absence of size constancy in infants prior to the onset of sensitivity to binocular disparity.

General Discussion

Taken together, these experiments indicate that the emergence of sensitivity to binocular disparity is a major milestone in perceptual development. In Experiments 1 and 2, 5- and 4-month-old infants showed a more consistent reaching preference for the nearer object in the binocular condition than in the monocular condition, indicating that binocular depth perception is more accurate than monocular depth perception in infants at these ages. In Experiment 3, infants in the disparity-insensitive group reached for the nearer object only slightly more often than chance, indicating only moderately accurate depth perception, whereas infants in the disparity-sensitive group reached consistently for the nearer object, suggesting accurate depth perception. In Experiment 4, disparity-insensitive infants failed to show size constancy. In contrast, disparity-sensitive infants showed clear evidence of size constancy. These findings indicate that the development of sensitivity to binocular disparity is accompanied by a substantial increase in infants' ability to perceive the distances and sizes of objects.

This conclusion is strengthened by the converging results of Experiments 3 and 4. Because these experiments used very different methods and measures of spatial perception, it is unlikely that the disparity-sensitive infants' superior performances in both experiments could have been due to extraneous variables. Although differences between the two groups in reaching skill could have influenced the results in Experiment 3, this variable cannot account for the results of Experiment 4. Similarly, although differences between the groups in visual acuity or sensitivity to monocular depth information may have influenced the results of Experiment 4, these variables cannot account for the results of Experiment 3. The similar findings of Experiments 3 and 4 further indicate that the superiority of spatial perception in disparity-sensitive infants is not limited to a particular task; furthermore, they suggest the hypothesis that disparity-sensitive infants may show more accurate spatial perception in a number of situations. For example, shape constancy, like size constancy, may depend on accurate distance perception (Rock, 1975). Perhaps disparity-sensitive infants can achieve more accurate shape constancy than can disparity-insensitive infants. Sensitivity to binocular disparity may be related to superior performance on nonspatial tasks as well, such as detecting camouflaged objects. Julesz (1971) pointed out that stereopsis is superbly adapted for this sort of task. Future research is also likely to reveal tasks for which sensitivity to disparity does not confer a perceptual advantage, because the importance of binocular information probably varies a great deal from situation to situation.

To our knowledge, this study provides the first firm evidence of a significant postnatal improvement in the infant's ability to perceive objects' sizes and distances. Although previous studies have found age differences in infants' responses to depth, they have not provided unambiguous evidence of developmental changes in the accuracy of depth perception. Walk (1969), for example, found that 65% of 7- to 9-month-old infants can be coaxed into crossing the deep side of a 10-in. deep (25.4 cm) visual cliff, whereas only 21% of 10- to 13-month-olds can be coaxed into crossing a 10-in. (25.4 cm) visual cliff. When depths of 20 in. (50.8 cm) and 40 in. (101.6 cm) were used, no age differences were found. Walk (1969) concluded from these findings that 10- to 13-month-old infants can make finer depth discriminations than can 7- to 9-month-olds. In light of more recent data, however, Walk's conclusions do not appear to be warranted. Findings from the present study and from a study by Granrud, Yonas, and Pettersen (1984) indicate that 4- to 7-month-old infants reach consistently for the nearer of two objects whose distances differ by 7 to 10 cm. Moreover, Yonas, Sorknes, and Smith (1983) found that 7-month-old infants reliably discriminate differences in object distance as small as 2 cm. These findings clearly indicate that 7-month-old infants can make much finer depth discriminations than those required in the Walk study, suggesting that the age difference observed by Walk (1969) resulted from a change in infants' responses to depth, not in their ability to perceive depth. For example, 10- to 13-month-olds may be more cautious on the visual cliff than 7- to 9-month-olds and, unlike the younger infants, realize that even a 10-in. (25.4 cm) cliff can be dangerous.

A similar argument can be made regarding the Pettersen, Yonas, and Fisch (1980) finding that 10-week-old infants blink more frequently than 6-week-olds in response to optical information specifying impending collision with an approaching object. Although this age difference may reflect an improvement in the ability to perceive impending collision, it may reflect development in infants' responses to impending collision. Moreover, as Yonas points out, a blink response to impending collision may be activated by a "process so primitive that it would be unwarranted to infer that spatial information is being picked up" (1981, p. 329). Thus, the age difference found by Pettersen et al. may result from development in a mechanism unrelated to the perception of three-dimensional space. Although recent findings suggest that there may be important changes in spatial perception between 5 and 7 months, when infants appear to develop sensitivity to the pictorial depth cues of interposition, relative size, familiar size, and shading (Granrud, Haake, & Yonas, 1985; Granrud & Yonas, 1984; Granrud, Yonas, & Opland, 1985; Kaufmann et al., 1981; Yonas, Cleaves, & Petterson, 1978; Yonas, Granrud, & Pettersen, 1985; Yonas et al., 1982), it remains unknown whether sensitivity to pictorial depth cues facilitates spatial perception in naturalistic situations in which multiple sources of depth information are available.

The present study provides firmer evidence of a postnatal increase in the accuracy of infant spatial perception. Its findings cannot be attributed plausibly to development in infants' responses rather than to the accuracy of their spatial perception. Results from the monocular condition in Experiment 3 suggest that there were no important differences in the groups' reaching accuracy or in their motivation to reach for the nearer object. Thus, the disparity-sensitive infants' superior binocular performance appears to have resulted from more accurate spatial perception. In light of this finding, the hypothesis that spatial perception is fully functional in the earliest months of life, prior to the emergence of binocular sensitivity, no longer seems tenable.

An additional implication of this study is that stereopsis is present in 4-month-old infants who are sensitive to binocular disparity. Several previous studies had shown that infants can detect binocular disparity (Birch et al., 1982, 1983; Fox et al., 1980; Held et al., 1980; Petrig et al., 1981), but none had found clear evidence that infants can perceive depth from disparity. For example, Held et al. found that infants can discriminate a stereogram from a similar display containing no binocular disparity. This finding indicates that infants can detect disparity but does not tell us whether infants perceive the depth specified by disparity. It is possible that infants discriminated the displays based on the disparity itself without perceiving depth. Although detection of disparity is typically accompanied by depth perception in adults, we cannot be certain that this is true in infants. Detection of disparity and depth perception from disparity may be accomplished by separate components in the stereopsis system. If so, it is possible that the disparity detection component is functional earlier in development than is the depth perception component. In light of this possibility, we cannot infer that infants have stereopsis from the finding that they can detect disparity. However, the findings from Experiments 3 and 4, indicating that spatial perception is significantly more accurate in disparity-sensitive 4-month-olds than in disparity-insensitive 4-month-olds, suggest that disparity-sensitive infants can use binocular disparity to perceive depth and to increase the accuracy of their spatial perception. This implies that stereopsis is present in these infants and, further, that stereopsis and sensitivity to binocular disparity appear at the same time in development. These findings also suggest that the Held et al. (1980) method is a valid measure of infant stereopsis, and not only of infants' sensitivity to binocular disparity. We must emphasize that these are tentative conclusions, however, given that this study provides only indirect evidence of infant stereopsis. We cannot yet rule out the possibility that other aspects of binocular vision, which co-emerge with sensitivity to binocular disparity, contribute to the superior spatial perception of disparity-sensitive infants. Future studies should seek more direct evidence of stereopsis in infants and should make a finer-grained analysis of the relation between binocular vision and infant spatial perception.

This study raises several additional questions and hypotheses that merit future investigation. One interesting issue is raised by behavioral (Birch et al., 1982; Richards, 1971) and neurophysiological (Poggio & Fischer, 1977) evidence suggesting that there are two separate visual mechanisms for detecting binocular disparity: one sensitive to crossed disparity and another sensitive to uncrossed disparity (for a recent review of these studies, see Mustillo, 1985). Because sensitivity to uncrossed disparity appears to develop later than does sensitivity to crossed disparity (Birch et al., 1982), it is reasonable to assume that both mechanisms were operative in the disparity-sensitive infants in the present study. By investigating infants' spatial perception during the transitional period, in which only one disparity-sensitive mechanism is functioning, future research could potentially reveal each mechanism's contribution to spatial perception. A second issue meriting future investigation is the relation between spatial perception and the development of stereoacuity. Although this study treated sensitivity to binocular disparity as an all-or-none ability, the development of sensitivity to disparity appears to be more continuous. Birch et al. (1982) found evidence of considerable improvement in stereoacuity after sensitivity to disparity has emerged, and adult levels of stereoacuity, that is, sensitivity to about 5–10 s of binocular disparity, have not yet been observed in children under 3–5 years of age (Fox, Patterson, & Francis, 1984). As stereoacuity improves, perhaps there is concomitant improvement in the accuracy of spatial perception. Alternatively, increased sensitivity to monocular depth information after 4 months may reduce the importance of stereopsis and attenuate the superiority of binocular compared to monocular depth perception in older infants and children.

To summarize, Experiments 1 and 2 replicate and extend the findings of Granrud, Yonas, and Pettersen (1984), showing that for 4- and 5-month-old infants binocular depth perception is more accurate than is monocular depth perception, even when a considerable amount of monocular depth information is available. The results from Experiment 2 further show that 4-month-old infants' reaching is influenced by object distance and that reaching can be a valid measure of perceived relative distance in 4-month-olds. Experiments 3 and 4 found that distance and size perception are substantially more accurate in disparity-sensitive 4-month-olds than in disparity-insensitive 4-month-olds, indicating that the development of sensitivity to binocular disparity is accompanied by a significant increase in the accuracy of infant spatial perception.

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