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Infants Distance Perception from Linear Perspective and Texture Gradients

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This study investigated 5- and 7-month-old infants' abilities to perceive objects' distances from pictorial depth cues, the depth cues available to a stationary, monocular viewer. Infants viewed a display in which texture gradients and linear perspective, two pictorial depth cues, created an illusion of two objects resting at different distances on a textured surface. Under monocular viewing conditions, 7-month-olds reached preferentially for the apparently nearer object, indicating that they perceived the objects' relative distances specified by pictorial depth cues. Under binocular viewing conditions, these infants showed no reaching preference. This finding rules out interpretations of the results not based on the objects' perceived distances. The 5-month-olds' reaching preferences were not significantly different in the experimental (monocular) and control (binocular) conditions. These infants, therefore, did not show clear evidence of distance perception from pictorial depth cues.

depth perception pictorial depth cues linear perspectives
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It has been well documented that young infants possess at least some degree of visual depth perception (Caron, Caron, & Carlson, 1979; Day & McKenzie, 1981; Gibson & Walk, 1960). The primary goal of recent infant depth perception research has been to identify developmental changes in depth perception, with considerable interest focusing on changes in infants' sensitivity to the visual information that specifies depth (Yonas & Granrud, 1985). Recent findings indicate that young infants may be insensitive to several important sources of information used by adults in depth perception. Sensitivity to binocular dis-

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parity, the stimulus information for stereoscopic depth perception, appears to develop between 3 and 4 months of age (Birch, Gwiazda, & Held, 1982; Fox, Aslin, Shea, & Dumais, 1980; Held, Birch, & Gwiazda, 1980), and sensitivity to pictorial depth information, the depth information available to a stationary monocular observer, may be absent until 6 to 7 months of age (Yonas & Granrud, 1985). Recent findings by Granrud (1986) suggest that insensitivity to stereoscopic information is related to significant limitations in depth perception accuracy. If infants are insensitive to pictorial information until 6 to 7 months of age, it would suggest that spatial perception is not fully effective for at least several months after the onset of stereopsis, since pictorial information is the only depth information available in many situations. For example, because binocular sensitivity to differential depth decreases rapidly with increases in distance, pictorial cues are frequently the only cues that specify the spatial layouts of distant scenes and the three-dimensional shapes of distant objects. Additional research is needed, however, to determine whether young infants are insensitive to pictorial depth information.

A consistent developmental pattern has emerged from recent studies of infants' sensitivity to pictorial depth information (or pictorial depth cues). Seven-month-old infants perceive the spatial layout depicted in Ames' (1951) trapezoidal window illusion, an illusion created by several pictorial depth cues (Kaufmann, Maland, & Yonas, 1981; Yonas, Cleaves, & Pettersen, 1978), and they respond appropriately to the pictorial depth cues of familiar size (Granrud, Haake, & Yonas, 1985; Yonas, Pettersen, & Granrud, 1982), relative size (Yonas, Granrud, & Pettersen, 1985), interposition (Granrud & Yonas, 1984), and shading (Granrud, Yonas, & Opland, 1985). In contrast, 5-month-olds showed no evidence of sensitivity to pictorial depth cues in these studies. These findings suggest that the ability to perceive depth from pictorial cues may first appear between 5 and 7 months of age. The similar developmental patterns found in these studies further suggest that a common mechanism may be involved in the development of sensitivity to many or all pictorial depth cues. Before we can draw firm conclusions regarding the mechanisms underlying the development of sensitivity to pictorial depth cues, however, we need clearer evidence of when sensitivity to pictorial cues first appears.

The present study had two primary goals. The first was to investigate further 7-month-old infants' sensitivity to pictorial depth cues. We asked whether 7-month-olds can perceive objects' relative distances from texture gradient and linear perspective information provided by texture on a surface receding in depth. These cues provide effective sources of distance information for adults (Gibson, 1950) and children (Yonas & Hagen, 1973), but their role in infant distance perception is not yet known. The second goal was to seek evidence of responsiveness to pictorial depth cues in 5-month-old infants. We cannot be certain from previous studies that 5-month-olds are incapable of perceiving depth from pictorial cues. It is possible that studies using more sensitive measures or more effective stimuli will reveal sensitivity to pictorial cues in 5-month-olds. In this study, we attempted to create a more effective pictorial display than those used in previous studies. This display, modelled after one created by Gibson (1950, p. 179), produced a compelling illusion of two objects resting at different distances on a textured surface receding in depth (see Figure 1). Distance was specified in the display by the pictorial depth cues of linear perspective and texture gradients (i.e., the gradual decrease in texture size and increase in texture density from the bottom to the top of the display).[1]

Five- and 7-month-old infants' reaching behavior was observed as they viewed the display shown in Figure 1. Because infants at these ages reach preferentially for the nearer of two objects (Granrud, Yonas, & Pettersen, 1984), it was hypothesized that infants capable of perceiving distance from pictorial cues would reach more frequently for the lower, apparently nearer object than for the higher, apparently more distant object. Infants might reach preferentially for the lower object based on some factor other than the objects' perceived distances, however. For example, reaching downward for the lower object may require less effort than reaching upward for the higher object. In order to control for this possibility, infants were tested under both monocular and binocular viewing conditions. In the monocular condition, infants wore an adhesive eyepatch over one eye. A reaching preference based on the objects' relative heights, or on any feature of the display other than the objects' perceived distances, should be uninfluenced by the presence or absence of the eyepatch, and should be equivalent in both viewing conditions. If preferential reaching is guided by perceived distance, however, a significantly greater reaching preference should be observed in the monocular condition than in the binocular condition, since binocular depth information (binocular disparity and convergence) should specify that the two objects are equidistant and result in a reduced reaching preference in the binocular condition (several studies have found that for 5- and 7-month-olds, conflicting binocular depth information overrides the effects of pictorial depth cues [e.g., Yonas & Granrud, 1985]).

METHOD

Subjects

Sixty-one infants completed the experiment and were included in the sample: 27 7-month-olds (12 males and 15 females; mean age = 206.4 days; age range = 199–211 days) and 34 5-month-olds (17 males and 17 females; mean age = 148.4 days; age range = 141–157 days.[2] An additional 4 7-month-olds and 8 5-month-

[1] The objects' relative heights in the visual field may provide an additional cue for the objects' relative distances. It is not clear, however, that relative height in the visual field is an effective depth cue. Gibson (1950), for example, has argued persuasively that relative height is typically correlated with texture gradient information, but is not an independent depth cue.

[2] Since earlier studies had failed to find responsiveness to pictorial depth cues in 5-month-olds, a larger sample of 5-month-olds was tested to increase this study's statistical power and maximize the likelihood of finding responsiveness in 5-month-olds if it were present.

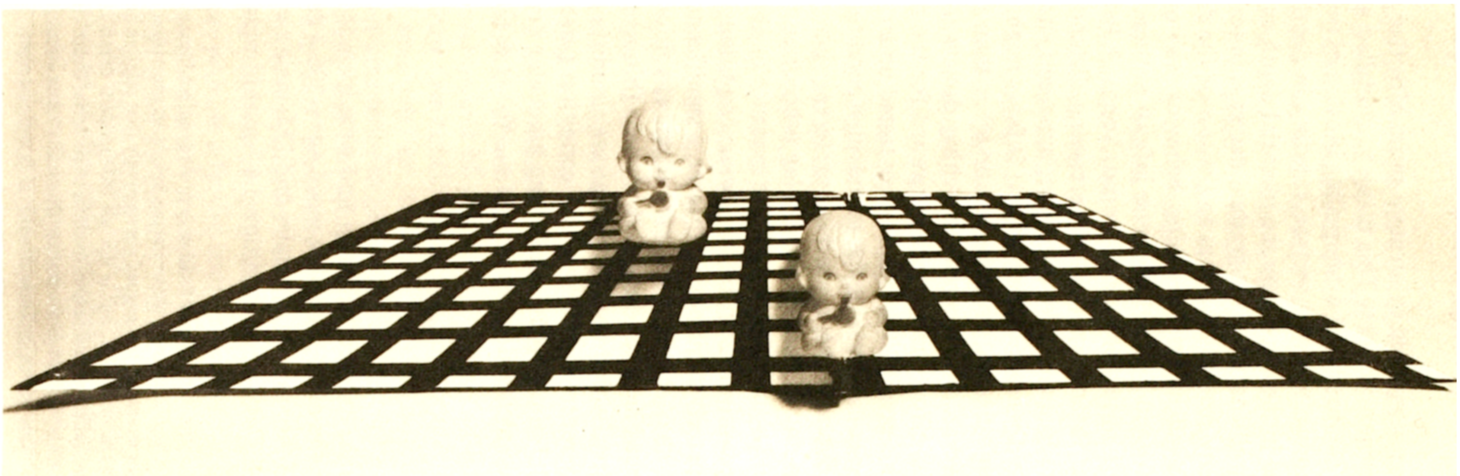

Figure 1. Photograph of the experimental display from the infant's viewpoint. The two dolls were equal in size and distance from the infant. The background surface was vertical, but linear perspective and texture gradients created the illusion of a horizontal surface receding in depth.

olds began the experiment but were excluded from the sample because they did not reach for the stimulus objects at least four times in each viewing condition.

Apparatus

Infants viewed the display pictured in Figure 1 while sitting in a self-supporting Gerry-brand infant carrier. The display consisted of two three-dimensional toy dolls suspended in front of a vertically oriented, trapezoidal-shaped photograph depicting a surface receding in depth. Each doll measured 8 × 6 × 6.5 cm and subtended a visual angle of approximately 17.7°, measured vertically, at the infant's observation point. The dolls were held in place against the photograph by metal clips, not visible to the infant, attached to the back of each doll. At their nearest points, the dolls were approximately 20 cm from the infants' eyes, and 6.5 cm nearer to the infant than the photograph. The photograph, taken of a rectangular, white, horizontal surface patterned with regularly spaced black lines, was 12 cm high, 94 cm wide at the lower edge, and 39 cm wide at the upper edge. Although the two dolls were equidistant, the display created an illusion that the dolls were resting on a horizontal surface at different distances from the observer.

The display was suspended 7.5 cm in front of a homogeneous white background (92 × 122 cm) by rods that were not visible to the infant. The display was illuminated by florescent ceiling lights and by a 150-watt incandescent lamp behind the infant 45 cm from the display. Each experimental session was videotaped by a camera mounted in the ceiling above the infant. This camera arrangement provided a top view of the infant and the display for scoring the infants' reaching behavior.

Procedure

Each infant was tested in two viewing conditions: a monocular viewing condition, in which the infant wore an adhesive eyepatch over one eye (randomly chosen), and a binocular viewing condition, in which both eyes were uncovered. The initial viewing condition, monocular or binocular, was chosen randomly; eight trials were presented in this condition. After a short break, eight trials were presented in the other viewing condition. Of the 27 7-month-olds tested, 14 received the monocular condition first; of the 34 5-month-olds, 16 received the monocular condition first.

Prior to the beginning of each trial, the display was occluded by a 43 × 50 cm screen held by the experimenter. When the infant was looking toward the display, the screen was raised to initiate a trial. The trial was terminated, and the display was again occluded, after the infant touched one or both of the simulus objects, or after 30 s had elapsed without a reach occurring. If the infant looked away from the display during a trial, the experimenter attempted to draw the infant's attention back to the display by tapping on the back of the white background surface along its midline. The higher and lower objects' left-right positions were varied randomly. The objects' positions were changed between trials while the display was occluded. This procedure was continued until the infant completed 16 trials (8 monocular and 8 binocular) or became too inattentive or fussy to continue. Only infants who reached for the stimulus objects at least four times in each viewing condition were included in the sample.

Each infant's reaching behavior was scored from the videotape record of the experiment. A reach was scored if the infant touched one or both of the objects; only the first reach occurring in each trial was scored. Reaches were scored in three categories: as contacting the higher object, the lower object, or both objects simultaneously. Reaches scored as contacting both objects simultaneously and trials in which no reach occurred were excluded from the data analysis, since these trials were uninformative regarding infants' reaching preferences (3% and 6% of the 5- and 7-month-olds' trials, respectively, were scored in three categories). As a result, the percentages of reaches scored to the higher and lower objects summed to 100.

One experimenter scored the reaching behavior of every infant. A random selection of 199 trials from the 5-month-old sample and 179 trials from the 7-month-old sample was also scored by a second observer who was unfamiliar with the hypotheses of the study. Interjudge agreement was calculated using the Kappa statistic (κ) (Bartko & Carpenter, 1976). Agreement between the two judges' scores was $\kappa = .98$ for the 5-month-old sample and $\kappa = .94$ for the 7-month-old sample.

RESULTS AND DISCUSSION

Table 1 presents the mean number of reaches scored and the mean percentages of the infants' reaches that first contacted the lower object. Percentages of reaches to the lower object were analyzed in a $2 \times 2 \times 2$ mixed-design analysis of variance with Age (5 and 7 months) and Order (monocular condition first vs. binocular condition first) as between subjects factors and Viewing Condition (monocular and binocular) as a within subjects factor. This analysis revealed a significant main effect for Viewing Condition, $F(1, 59) = 8.37$, $p < .01$. No other effects reached statistical significance ($p > .05$).

TABLE 1
Mean Number of Reaches and Mean Percentage of Reaches to Lower Object

	Mean Number of Reaches *(SD)*	Mean Percentage of Reaches to Lower Object *(SD)*
7-month-olds		
Monocular Condition	7.7 (0.8)	65.5 (17.1)
Binocular Condition	7.5 (0.9)	54.5 (19.1)
5-month-olds		
Monocular Condition	7.7 (0.9)	59.8 (16.6)
Binocular Condition	7.9 (0.5)	53.8 (19.2)

The main effect for Viewing Condition indicates that the infants reached more consistently for the lower object in the monocular condition than in the binocular condition. This finding indicates that the infants perceived the objects' distances specified by pictorial depth cues in the experimental display. It is not clear from this analysis, however, that infants in both age groups perceived depth from pictorial cues. Planned comparisons, using t tests, were performed to analyze each group's data separately, in order to determine whether infants in each age group responded to pictorial depth cues.[3] The 7-month-olds' reaching preference for the lower object was significantly more consistent in the monocular condition than in the binocular condition, $t(26) = 4.73$, $p < .01$. This finding indicates that the infants' monocular condition reaching preference was based on the objects' perceived distances, not on two-dimensional features in the display, such as the objects' relative heights, since equivalent reaching preferences would be expected in the two viewing conditions if reaching were based on two-dimensional features. In the monocular condition, the 7-month-olds apparently responded to linear perspective and/or texture gradient information specifying that the stimulus objects were resting at different distances on a surface receding in depth. In the binocular condition, they apparently responded to binocular information specifying that the two objects were equidistant.

The 5-month-olds' reaching preferences were not significantly different in the two viewing conditions, $t(33) = 1.42$, $p > .05$. Although these infants exhibited a significant reaching preference for the lower object in the monocular condition, $t(33) = 3.38$, $p < .01$, we cannot rule out the possibility that this reaching preference was based on some feature in the display other than the objects' perceived relative distances. The 5-month-olds, therefore, did not show clear evidence of sensitivity to pictorial depth cues. It is unlikely that these infants' failure to respond to pictorial cues resulted from the inadequacy of reaching as a measure of perceived depth in 5-month-olds. Several studies have found that 5-month-olds reach consistently for the nearer, or apparently nearer, of two objects when motion-carried or stereoscopic depth information is available (Granrud, 1986; Granrud Yonas, & Pettersen, 1984; Granrud et al., 1984; Yonas, Cleaves, & Pettersen, 1978). However, this study does not demonstrate that 5-month-olds are insensitive to pictorial depth cues. It is possible, for example, that 5-month-olds can perceive distance from pictorial cues, but that they detected accommodation, relative size, and/or motion parallax information specifying that the objects were equidistant, and that these conflicting cues attenuated the infants' monocular reaching preference. Although it is unlikely that conflicting cues influence reaching in 5-month-olds but not in 7-month-olds, it is possible that a more sensitive test of 5-month-olds' distance perception from pictorial depth cues could be achieved if conflicting

[3] The results of more statistically conservative Tukey comparisons supported the same conclusions as the results of the t tests.

cues could be eliminated. Moreover, although the 5-month-olds' reaching preferences did not differ significantly in the two viewing conditions, the slightly more consistent reaching preference found in the monocular condition suggests that some 5-month-olds may have responded to the pictorial cues in the display. Perhaps clearer evidence of sensitivity to pictorial cues would be found if a slightly older group of infants were tested.

Although we cannot be certain that 5-month-olds are incapable of perceiving depth from pictorial cues, the results of this study are consistent with the developmental pattern found in previous studies of infants' sensitivity to pictorial depth cues (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). These studies suggest that between 5 and 7 months of age infants may become sensitive to many different pictorial depth cues. Additional research is needed, however, to determine when sensitivity to pictorial depth cues first emerges. Future studies should continue to seek evidence of sensitivity to pictorial cues in 5-month-olds and younger infants. Another interesting issue for future studies is whether there is simultaneous emergence of sensitivity to all pictorial depth cues, which would suggest that a common mechanism is involved in this development, or staggered development of sensitivity to different cues, which would suggest that distinct mechanisms are involved.

The finding that 7-month-old infants can perceive objects' relative distances specified by linear perspective and texture gradients suggests that even early in life the visual system exploits stable properties of the environment to constrain the possible interpretations of retinal images. The retinal image projected by Figure 1 provides ambiguous information for the stimulus objects' relative distances, because this retinal image could be projected by many different three-dimensional arrangements of the objects and background surface. For example, this retinal image could be projected by an object resting on a horizontal surface next to an equidistant and equal-sized object floating several centimeters above the surface, by two different-sized objects resting on a horizontal surface at different distances, or by two equidistant objects suspended at different heights in front of a vertical, trapezoidal-shaped surface (as it was in this experiment). However, Figure 1 is not normally seen as ambiguous. Adults typically report that the figure depicts two objects resting at different distances on a horizontal surface; 7-month-old infants apparently perceive the figure this way as well. That this interpretation is favored over other possible interpretations suggests that the visual system constrains the interpretation of this retinal image by making two assumptions about the scene that is being viewed. First, the visual system interprets the gradual decrease in texture size and increase in texture density from the bottom to the top of the image as specifying an increase in distance along a surface. This interpretation depends on the assumption that texture is at least approximately uniform in size and spacing across the surface (a related assumption might be that the lines on the surface are parallel). Second, the visual system apparently assumes that objects rest on surfaces and do not float in mid-air, or that objects and surfaces that are adjacent in the retinal image are also physically adjacent. Without this assumption, linear perspective and texture gradients on the surface could provide no information for objects' distances.

We do not mean to imply that these assumptions are explicitly represented. It is not plausible that 7-month-old infants consciously think that objects rest on surfaces rather than float in mid-air or that visible texture is distributed uniformly across surfaces. It is more likely that these assumptions are implicit in the functioning of automatic "decoding principles" (Johansson, 1970) used by the visual system to extract information from the light reaching the eyes. It is also important to note that these assumptions can be overridden by contradictory evidence. For adults and 3-year-old children, for example, a gap between an object and its cast shadow specifies that the object is floating in space rather than resting on a surface (Yonas, Goldsmith, & Hallstrom, 1978).

Although these assumptions result in an illusion when viewing Figure 1 (the objects are actually equidistant), it is likely that they result in veridical perception in natural environments, because they reflect stable properties of the environment to which the visual system is adapted. Gibson (1950) pointed out that visible texture is stochastically regular in size and spacing on most surfaces in terrestrial environments, and that objects indeed rest on surfaces rather than float in mid-air. These two facts about the world formed the foundation of Gibson's (1950) "ground theory" of visual perception. The findings of the present study suggest that decoding principles based on these stable properties of terrestrial environments are incorporated into the functioning of the visual system by at least 7 months of age.

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