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Infants' Sensitivity to the Depth Cue of Height-in-the-Picture-Plane

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Five- and 7-month-old infants' sensitivity to the pictorial depth cue of height-in-the-picture-plane was assessed. Infants were presented with 2 objects, 1 higher than the other, and their reaching was recorded under monocular and binocular viewing conditions. The results showed that both age groups reached significantly more to the lower, apparently closer object under monocular view and that they reached equally to the 2 objects under binocular view. The results suggest that both 5- and 7-month-old infants are sensitive to the depth information provided by height-in-the-picture-plane. Demonstration of pictorial depth sensitivity at 5 months has implications for the mechanism underlying the onset of sensitivity to this type of depth information.

Pictorial depth cues provide information for depth to observers under stationary conditions and when binocular information is not available (e.g., at distances greater than 3 m). Yonas and his colleagues have conducted systematic research on the development of sensitivity to pictorial depth information by assessing infants' sensitivity to a number of cues: shading, linear perspective, interposition, texture gradient, familiar size, relative size, and surface contour (Arterberry, Yonas, & Bensen, 1989; Granrud, Haake, & Yonas, 1985; Granrud, Yonas, & Opland, 1985; Granrud & Yonas, 1984; Sen, Yonas, & Knill, 2001; Yonas & Granrud, 2006; Yonas, Granrud, Arterberry, & Hanson, 1986; Yonas, Granrud, & Pettersen, 1985; Yonas, Pettersen, & Granrud, 1982). One pictorial depth cue that has not been investigated to date is height-in-the-picture-plane. This study addressed 5- and 7-month-old infants' sensitivity to this cue for depth.

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Studies of the development of pictorial depth perception reveal a consistent pattern (see Table 1). Seven-month-olds but not 5-month-olds show sensitivity to the depth cues of shading, linear perspective, interposition, texture gradient, familiar size, relative size, and surface contour (see Yonas, Arterberry, & Granrud, 1987a, for a review). All of this research consisted of cross-sectional studies using reaching as a measure. Reaching is an appropriate dependent variable because it leaves little question of whether infants perceived a depth difference or not. When infants of this age are presented with a real depth difference, they consistently reach for the closer of two objects, even with separations as small as a few centimeters (Yonas & Granrud, 1985).

A longitudinal study, in which the same infants were assessed every 2 weeks between the ages of 5 and 7 months for sensitivity to the depth cues of linear perspective and texture gradients, allowed for a finer analysis of the emergence of sensitivity to pictorial depth information both within and across children (Yonas, Elieff, & Arterberry, 2002). The resulting picture was one of variability. Of 7 infants tested between the ages of 20 and 32 weeks of age, 1 showed sensitivity to the available depth information at 22 weeks, 1 at 24 weeks, 2 at 26 weeks, 2 at 28 weeks, and 1 at 32 weeks, the last date tested (Yonas et al., 2002, Experiment 3). Thus, for most infants, the onset of pictorial depth sensitivity may occur between 22 and 32 weeks and the time table for full emergence may take 2 to 8 weeks. This view of the development of pictorial depth sensitivity is less absolute than previously thought (e.g., Kellman & Arterberry, 1998, 2006), and other researchers have suggested that even younger infants may be sensitive to static information that provides three-dimensional perspective for adults (Bertin & Bhatt, 2006; Bhatt & Bertin, 2001; Bhatt & Waters, 1998; Kavsek, 1999; Putaansuu & von Hofsten, 1991).

This study provides an assessment of the development of another pictorial depth cue, the results of which will contribute to our understanding of the emergence of sensitivity to pictorial depth information. The cue of height-in-the-picture-plane has also been named relative height in the field (Epstein, 1966) and relative upward location in the field (J. J. Gibson, 1950). Like many pictorial depth cues, height-in-the-picture-plane is rarely found in isolation in natural scenes. For example, in Figure 1, depth is depicted by linear perspective (converging lines created by the trees), familiar or relative size (decreasing size of the trees with distance), texture gradients (grass), and height-in-the-picture-plane. The key component of height-in-the-picture-plane is the position of objects relative to the horizon. In Figure 1, the trees that are closer to the horizon appear to be farther away. Even against a blank or randomly textured background, higher objects are typically perceived by adults as being farther away (Epstein, 1966; J. J. Gibson, 1950; see Sedgwick, 1986, for a review). J. J. Gibson suggested that this is due to the fact that a blank background suggests a terrain or floor.

Each pictorial depth cue relies on at least one assumption that pertains to a regularity in the environment (J. J. Gibson, 1950). For example, light comes from above (shading), texture elements are regular in size (texture gradient), parallel

TABLE 1
Summary of Results of Previous Cross-Sectional Studies Addressing Infants' Pictorial Depth Sensitivity

		7-Month-Olds				5-Month-Olds			
		Monocular		Binocular		Monocular		Binocular	
Depth Information	*Design*	*M*	*SD*	*M*	*SD*	*M*	*SD*	*M*	*SD*
Attached shadows[a]	Within	62.80	14.70	51.40	15.20	53.80	18.50[j]	50.00	19.80
Cast shadows[b]	Within	58.99	18.60	50.28	17.47	49.59	21.22[j]	49.72	22.25
Familiar size[c]	Between	4.30	3.20	1.39	1.70	1.91	2.14	.36	1.19
Familiar size[d]	Between	60.51	16.60	47.52	8.61	47.91	12.40[j]	—	—
Interposition[e]	—	61.00	9.00	—	—	56.00	10.00	—	—
Linear perspective and texture gradient[f]	Within	65.50	17.10	54.50	19.10	59.80	16.60	53.80	19.20
Linear perspective and texture gradient[g]	Between	72.30	15.40	39.20	16.00	54.20	21.40[j]	47.50	19.80
Relative size (disc stimuli)[h]	Between	72.60	15.65	54.10	21.01	69.50	25.49	60.10	18.33
Relative size (triangle stimuli)[h]	Between	60.80	12.07	40.30	12.53	52.20	27.28[j]	62.70	12.52
Surface contour[i]	Within	54.50	18.20	36.50	15.00	37.50	15.20	44.50	13.20

Note. Values are mean percentage and standard deviation of reaching for the apparently closer object or surface by 5- and 7-month-old infants, unless otherwise noted. Design indicates whether monocular and binocular conditions were within or between subjects.

[a]Granrud, Yonas, and Opland (1985). [b]Yonas and Granrud (2006). [c]Yonas, Pettersen, and Granrud (1982). Mean duration of reaching in a 30-sec trial. [d]Granrud, Haake, and Yonas (1985). [e]Granrud and Yonas (1984). [f]Yonas, Granrud, Arterberry, and Hanson (1986). [g]Arterberry, Yonas, and Bensen (1989). [h]Yonas, Granrud, and Pettersen (1985). [i]Sen, Yonas, and Knill (2001). Data originally presented as mean number of reaches and chance is 33% as there were three regions of interest (near, middle, and far). [j]The mean percentage of reaching was significantly lower than the 5-month-olds' monocular performance in this study.

FIGURE 1 A naturalistic example of the depth cue of height-in-the-picture-plane. Objects closer to the horizon are perceived as being farther away.

lines converge with distance (linear perspective), surfaces that cover other surfaces are closer (interposition), and object sizes remain constant (familiar size). For height-in-the-picture-plane as depicted in Figure 1, infants need to perceive an object relative to the horizon and finding the horizon may not be particularly difficult if one perceives the ground plane. Thus, it is possible that sensitivity to height-in-the-picture-plane might emerge earlier than other pictorial depth cues.

Infants' sensitivity to height-in-the-picture-plane was tested in isolation from other pictorial depth information. The procedure and stimuli were modeled after the work by Yonas et al. (1986) and Arterberry et al. (1989). In these previous studies, infants were presented with a trapezoid-shaped board in which linear perspective and texture gradients provided information for surface slant. Two objects were placed on the board, one higher than the other. When viewed monocularly by adults, the lower object appeared to be closer than the higher object. Infants' reaching to the two objects was recorded. For this study, the same display was used except that the converging lines and regular texture were replaced with random texture (see Figure 2). This display was also similar to the "outline" display used by Epstein (1966) in a study with adults.

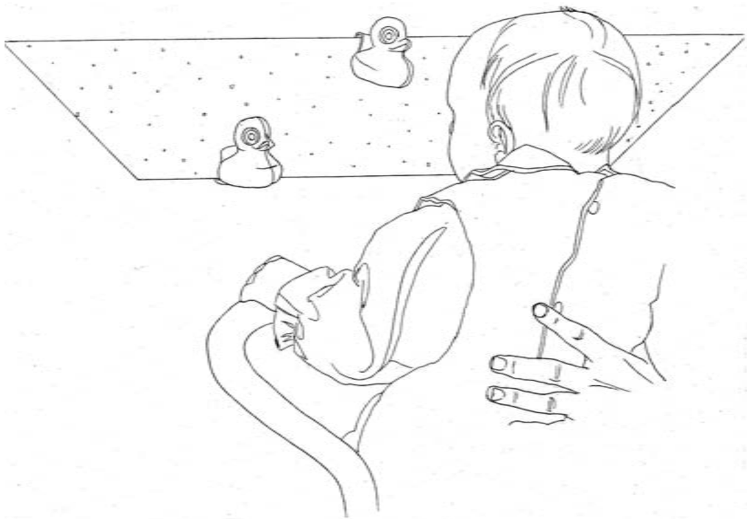

FIGURE 2 Schematic diagram of the test display isolating height-in-the-picture-plane information for depth (drawing by C. M. Lynch).

Both within-subjects and between-subject designs have been employed to assess infants' sensitivity to pictorial depth information (see Table 1). In within-subjects designs, the same infant is tested both monocularly and binocularly. This design allows for a direct comparison across viewing conditions. However, the number of reaches per viewing condition is typically not more than six because infants become fussy with repeated trials. Between-subject designs test different infants under monocular and binocular conditions, but they allow for more trials per infant per condition (12 on average). One might expect less variability in a within-subjects design, but in practice that is not the case (see standard deviations in Table 1). Thus, in this study maximizing the number of reaches per infant per viewing condition guided the decision to conduct a between-subject assessment.

Five- and 7-month-old infants were tested either monocularly or binocularly, and their reaching to the two objects was recorded. Under monocular viewing conditions, the relative distance of the two objects was specified by height-in-the-picture-plane, indicating that the lower object was closer. It was predicted that infants who were sensitive to the available depth information would reach significantly more to the lower object under monocular view. Infants were predicted to reach equally to the two objects under binocular view because stereopsis overrides pictorial information for depth, and this source of depth information is available to infants by 4 months of age (e.g., Fox, Aslin, Shea, & Dumais, 1980; Held, Birch, & Gwiazda, 1980).

METHOD

Participants

Forty-one 7-month-olds (20 monocular, 21 binocular; *M* age = 217.1 days; range = 199–226 days) and forty-two 5-month-olds (21 monocular, 21 binocular; *M* age = 150.1 days; range = 133–162 days) participated. Twenty-six additional infants were tested but were excluded from the analyses due to failure to meet the criterion of reaching at least 6 times out of a maximum of 16 trials ($n = 22$) or fussiness ($n = 4$).

Apparatus

The infants were seated in a Gerry infant carrier in front of the suspended display (Figure 2). Infants were positioned in the carrier such that when they extended their arm forward it would touch a point above the midpoint of the display. The display was a trapezoid-shaped board that was covered with dots of varying sizes and densities. Mean density for the surface was 8.3 dots/cm^2. The board measured 93 cm across the top, 39 cm on the bottom, and was 12.3 cm high. Pairs of three-dimensional plastic toys were hung on the board (blue ducks, orange fish, green frogs, yellow fish; *M* size = 7.88 × 6.13 × 5.25 cm; mean visual angle = 20.20° vertically). These toys were attached to the display using plastic clips that were not visible to the infant. One of the toys was attached to the top of the board, and the other was attached to the bottom of the board. Average vertical distance between the bottom of the top toy and the top of the bottom toy was 1.9 cm, and average horizontal distance was 3.8 cm.

The display was suspended in front of the infant by clamps in the back that were not visible from the front. A black cloth measuring 92 × 109 cm served as a homogeneous background behind the display board. Between trials, the display was covered by a 43.5 × 51.5 cm red occluder that had colorful dinosaur stickers on it. The entire apparatus was illuminated by fluorescent ceiling lights in the testing room. Each session was videotaped by an overhead camera.

Procedure

Each infant was randomly assigned to either the monocular or binocular condition. In the monocular condition, an eye patch was placed over one of the infant's eyes; the eye covered was chosen randomly.

Before each session began, the display board was covered from view by the occluder. The experimenter attached the pair of toys to the board, one to the left and one to right of midline of the infant and one at the top and one at the bottom of the display. The order for the left–right positioning of the top and bottom object was predetermined and random, with the constraint of no more than two trials in a row in which the toys were in the same location. After drawing the infant's attention forward, the experimenter removed the occluder. The experimenter did not hide during each trial, as she needed to monitor the infant's behavior toward the objects (or other parts of the display). If the infant did not look at the display, the experimenter would try to attract his or her attention toward the display by snapping her fingers behind the display (in the center) or calling the child's name, without attempting to bias the infant's attention to one or the other toy. A trial was considered complete when the infant touched one of the objects while looking at the display. At this point, the experimenter returned the occluder to hide the display from the infant's view while the objects were changed. If a reach did not occur after 30 sec, the next trial was administered. The total number of trials was 16, but the session ended early if the child became too fussy or bored to continue.

All infants were scored for reaches from the video record. A reach was counted as successful if the infant touched the object while he or she was looking at it. Experimenters coded whether the child reached for the higher or lower object and whether or not the child was looking at the object during the reach. Monitoring of both looking and reaching ensured that only intentional reaches, as opposed to random arm movements, were counted. A subset of trials ($n = 292$) were coded by two experimenters to obtain a measure of reliability; agreement was $k = 0.96$ (Bartko & Carpenter, 1976).

RESULTS

Mean number of reaches and mean percentage reaching to the lower object by monocular and binocular 5- and 7-month-olds is shown in Table 2. Preliminary analyses revealed no sex differences, so the analyses were collapsed across boys and girls.

TABLE 2
Mean Number of Touches and Mean Percentage of Reaches to the Apparently Closer (the Lower) Object by 5- and 7-Month-Old Infants

		View			
		Monocular		*Binocular*	
Age		*No. of Reaches*	*Percentage to Lower Object*	*No. of Reaches*	*Percentage to Lower Object*
5 months	*M*	12.62	60.25*	13.10	41.87
	SD	3.12	16.98	3.16	19.10
7 months	*M*	11.75	61.04*	13.62	54.51
	SD	3.14	22.40	2.96	21.59

*$p < .05$.

Infants' mean number of reaches was analyzed in a 2 × 2 analysis of variance (ANOVA) with age (5 months, 7 months) and view (monocular, binocular) as between-subject factors. The analyses revealed no significant main effects or interactions, all Fs(1, 79) < 2.97, *ns,* indicating no difference among the age groups or viewing conditions in terms of the number of trials with a reach.

Fourteen out of twenty-one 5-month-olds and thirteen out of twenty 7-month-olds reached to the apparently closer than farther object under monocular view on more than 50% of trials with a reach. Under binocular view, seven out of twenty-one 5-month-olds and eleven out of twenty-one 7-month-olds reached greater than 50% to the apparently closer than farther object. The percentage of reaching to the lower object was compared to chance for each age group and each viewing condition. Both 5- and 7-month-olds viewing the displays monocularly showed a reaching performance that was significantly above chance (50%); however, neither age group showed above chance performance in the binocular condition (see Table 2). Infants' percentage of reaching to the lower object was analyzed in a 2 × 2 ANOVA with age (5 months, 7 months) and view (monocular, binocular) as between-subject factors. The analyses revealed a significant main effect for view, $F(1, 79) = 7.96, p < .01$, partial $\eta^2 = .09$. No other significant main effects or interactions were found. Infants reached significantly more for the lower object in the monocular than the binocular condition ($M = 60.63$, $SD = 19.56$; $M = 48.19$, $SD = 21.13$, respectively). Infants of both ages reached for the apparently closer object in the monocular condition, and they reached equally to the two objects in the binocular condition. Note that the pattern of results across the monocular and binocular conditions cannot be attributed to the ease of reaching to the lower of the two objects because such a bias was not present in the binocular condition.

To compare 5-month-old infants' monocular performance in this study with previous studies, independent sample t tests were conducted on the reaching performance to the apparently closer object or surface for each study listed in Table 1, as long as reaching was used as the dependent measure and infants' reaches were coded dichotomously (e.g., in Sen et al., 2001, infants' reaching to three regions of the display were reported). Infants in this study reached significantly more to the closer objects or regions specified by height in the picture plan than to objects or regions with relative distance that was specified by attached shadows (Granrud, Yonas, & Opland, 1985), $t(48) = 3.61, p < .01$; cast shadows (Yonas & Granrud, 2006), $t(62) = 3.34, p < .01$; familiar size (Granrud, Haake, & Yonas, 1985), $t(37) = 5.53, p < .01$; and relative size (triangle condition[1]; Yonas et al., 1985), $t(39) = 2.99, p < .01$. Five-month-old infants in this study did not reach significantly more

[1]Comparisons with infants' performance with the relative size disc stimuli (Yonas et al., 1985) were not made because in that study 5-month-olds showed significantly higher reaching to the larger than the smaller disc in both the monocular and binocular conditions, suggesting that some aspect of the display, other than the available pictorial depth information, may have guided infants' reaching.

to the closer object than 5-month-olds reaching to the closer side of a surface specified by interposition (Granrud & Yonas, 1984), $t(39) = 2.00$, *ns.* The comparisons to previous studies assessing 5-month-olds' sensitivity to linear perspective and texture gradient provided mixed results. In one case, 5-month-olds in this study reached significantly more often for the apparently closer than farther object (Arterberry et al., 1989), $t(39) = 3.57$, $p < .01$, but in another case, they did not (Yonas et al., 1986), $t(53) = .21$, *ns.*

DISCUSSION

Five- and 7-month-old infants were tested for sensitivity to the pictorial depth cue of height-in-the-picture-plane. Both age groups reached significantly more to the apparently closer object (the lower one) when tested monocularly, suggesting that they were using the available depth information. When tested binocularly, infants reached equally to the two objects, as predicted, because the available binocular information would override the depth information provided by height-in-the-picture plane.

The finding that 7-month-old infants are sensitive to height-in-the-picture-plane for depth is consistent with a large body of research demonstrating pictorial depth sensitivity at this age. By 30 to 32 weeks of age, infants are able to use the depth cues of shading, linear perspective, interposition, texture gradient, familiar size, relative size, and surface contour to guide their reaching (Arterberry et al., 1989; Granrud, Haake, & Yonas, 1985; Granrud & Yonas, 1984; Granrud, Yonas, & Opland, 1985; Sen et al., 2001; Yonas & Granrud, 2006; Yonas et al., 1986; Yonas et al., 1985; Yonas, Pettersen, & Granrud, 1982).

The finding that 5-month-olds are sensitive to height-in-the-picture-plane for depth may be the first clear demonstration of pictorial depth sensitivity in a group of infants of this age. Monocular 5-month-olds in this study reached significantly more to the apparently closer object than monocular 5-month-olds who were tested for sensitivity to shading, familiar size, relative size, and, at least in one case, linear perspective and texture gradient information. Other research with 5-month-olds or younger infants have shown some infant sensitivity to various cues, such as line junctions, textural arrangements, shading, and luminance cues, that depict the third dimension for adults. It is unclear, however, whether infants in these studies perceived the third dimension because looking time was used as the dependent measure (Bertin & Bhatt, 2006; Bhatt & Bertin, 2001; Bhatt & Waters, 1998; Kavsek, 1999; Putaansuu & von Hofsten, 1991). For example, Bertin and Bhatt (2006) studied the pop-out effect in which infants viewed two-dimensional drawings of three-dimensional shapes. When shading and line junction information indicated a change in orientation, infants looked longer to the changed display. This work, and that of others, suggests that infants responded to a change in the display but not necessarily that they perceived the third dimension using the available pictorial information. When an infant reaches to the closer of two objects, there is little question that he or she perceived the depth difference. When an infant looks at a display that has regions of differing depth, one has less confidence that the infant perceived the third dimension. In this case, it is possible that the infant is responding to some two-dimensional difference in the region of the display that looks three-dimensional to adults.

One strategy used to test depth perception in infants without relying on reaching as a measure is the use of the transfer-across-cues paradigm (Arterberry, Bensen, & Yonas, 1991; Yonas, Arterberry, & Granrud, 1987b). For example, in Arterberry et al. (1991), infants were habituated monocularly to a photograph of a rectangular window slanted in depth (a trapezoidal window). The window's apparent orientation was specified by linear and angular perspective, shading, and relative size information. Following habituation, infants binocularly viewed a real window slanted in depth and the same photograph from the habituation phase. If infants were sensitive to the pictorial depth information in the habituation phase and perceived the window as slanted in depth, they were predicted to generalize habituation to the real window (because under binocular view it looked slanted) and dishabituate to the photograph (because under binocular view it now looked flat). Seven-month-old infants, but not 5-month-old infants, showed the predicted pattern of looking. This study was originally conducted to rule out the possibility that immaturity of reaching in 5-month-olds accounted for the lack of pictorial depth sensitivity in this age group. This paradigm, however, can be used with infants younger than 5 months of age, and it would be a good approach to studying sensitivity to height- in-the-picture-plane, and other sources of depth information such as those identified by Bhatt and his colleagues (Bertin & Bhatt, 2006; Bhatt & Bertin, 2001; Bhatt & Waters, 1998), in infants younger than 5 months.

Recall that the display used in this study was very similar to the display used by Yonas and his colleagues (Arterberry et al., 1989; Yonas et al., 1986) to study infants' sensitivity to texture gradient and linear perspective. In fact, height-in-the-picture-plane was also present in that display, but 5-month-olds did not show sensitivity to the available depth information. To isolate height-in-the-picture-plane, linear perspective and texture gradient information were eliminated, and 5-month-olds showed sensitivity to the available pictorial depth information. This finding is curious because it suggests that a display with less information resulted in better performance. Perhaps the receding surface in the display, a necessary condition for using height-in-the-picture-plane, was more salient for 5-month-olds when height-in-the-picture-plane was in isolation of linear perspective and texture gradient information. Alternatively, in the full-cue display, 5-month-olds may have received conflicting information because they were sensitive to some of the depth information (height-in-the-picture-plane) but not others (linear perspective and texture gradient).

Demonstration of sensitivity to at least one pictorial depth cue at 5 months of age has implications for the development of a pictorial depth perception mechanism. First, in conjunction with the longitudinal study by Yonas et al. (2002), it appears that the emergence of pictorial depth sensitivity is variable and protracted, and some pictorial depth cues emerge before others. This is in contrast to the emergence of sensitivity to binocular disparity, which emerges rapidly around 16 weeks of age (Held et al., 1980).

Second, this finding is problematic for a biological explanation that posits maturation of a single mechanism for development. The appearance of various pictorial cues around the same time has been interpreted as suggesting that maturation of some higher visual processing area in the nervous system is the mechanism (Gunderson, Yonas, Sargent, & Grant-Webster, 1993). Gunderson et al.'s (1993) research with macaque monkeys lends additional support to a maturational explanation. In macaques, pictorial cues appear as a group around 7 to 8 weeks of life. A key to this interpretation is that the timing fits the rough ratio of 1:4 in terms of time after birth in nonhuman primates and humans that fits the maturation of numerous other abilities. The appearance of sensitivity to one pictorial cue up to 2 months before the others in human infants makes it less likely that a single mechanism may account for the emergence of all the pictorial depth cues.

An alternative explanation for the onset of pictorial depth sensitivity is learning (e.g., Granrud, Haake, & Yonas, 1985). As mentioned earlier, each pictorial depth cue relies on the perceiver's sensitivity to some reliable aspect of the environment (e.g., light comes from above and texture elements are regular in size). A learning argument may need to start with the origins of these assumptions and the experiences that might be necessary for learning (or discovering) them (E. J. Gibson, 1969). The earlier appearance of height-in-the-picture-plane as compared to other pictorial depth information suggests that different cues may need different learning opportunities and that these learning opportunities have different time tables.

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