The development of the ability of infants to utilize static cues to create and access representations of object shape

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A "transfer-across-depth-cues" method was used to explore the development of the ability to generate and use spatial representations of an object as specified by static pictorial depth cues. Infants were habituated to an object with depth specified by one cue and then presented with the same shape with depth specified by a different cue. Only if an abstract representation of that object had been formed could transfer across cues occur. Shading and line junctions uniquely determined the 3D shapes in these displays so that they appeared to be either a slice of cake with a flat top or a rocket. Without these cues, both line drawings were identical. Infants aged 6 to 7 months showed significant evidence of transfer, while infants aged 4 to 5 months did not. A control experiment demonstrated that the younger infants could discriminate between the objects when a single depth cue specified the shapes. These results are similar to our previous findings, which indicated that 6- to 7-month-old infants show transfer across shading and surface-contour cues, specifying convex and concave surfaces (A. Tsuruhara, T. Sawada, S. Kanazawa, M. K. Yamaguchi, & A. Yonas, 2009). This work supports the hypothesis that the ability to form 3D spatial representations from pictorial depth cues develops at about 6 months of age.

Keywords: infant shape perception, pictorial depth cues, shading, line junction, perceptual development

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Introduction

Adults perceive the distance and 3D shape of objects using many visual depth cues (Cutting & Vishton, 1995; Howard & Rogers, 2002). The development of sensitivity to these many sources of information is not a unitary story. Infants respond to motion-carried information for objects, layouts, and events in the first weeks after birth. Binocular sensitivity appears later (see Kellman & Arterberry, 2006, for a review of this literature). This study deals with the development of sensitivity to a class of information, which becomes functional later in development, pictorial depth cues. These provide spatial information when a scene is viewed with one eye and without motion. They are traditionally referred to as "pictorial depth cues" because they are the only cues for depth available in pictures.

The purpose of the present study was to investigate the development of the ability to transfer information for the shape of an object provided by one pictorial depth cue to a second pictorial depth cue. Transfer from one depth cue to another requires that both cues are involved in the creation of a spatial representation of the object because the displays share no low-level information to differentiate the shapes.

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Recently, Tsuruhara, Sawada, Kanazawa, Yamaguchi, and Yonas (2009) examined the development of the ability to form an abstract representation, which could be accessed by different pictorial depth cues. In that study, a "transfer-across-depth-cues" method (Arterberry, Bensen, & Yonas, 1991; Yonas, Arterberry, & Granrud, 1987; Yonas & Pick, 1975) was used wherein infants were first habituated to a shape specified by one cue. Following habituation, infants' looking preference was tested with the same shape and a novel shape, both specified by a different depth cue. Only if infants perceived 3D shape from each of the pictorial depth cues and both cues activated a spatial representation could they identify one shape as novel and the other as habituated. Generally, infants are known to look longer at novel than at habituated stimuli (Fantz, 1964). Therefore, one would expect infants to show an increased looking preference for the novel shape when compared to any preference measured before habituation. Conversely, if they did not have a common representation across depth cues, one would expect preferential looking to be unchanged by the experience of viewing the habituation displays. By using this "transfer-across-depth-cues" method, one can rule out the possibility that infants respond to an aspect of the display other than its 3D shape.

Studies using this method have shown that 4-month-old infants transfer habituation to shape across non-pictorial depth cues. Yonas et al. (1987) found that when infants were habituated to a planar object or a volume specified by purely motion-carried information, they showed transfer to a display in which only binocular information for 3D shape was available. On the other hand, using the "transfer-across-depth-cues" method, Tsuruhara et al. (2009) found that while 6- to 7-month-old infants used information from shading and surface contours to form a specific representation of the shape of a surface, 4- to 5-month-olds did not.

Using different methods, other researchers reported evidence of sensitivity to pictorial depth cues at younger ages. For example, Bhatt et al. (Bertin & Bhatt, 2006; Bhatt & Bertin, 2001; Bhatt & Waters, 1998) found sensitivity to pictorial cues in infants as young as three months of age. In addition, 4-month-old infants looked longer at impossible events (Yonas & Granrud, 2007; Yonas, Granrud, Le, & Forsyth, 2007) and impossible objects (Shuwairi, 2009; Shuwairi, Albert, & Johnson, 2007), as specified by pictorial depth cues. Furthermore, a recent meta-analysis of 16 studies using preferential reaching to assess sensitivity to pictorial cues found reliable evidence of responsiveness to depth in 5-month-olds (Kavšek, Granrud, & Yonas, 2009).

On the other hand, work by Tsuruhara et al. (2009) showed no evidence of sensitivity to pictorial depth cues in 3- to 5-month-olds. A possible explanation for this contradiction is that the ability to form a representation of shape requires additional processes not required for looking at the more interesting side or reaching for the closer side of a display. Findings from studies (Bertin & Bhatt, 2006; Bhatt & Bertin, 2001; Bhatt & Waters, 1998; Shuwairi, 2009; Shuwairi et al., 2007; Yonas & Granrud, 2007; Yonas et al., 2007) indicating that infants have some sensitivity to pictorial depth cues do not allow us to conclude that infants use abstract representations to store spatial information over time and integrate information from different pictorial cues.

It may be that the absence of transfer in 4- to 5-month-old infants in the work by Tsuruhara et al. (2009) resulted from their use of particular shapes and cues that were too similar. In that study, shading and surface contours specified two 3D surfaces. Because the two surfaces were identical except for a depth reversal (Figure 1), the two shapes may have appeared the same to the younger infants. Due to the depth reversal ambiguity of their displays, both concave and convex interpretations were possible. The shapes of the surfaces specified by shading were disambiguated by the assumption that light comes from above (Howard, Bergstrom, & Ohmi, 1990; Ramachandran, 1988, 1995; Yonas, Kuskowski, & Sternfels, 1979). In a similar fashion, the shapes specified by surface contours were disambiguated by the assumption that the scene was viewed from above (Landy, Maloney, Johnston, & Young, 1995; Mamassian & Landy, 1998, 2001; Reichel & Todd, 1990). By "assumption," we mean a bias that the visual system employs to make 3D perception stable when a 2D image has multiple 3D interpretations. Hence, the transfer effect observed in Tsuruhara et al. (2009) depended on infants' ability to use these assumptions. If such are not available early in development, 3D shapes may be

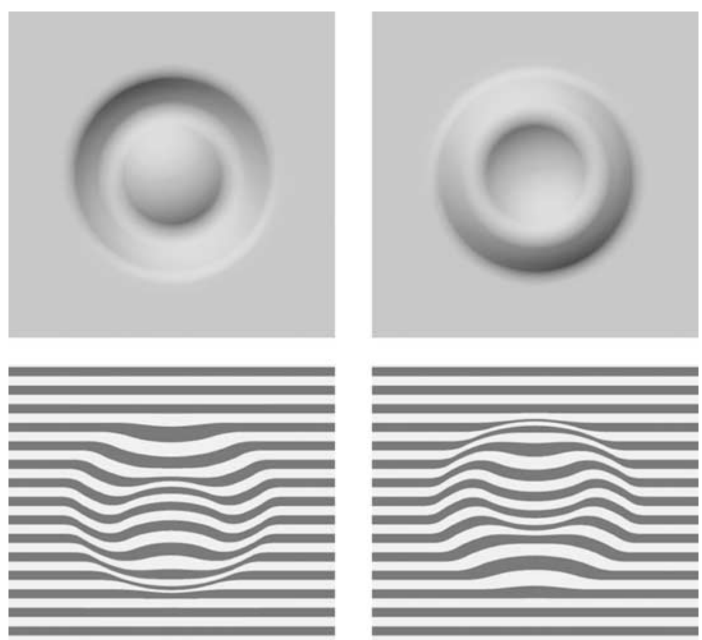

Figure 1. Shading and surface contour displays used in Tsuruhara et al. (2009): "center-convex" on the left and "center-concave" on the right.

perceived from these depth cues; however, their shape would appear unstable. If this were the case, infants would not show transfer although they may perceive and be able to create a spatial representation of the 3D layout.

In contrast to Tsuruhara et al.'s (2009) study, we presented objects rather than surfaces to our infants. In this research, assumptions of the direction of illumination and the station point of the viewer were not required and the objects were noticeably different in shape. If the failure of 4- to 5-month-old infants to show evidence of transfer was caused by the particular layouts and cues used by Tsuruhara et al. (2009), we expected that younger infants would show evidence of transfer in the present study.

Shading and line junction provided depth information in this study (Figure 2). Two types of 3D shapes were adapted from Barrow and Tenenbaum (1981): one was similar to a slice of cake with a planar top and the other one to a rocket with a conical point. Barrow and Tenenbaum (1981) observed that the 2D line drawings of the visible parts of these two 3D shapes are almost identical from particular viewpoints. In our study, the 3D shape of the cake was slightly modified from that in Barrow and Tenenbaum so that the line drawings were identical (Figure 3). The ambiguity in the 3D interpretation of Figure 3 was removed by the depth cues we used.

Displays with shading cues were generated by simulating the 3D shapes with uniform reflectance of Lambertian surfaces. The 3D shapes were illuminated by a single light placed at the top and to the right of the shapes. Displays with line-junction cues were generated by adding 2D contours to the ambiguous line drawing of the 3D shapes. These additional 2D contours represent the back and hidden part of the 3D shapes and, therefore, indicate the whole structure of the shapes (see Pizlo, Sawada, Li, Kropatsch, & Steinman, 2010). The luminance values of the 2D contours were adjusted so that closer contours had higher luminance contrast, i.e., aerial perspective, in order to resolve the depth reversal ambiguity of the display.

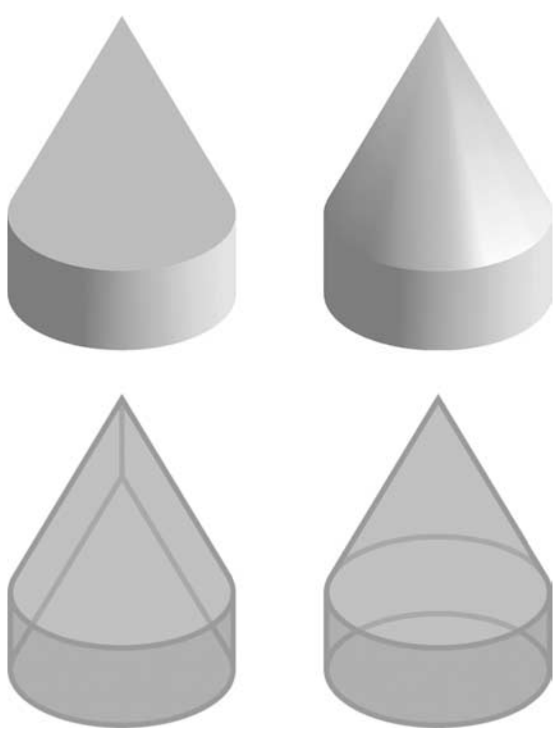

Figure 2. Shading and line-junction displays used in this study: (left) a slice of cake with a planar top and (right) a rocket with a conical point.

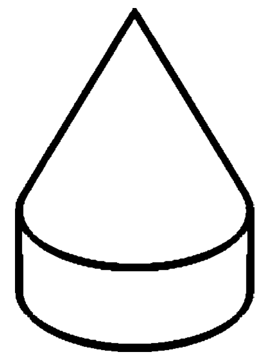

Figure 3. An ambiguous 2D line drawing of the 3D shapes used in this study. This line drawing is consistent with the visible parts of both the cake shape and the rocket shape viewed from a particular viewpoint (see Barrow & Tenenbaum, 1981). In this study, the ambiguity in the 3D interpretation of this line drawing was removed by the depth cues as in Figure 2.

If, with all of the above-mentioned improvements in methodology over Tsuruhara et al.'s (2009) study, we failed to demonstrate evidence of transfer, we would find ourselves in a difficult but familiar region of developmental science. It is logically impossible to prove the null hypothesis. That is, one cannot conclude that a particular ability is absent when experiments fail to provide evidence that infants possess that ability. However, additional studies can increase our understanding of the development of a skill. We can refine our methods to reduce variability, increasing the power of our studies, and we can employ control conditions that rule out alternative explanations. In the present study, we attempted to increase our capacity to detect whether 4- and 5-month-old infants create spatial representations from pictorial cues.

Experiment 1

Methods

Participants

The final sample in the experiment consisted of twenty-four 4- to 5-month-old infants (12 females and 12 males) and twenty-four 6- to 7-month-old infants (12 females and 12 males). The mean age of the younger group was 136.3 days (*SD* = 13.9 days) and that of the older group was 192.7 days (*SD* = 13.9 days). Data from an additional 10 infants were excluded based on their looking times: a combined looking time of less than 6 s in the two pre-test trials or in the two post-test trials (7), or longer combined looking times in the last three habituation trials than in the first three (3). Note that the looking times in the last three habituation trials were expected to be shorter than those in the first three habituation trials if the infants were habituated. An additional 11 infants did not complete the experiment because of fussiness. The participants were recruited using advertisements in newspapers. All participants were full term at birth and healthy at the time of testing.

Apparatus

Each infant sat on his or her parent's lap in front of a 22-inch CRT monitor (Mitsubishi DP2070SB), on which all stimuli were displayed. The distance from the center of the screen to each infant's eyes was maintained at approximately 40 cm. The infant and the monitor were located inside an enclosure, which was made of iron poles. A black cloth surrounded the monitor and the room was kept dark during the trials so that the edge of the screen was not clear. The width and height of the screen were 53.1 degrees and 41.1 degrees (respectively) of visual angle. The resolution of the screen was set at 1024 × 768 pixels. There were two loudspeakers, one on either side of the monitor. A CCD camera, located just below the monitor, was used to videotape the infant's behavior throughout the experiment. The experimenter observed the infant's behavior via a TV monitor connected to the camera.

Stimuli

See Figure 2 for images of our displays. Shading and line-junction cues were used to represent two types of 3D objects: a slice of cake with a planar top and a rocket with a conical point.

Two images were presented at the left and right edges of the screen and equidistant from the top and bottom of the screen. The distance from the center of the screen to the center of each image was 18.0 degrees of visual angle. The width and height of each image was 16.2 degrees and 24.3 degrees (respectively) of visual angle for both the shading and line-junction displays. Luminance of the background was 102.0 cd/m^2. Average luminance values of each image specified by the shading cue were 55.0 cd/m^2 for the cake and 55.2 cd/m^2 for the rocket. Average luminance values of each image specified by the line-junction cue were 55.1 cd/m^2 for the cake and 55.2 cd/m^2 for the rocket.

Procedure

We used a habituation–novelty preference procedure to test infants' ability to create representations of 3D shape from different pictorial cues. The transfer-across-cues method was used in which the cue specifying shape in the habituation trials was different from the cue that specified shape in the test trials. The pre- and post-habituation test phases were identical in every condition to compare each infant's preferential looking before and after the habituation. The combinations of shapes and cues are shown in Figure 4. For each age group, six infants were randomly assigned to each of four habituation groups: a slice of cake, specified by shading; a rocket, specified by shading; a slice of cake, specified by line junction; a rocket, specified by line junction.

The experiment consisted of three phases: the pre-test, the habituation, and the post-habituation test. First, infants were presented with two 10-s pre-test trials. Then, they viewed six 15-s habituation trials, which were immediately followed by two 10-s post-habituation test trials.

Prior to each trial, a black-and-white fixation figure, accompanied by a short sound, was presented at the center of the monitor. The fixation figure was one of three face-like figures, which was randomly changed across trials,

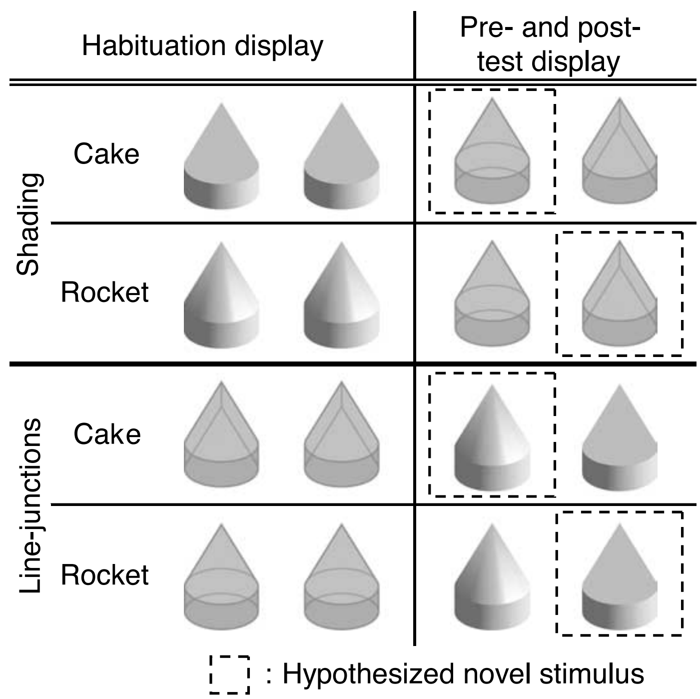

Figure 4. The four combinations of habituation display, pre- and post-habituation test displays, and hypothesized novel stimulus in Experiment 1. On habituation trials, the two identical shapes were presented at the left and right sides of the screen. In the pre- and post-habituation tests, a slice of cake shape and a rocket were presented at the left and right sides of the screen. The cues that specified the shapes were changed between habituation and test trials.

and the width and height of each fixation figure was 10.6 degrees of visual angle. When the infant looked at the fixation figure, the experimenter initiated the trial. In the pre-tests and the post-habituation tests, the fixation figure disappeared and a cake shape and a rocket shape were presented at the left and right sides of the screen. The positions of the two shapes were counterbalanced across participants on the first test trial and reversed on the second trial in both pre- and post-habituation tests. In these test trials, the presentation time of the displays was fixed. On habituation trials, the fixation figure disappeared and two identical habituation objects were presented, one on each side of the screen. Habituation trials were terminated if the infant looked away from the monitor for at least 2 s, or when the trials reached a 15-s maximum.

One observer, who was unaware of the stimulus identity, measured each infant's fixations to the left and right sides of the monitor from video recordings. Only the infant's looking behavior was visible in the video.

Results

Habituation trials

The individual looking times were averaged across the first three and the last three trials (Table 1). Before analyzing, we excluded infants who showed longer combined looking times in the last three habituation trials than in the first three. Histograms for each cell were examined and no obvious deviations from normality were observed.

To directly examine differences in the amount of habituation between the age groups and the types of cue and shape, a 2 × 2 × 2 × 2 ANOVA was performed for the looking times: (i) the trial (the first three and the last three) as a within-participants factor, (ii) the age of infants (4 to 5 months and 6 to 7 months) as a between-participants factor, (iii) the cue presented in the habituated displays (shading and line junction) as a between-participants factor, and (iv) the shape of the habituated displays (the cake and rocket) as a between-participants factor. The ANOVA revealed a significant decrease in looking times over trials [$F(1, 40) = 133.7$, $p < 0.01$]. The main effects of age, cue, and shape, and all interactions were not significant.

To make sure that the infants in each condition and in each age habituated to the displays, we conducted planned comparisons using multiple *t*-tests that were independent of each other. The *t*-tests compared looking times in the first three and in the last three habituation trials for each condition and each age. Under the hypothesis that looking times should decrease with habituation, the *t*-tests were one-tailed. This analysis demonstrated significant differences in all conditions and ages [older infants: shading and cake, $t(40) = 4.70$, $p < 0.01$; shading and rocket, $t(40) = 4.03$, $p < 0.01$; line junction and cake, $t(40) = 3.21$, $p < 0.01$; line junction and rocket, $t(40) = 4.35$, $p < 0.01$; younger infants: shading and cake, $t(40) = 3.42$, $p < 0.01$; shading and rocket, $t(40) = 3.87$, $p < 0.01$; line junction and cake, $t(40) = 4.98$, $p < 0.01$; line junction and rocket, $t(40) = 4.14$, $p < 0.01$]. The results showed that participants in each age group significantly habituated to every habituation display and that there were no significant differences in the decrease in looking time between the age groups and the types of cue and shape.

Test trials

The mean *looking times* during the pre-tests and the post-habituation tests are shown in Table 2. The looking times on the two pre-test trials were combined and the looking times on the two post-test trials were also combined. Before analyzing, we excluded the infants whose combined looking times were less than 6 s in the two pre-test trials or in the two post-test trials.

As an index to test whether infants looked longer at the novel shape, *a novelty preference score* was calculated for each infant in the pre-tests and the post-habituation tests. Hereafter "novel shape" in pre-tests indicates the shape that was not presented in the following habituation phase. This was done by dividing the infant's looking time to the novel shape by the total looking time. Figure 5 shows the mean preference scores. Histograms for each cell were examined and no obvious deviations from normality were observed.

To examine whether infants showed a novelty preference and whether there were differences of the novelty

Habituation trials		Age: 4–5 months First three	Age: 4–5 months Last three	Age: 6–7 months First three	Age: 6–7 months Last three
Habituated cue	Habituated shape				
Shading	Cake	17.1 (1.8)	11.3 (1.9)	16.4 (2.2)	8.5 (1.8)
	Rocket	17.4 (1.2)	10.8 (2.0)	16.6 (2.2)	9.8 (1.6)
Line junctions	Cake	19.9 (1.5)	11.5 (1.5)	17.6 (1.2)	12.2 (1.0)
	Rocket	15.4 (1.9)	8.4 (1.0)	20.8 (2.1)	13.5 (2.7)

Table 1. Mean looking time (seconds) and standard errors (in parentheses) during the habituation trials in Experiment 1.

Test trials		Age			
		4–5 months		6–7 months	
		Pre-test	Post-test	Pre-test	Post-test
Habituated cue	Habituated shape				
Shading	Cake	9.2 (0.2)	8.6 (1.1)	10.6 (1.4)	8.5 (0.8)
	Rocket	9.4 (0.6)	8.9 (0.7)	11.9 (1.4)	8.3 (0.7)
Line junctions	Cake	10.4 (0.7)	8.0 (0.8)	9.9 (1.0)	9.2 (1.0)
	Rocket	8.7 (0.9)	8.5 (0.6)	9.5 (1.1)	9.0 (0.9)

Table 2. Mean looking time (seconds) and standard errors (in parentheses) during the test trials in Experiment 1.

preference between age groups, cue, and shape types, a 2 × 2 × 2 × 2 ANOVA was performed: (i) the pre- and post-test differences (the pre-test and the post-test) as a within-participants factor, (ii) the age of infants (4 to 5 months and 6 to 7 months) as a between-participants factor, (iii) the cue presented in the habituated displays (shading and line junction) as a between-participants factor, and (iv) the shape of the habituated displays (the cake and rocket) as a between-participants factor. The ANOVA revealed a significant main effect of the pre- and post-test differences [$F(1, 40) = 11.8$, $p < 0.01$] and an interaction between the pre- and post-test differences and age [$F(1, 40) = 8.62$, $p < 0.01$]. Tests of simple main effects showed a significant difference in the pre- and post-tests for 6- to 7-month-old infants [$F(1, 40) = 20.3$, $p < 0.01$] but not 4- to 5-month-old infants. In other words, there was a significant difference in novelty preference between the pre- and post-tests for the 6- to 7-month-old infants but not the 4- to 5-month-old infants. Other main effects and interactions were not significant.

To directly explore the novelty preference in each condition and in each age, we conducted planned comparisons using multiple *t*-tests that were independent of each other. The *t*-tests compared the novelty preference scores in the pre- and post-tests for each condition and each age. Under the hypothesis that the preference scores should increase after habituation, the *t*-tests were one-tailed. This analysis showed that the older infants significantly increased in their novelty preferences in three out of four conditions and demonstrated a marginally significant change in the other condition [shading and cake, $t(40) = 2.62$, $p < 0.01$; shading and rocket, $t(40) = 2.68$, $p < 0.01$; line junction and cake, $t(40) = 1.52$, $p < 0.07$; line junction and rocket, $t(40) = 2.13$, $p < 0.02$]. In younger infants, no significant difference was found [shading and cake, $t(40) = 0.13$, *ns*; shading and rocket, $t(40) = 0.13$, *ns*; line junction and cake, $t(40) = 0.23$, *ns*; line junction and rocket, $t(40) = 0.49$, *ns*].

Discussion

In Experiment 1, we examined the transfer between two pictorial depth cues, shading and line junction, using a "transfer-across-depth-cues" method (Arterberry et al.,

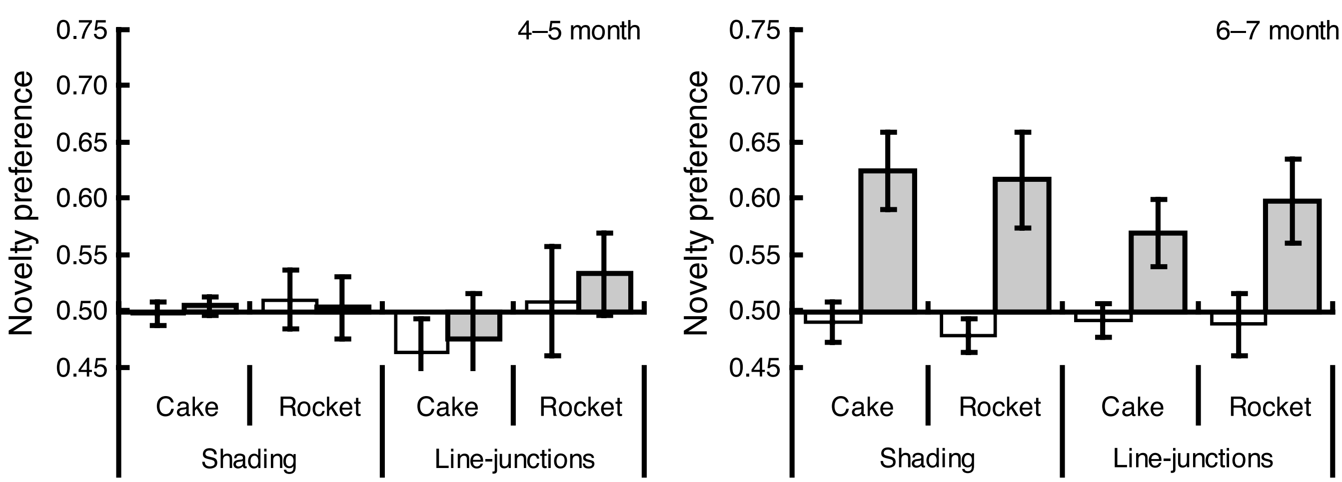

Figure 5. Mean novelty preference scores for each cue and shapes used in the habituation displays for each age group in Experiment 1. The left figure shows the results of the younger age group and the right figure shows the results of the older age group. A "Novelty preference" in the pre-test indicates "preference to the shape that was not presented in the following habituation phase." Error bars indicate standard errors.

1991; Yonas et al., 1987; Yonas & Pick, 1975). This method enabled us to investigate the development of infants' ability to represent a particular 3D shape from different pictorial depth cues. As summarized in Figure 5, 6- to 7-month-old infants showed a novelty preference despite the shift in the pictorial cue, while 4- to 5-month-old infants did not. In other words, the older group showed evidence of transfer between the shading cue and line junction. Though the novelty preference in older infants failed to reach significance in one out of four conditions, our results still present evidence of a common representation across different depth cues. Even if the transfer occurred from one cue to another but not in the opposite direction, there is no other explanation for the transfer except for a common representation across the cues. The results suggest that there is some improvement with age in the ability to generate and use a spatial representation from pictorial cues.

Another account, however, could explain the lack of evidence that 4- to 5-month-old infants transfer between the shading and line-junction cues. It is possible that the younger infants were unable to discriminate between the displays specified by each depth cue. In Experiment 2, we tested this possibility by using the same depth cue in both the habituation and test trials. If 4- to 5-month-old infants looked longer at the novel stimuli than at the habituated stimuli, it would indicate that they could discriminate between the two displays.

Experiment 2

Methods

Participants

The final sample in the experiment consisted of twenty-four 4- to 5-month-old infants (11 females and 13 males), with a mean age of 128.7 days (SD = 13.9 days). None of them had participated in Experiment 1. Data from an additional 7 infants were excluded based on their looking times: a combined looking time of less than 6 s in the two pre-test trials or in the two post-test trials (4), or longer combined looking times in the last three habituation trials than in the first three (3). An additional 7 infants did not complete the experiment because of fussiness.

Apparatus, stimuli, and procedure

The apparatus, stimuli, and procedure were the same as those in Experiment 1, except that in the both of the habituation and test trials, the same cue was used to specify shape. Six infants were randomly assigned to each of four habituation groups: a slice of cake, specified by shading; a rocket, specified by shading; a slice of cake, specified by line junction; and a rocket, specified by line junction.

Results

Habituation trials

The individual looking times were averaged across the first three and the last three habituation trials (Table 3). Before analyzing, we excluded infants who showed longer combined looking times in the last three habituation trials than in the first three. Histograms for each cell were examined and no obvious deviations from normality were observed.

To directly examine differences in the amount of habituation between the types of cue and shape, a 2 × 2 × 2 ANOVA was performed for the looking times: (i) the trial (the first three and the last three) as a within-participants factor, (ii) the cue presented in the habituated displays (shading and line junction) as a between-participants factor, and (iii) the shape of the habituated displays (the cake and rocket) as a between-participants factor. The ANOVA revealed a significant decrease in looking times over trials [$F(1, 20) = 69.5$, $p < 0.01$]. All other main effects and interactions were not significant.

To make sure that the infants in each condition habituated to the displays, we conducted planned comparisons using multiple t-tests that were independent of each other. The t-tests compared looking times in the first three and in the last three habituation trials for each condition. Under the hypothesis that the looking times should decrease with habituation, the t-tests were one-tailed. This analysis showed significant differences in all conditions [shading and cake, $t(20) = 3.38$, $p < 0.01$; shading and rocket, $t(20) = 3.83$, $p < 0.01$; line junction and cake, $t(20) = 4.15$, $p < 0.01$; line junction and rocket, $t(20) = 5.47$, $p < 0.01$]. The results indicate that participants significantly habituated to every habituation display and that there were no significant differences in the decrease in looking time between the types of cue and shape.

Test trials

The mean *looking times* during the pre-tests and the post-habituation tests are shown in Table 4. The looking times on the two pre-test trials were combined and the looking times on the two post-test trials were also combined. Before analyzing, we excluded the infants

Habituation trials		First three	Last three
Habituated cue	Habituated shape		
Shading	Cake	27.0 (2.7)	18.3 (3.9)
	Rocket	22.1 (2.0)	16.1 (1.6)
Line junctions	Cake	22.3 (3.8)	13.3 (3.5)
	Rocket	19.9 (4.2)	9.4 (1.1)

Table 3. Mean looking time (seconds) and standard errors (in parentheses) during the habituation trials in Experiment 2.

whose combined looking times were less than 6 s in the two pre-test trials or in the two post-test trials.

As an index to test whether infants looked longer at the novel shape, *a novelty preference score* was calculated for each infant in the pre-tests and the post-habituation tests, in the same way as in Experiment 1. Figure 6 shows the mean preference scores. Histograms for each cell were examined and no obvious deviations from normality were observed.

To examine whether the infants showed a novelty preference and whether there were any differences of the novelty preference between the cue and shape types, a 2 × 2 × 2 ANOVA was performed: (i) the pre- and post-test differences (the pre-test and the post-test) as a within-participants factor, (ii) the cue presented in the habituated displays (shading and line junction) as a between-participants factor, and (iii) the shape of the habituated displays (the cake and rocket) as a between-participants factor. The ANOVA revealed a significant main effect of the pre- and post-test differences [$F(1, 20) = 20.0$, $p < 0.01$]. The main effect of the cue and the interaction were not significant. The results indicate that the preference scores were significantly different between the pre-tests and the post-tests for both of the two cue types.

To directly explore the novelty preference in each condition, we conducted planned comparisons using multiple *t*-tests that were independent of each other. The *t*-tests compared the novelty preference scores in the pre- and post-tests for each condition. Under the hypothesis that the preference scores should increase after habituation, the *t*-tests were one-tailed. This analysis showed that the infants significantly increased in their novelty preferences in all conditions [shading and cake, $t(20) = 1.96$, $p < 0.04$; shading and rocket, $t(20) = 2.62$, $p < 0.01$; line junction and cake, $t(20) = 1.79$, $p < 0.05$; line junction and rocket, $t(20) = 2.75$, $p < 0.01$].

Discussion

The purpose of Experiment 2 was to examine whether 4- to 5-month-old infants could discriminate between the rocket and cake displays used in Experiment 1 when transfer across cues was not required. Infants were habituated to one of the shapes and then shown the same shape and the novel shape depicted with the same cue

Test trials		Pre-test	Post-test
Habituated cue	Habituated shape		
Shading	Cake	9.7 (2.7)	9.3 (3.9)
	Rocket	13.3 (2.0)	11.5 (1.6)
Line junctions	Cake	11.2 (3.8)	10.9 (3.5)
	Rocket	11.7 (4.2)	10.3 (1.1)

Table 4. Mean looking time (seconds) and standard errors (in parentheses) during the test trials in Experiment 2.

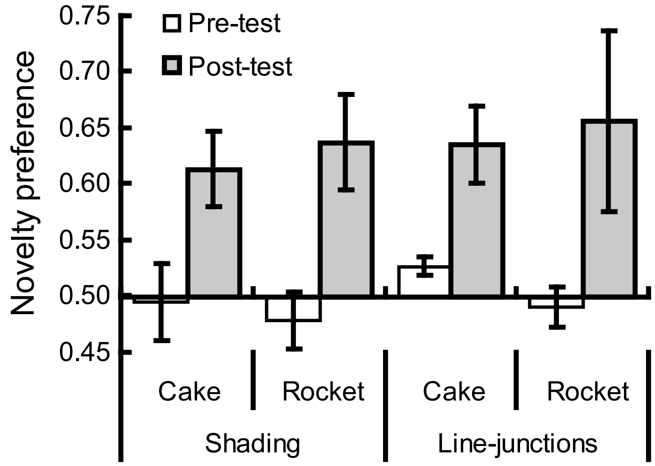

Figure 6. Mean novelty preference scores for each cue and shape used in the habituation displays in Experiment 2. Error bars indicate standard errors.

used in the habituation trials. Four- to five-month-old infants showed a novelty preference, demonstrating that they could discriminate between the two displays used in Experiment 1 when depicted by the same depth cue.

General discussion

The purpose of this study was to investigate the development of infants' ability to represent particular 3D objects from information provided by different pictorial depth cues. We applied a "transfer-across-depth-cues" method to examine the transfer between two pictorial cues, shading and line junctions, both of which adults use to perceive 3D shape. In the experimental trials, infants were first habituated to a shape specified by one cue. Following habituation, they were shown the same object and a novel object, both specified by another depth cue. If our participants looked longer at the novel shape than at the habituated shape, despite the shift in the pictorial cue, it would indicate that they could perceive 3D shape from both cues and that each cue was activating a common representation of spatial structure.

Infants aged 6 to 7 months showed a novelty preference despite the shift in the pictorial cue, while infants aged 4 to 5 months did not, as shown in Figure 5. In Experiment 2, it was confirmed that the absence of the transfer in young infants was not caused by their inability to discriminate between the displays. Instead, the difference between the two age groups suggests that there is a developmental change in ability to employ a common representation to transfer spatial information across pictorial depth cues. Though our results did not clearly demonstrate transfer for every cue and every shape in all directions, our results still suggest that 6- to 7-month-old infants have the ability to use a common representation across the different depth cues.

Even if the transfer occurred from one cue to another, but not in the opposite direction, there is no other explanation for the transfer except for a common representation across the cues.

The findings presented here are similar to those of Tsuruhara et al. (2009), which examined transfer across shading and surface-contour cues. In that study, the assumptions that light comes from above and that the viewer is looking at the surface from above were required to recover the specific 3D shape of surfaces that were identical except for a depth reversal. These assumptions were not required in this study, which used very different objects. Despite our efforts to make it easier to transfer information across cues, our 4- and 5-month-old participants did not show evidence of transfer. While one must be careful not to conclude the null hypothesis and while the results consist of the average tendencies for each age group, both the earlier work and ours support the notion that the development of the ability to create and use a spatial representation of a particular 3D shape develops at approximately 6 months of age. This developmental change does not seem to be specific to the particular pictorial cues used.

More specifically, our results suggest that processes additional to depth sensitivity are necessary for the transfer of shape from one pictorial cue to another and that one or more of these may grow stronger with development. One process that might be absent in young infants involves the ability to encode information into a representation from a particular depth cue. Or, even though young infants may be capable of creating spatial representations, they may not be able to access such from other pictorial cues. For example, they may be able to transfer shape from motion parallax to shading but not from shading to motion parallax. Previous studies have found evidence that young infants form an abstract representation of shape specified by motion-carried information (Arterbery & Yonas, 1988, 2000; Kellman, 1984; Kellman & Short, 1987; Owsley, 1983; Ruff, 1978; Yonas et al., 1987). Kavšek (2001) varied a viewer's station point between habituation and test and found that 9-month-old infants formed 3D representations of a box and a cylinder from line drawings, but 7-month-olds did not show evidence of this ability.

Another factor that could account for developmental change is that information may be less specific or decay more rapidly over time for younger infants (e.g., similar to the change in rate of decay observable in object permanence studies). Future research will be needed to test these possibilities and explore the development of the specific processes that account for the observed change with age.

To summarize what is known about the development of sensitivity to static monocular depth information: around 3 or 4 months, infants can detect variations in a display created by line junctions, shading, and linear perspective (e.g., Bertin & Bhatt, 2006; Bhatt & Bertin, 2001; Bhatt & Waters, 1998; Shuwairi, 2009; Shuwairi et al., 2007; Yonas & Granrud, 2007; Yonas et al., 2007). In these studies, the differences in the displays that influence looking preferences in infants are ones that adults experience as differences in 3D structure. Young infants may perceive these displays in the same way as adults, but we cannot be certain that that is the case.

Several studies that have investigated the ability of infants to perceive depth from pictorial cues have used preferential reaching to evaluate the perception of depth. Accurate reaching requires the pickup of information for spatial layout in all three axes of space. When binocular information is available, 4-month-old infants reach more often when an attractive object is placed within reach than when it is beyond reach. By 5 months, infants show a precise appreciation of the possibility of contact (Yonas & Hartman, 1993). Although there is a substantial increase from 5 to 7 months in the proportion of infants who demonstrate preferential reaching to the apparently closer part of a display, evidence suggests that 5-month-olds are sensitive to many pictorial depth cues (Kavšek et al., 2009). That infants do not reach for objects that are beyond reach suggests that they understand not only that a display has depth but also appreciate how close the object is to them.

The current study provides evidence that supports a notion that, at approximately 6 months, infants develop the ability to form a representation of shape that is the basis of transfer from one static monocular depth cue to another. This ability cannot function on the basis of proximal or low-level properties of the displays but must access an abstract spatial representation. One can speculate about physiological processes that may underlie the ability to form such representations. For example, it is possible that this developmental change may be mediated by the maturation of the ventral visual pathways (Goodale & Milner, 1992; Milner & Goodale, 1995; Mishkin, Ungerleider, & Macko, 1983; Ungerleider & Mishkin, 1982). Prior development of the dorsal pathway could allow infants to act in space, identify *where* an object is, and *how* to look at or reach for it. Later development of the ventral stream may make it possible for infants to create a viewpoint-independent representation of an object's 3D structure from static images and thus store *what* an object is so that all depth cues can access that representation. The current study suggests that this ability develops at approximately 6 months of age.

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