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Infants' discrimination of shapes from shading and cast shadows

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Abstract Shadows are powerful cues in the perception of shapes. We can perceive shading and cast shadow implicitly. We investigated infants' ability to detect a single discrepant figure that was depicted by shading or cast shadow and examined the influence of the contrast polarity of shadows on this process. In Experiment 1, we manipulated the blur direction of a shadow to create stimuli that appeared either to be partially shaded or to cast a shadow and then used a preference to test whether this difference would allow 5- to 8-month-old infants to discriminate the figures that adults were able to perceive as different shapes. Only 7- to-8-month-old infants could differentiate one shading figure from cast shadow figures, and vice versa. In Experiment 2, we reversed the contrast polarity of the figure (dark object with a light shadow) and tested whether discrimination was affected. As has been found with adults, infants exposed to this condition were unable to discriminate the contrast-reversed shading and cast shadow figures. Our results suggested that an age of around 7 months is important for development of the ability to perceive shape differences from shading and cast shadows.

Keywords Development · Shadows · Visual search

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We can perceive shading and cast shadow implicitly. Previous studies showed that 7-month-old infants can perceive depth from shading and cast shadows (Granrud, Yonas, & Opland, 1985; Yonas & Granrud, 2006). Previously, Elder, Trithart, Pintilie, and MacLean (2004) showed that adults can rapidly discriminate simple and similar figures that differ in shading and cast shadow in a visual-search task. However, the ability to discriminate between shading and cast shadow has not been explored in infants.

We investigated infants' perception of shading and cast shadow by using a task similar to visual search. In our experiments, we tested whether infants could differentiate one shaded figure from other cast shadow figures, and vice versa. Previous studies explored infants' perception by testing whether they could detect a single discrepant element from homogeneous elements (Bertin & Bhatt, 2006; Bhatt & Bertin, 2001; Bhatt & Waters, 1998; Shirai, Kanazawa, & Yamaguchi, 2005). Shirai et al. (2005) tested infants' sensitivity to expansion and contraction in a visual-search task. They showed that 8-month-old infants showed preference for the single expanding element in contraction displays; however, they did not find the reverse preference (i.e., to a single contracting element in expansion displays). These results suggest that 8-month-old infants can discriminate expansion from contractions. Bhatt and Waters (1998) used a task similar to visual search and found that infants could detect the orientation of cubes (upright or inverted) depicted by shading and line junction. Three-month-old infants showed preference for one upright cube in a display of inverted cubes versus an identical array with only inverted cubes (and vice versa). In their control experiments, they used figures that were not perceived as 3-D structures and found that infants did not show any preference for one differently oriented figure. Therefore, 3-month-old infants have a sensitivity to orientation of cubes depicted by shading and line junction. Bhatt and colleagues' later studies explored infants' sensitivity to the line-junction cue only and to the rotation of 3-D shapes (Bertin & Bhatt, 2006; Bhatt & Bertin, 2001). By using a task such as a visual search, in which a single discrepant element is distinguished from a set of homogeneous elements, previous studies have revealed that the expansion and the orientation change of displays that appear to have 3-D structure for adults can determine infants' looking preference. The visual-search task is also used to study cast-shadow perception (Elder et al., 2004; Porter, Tales, & Leonards, 2010; Rensink & Cavanagh, 2004). However, as far as we know, our study is the first to investigate cast-shadow perception in infancy with this visual-search–like task.

Cavanagh and Leclerc (1989) proposed two requirements for perceiving shape from shadows: (i) shadows should be darker than the nonshadow area, and (ii) the order of lightness along borders of shadows should be consistent. Both requirements point to the importance of the contrast relationship between the shadow and the nonshadow for perceiving shape using shadows. Our previous study showed that 7-month-old infants already utilize this second requirement (Sato, Kanazawa, & Yamaguchi, 2015). We examined infants' ability to detect the relationship between object shapes and cast shadows. Detection of incongruency between the object shapes and the cast-shadow shapes was tested. Results showed that 7- to 8-month-old infants could detect this incongruency, but they could not detect incongruency from figures in which a white outline had been added to the original cast shadow. This suggested that the order of lightness along borders of shadows is important for recognizing the relationship between objects and cast shadows for 7- to 8-month-old infants.

In the current study, we focused on Cavanagh and Leclerc's (1989) first requirement, that shadows be darker than nonshadow areas. According to this requirement, when the contrast polarity of the shadows and nonshadows is reversed, the perception of the shadows should collapse, and, consequently, the 3-D information should also collapse. In the domain of face perception, Otsuka, Hill, Kanazawa, Yamaguchi, and Spehar (2012) showed effects of contrast polarity on infants' perception. They found that 3- to 4-month-old infants preferred to view an upright two-tone face rather than an inverted two-tone face. However, when the contrast polarities of these face images were reversed, the infants did not show any significant preference. Furthermore, in an adult study, Elder et al. (2004) found that reversed contrast can also influence shadow perception. Using a visual-search task, they compared the performance of searching for a shadow (shading or cast shadow) in a shadow condition and a contrast-reversed condition. In the contrast-reversed condition, all figures were perceived as 2-D images, not 3-D objects (i.e., reverse contrast interfered with search performance). On the basis of these results, we speculate that shadow perception in infancy would also be affected by reversal of contrast polarity.

In the current study, we investigated whether infants would be sensitive to shading and cast shadows. Also, we examined whether contrast polarity could affect shadow perception in infancy. We conducted two experiments to test the hypothesis that if infants could discriminate different shapes from shading and cast shadows, they could differentiate one shaded figure from other cast-shadow figures, and vice versa. We used the familiarization-novelty method with 5- to 8-month-old infants in two experiments. In Experiment 2, by using contrast-reversed figures from Experiment 1, we were able to confirm whether infants' preferences were based on shadow perception. Because our previous study showed that 7-month-old infants can perceive incongruence of cast shadows but 5-month-old infants cannot (Sato et al., 2015), we chose to include infants between 5 and 7 months of age as participants.

Experiment 1

We investigated whether infants are sensitive to shading and cast shadows, typical visual cues used by adults for perceiving 3-D shapes. To explore this proposition, we examined whether infants could differentiate one shaded figure from other cast-shadow figures, and vice versa. With a task similar to visual search, we used simple shading and cast-shadow figures, following Elder et al. (2004).

Method

Participants Participants were 16 infants ages 5 to 6 months (10 males, mean age 159.86 days, range 143 to 186 days) and 16 infants ages 7 to 8 months (10 males, mean age 236.75 days, range 212 to 252 days). An additional six infants were tested in this experiment, but they were excluded from analysis due to fussiness (n = 5), or a side bias greater than 90 % (n = 1).

This study was approved by the Ethical Committee of Chuo University (2014-1). Written informed consent was obtained from the parents of the infant participants.

Apparatus Throughout the experiments, all stimuli were displayed on a 21-inch color CRT monitor. The infant and CRT monitor were stationed inside an enclosure made of plastic poles covered with black cloth. Each infant sat on the lap of his or her parent in front of a monitor. The distance between the infants and the monitor was approximately 40 cm. One speaker was positioned on each side of the CRT monitor. There was a small-aperture CCD camera just below the monitor screen. Throughout the experiment, the infant's behavior was recorded digitally through this camera. The experimenter could observe the infant's behavior via a monitor connected to the camera.

Stimuli We created the shading figure and the cast-shadow figure from a crescent by using Adobe Illustrator. The crescent was black (mean luminance = 0.76 cd/m^2) and the background of the crescent was midgray (mean luminance = 14.8 cd/m^2). In the shading figure (see Fig. 1, left), the inner arc of the crescent was 10.78 cm and the outer arc of the crescent was 13.11 cm. The inner arc of the crescent was blurred with a Gaussian filter (radius = 42 pixels). In the cast-shadow figure (see Fig. 1, right), the inner arc of the crescent was 11.15 cm and the outer arc of the crescent was 13.77 cm. The outer arc of the crescent was blurred with a Gaussian filter (radius = 30 pixels). Adults perceive an illusory shape of a ball in the left figure (shading) and an illusory shape of a disk in the right figure (cast shadow). The cast-shadow figure was 9.29 degrees in diameter, and the shading figure was 8.86 degrees in diameter.

Procedure We used the familiarization-novelty preference procedure and the experiment was comprised of three phases: the prefamiliarization test, the familiarization phase, and the postfamiliarization test. The familiarization phase lasted 15 s in each of six trials. Test phases were presented for 10 s in each of two trials. In each phase, a cartoon with a short sound was presented at the center of the monitor to get the infant's attention at the outset of each trial. The experimenter initiated the trial when the infant looked at the cartoon.

The computer screen was vertically divided into left and right sides, and four figures were presented on each side (see Fig. 2). During the familiarization phase, infants were familiarized with four shading figures or cast-shadow figures on both sides of the screen. During pre- and postfamiliarization phases, one nonfamiliarized figure and three familiarized figures were presented on the left or right side of the screen (target side), and four familiarized figures were presented on the other (nontarget) side. On the target side, one nonfamiliarized figure was presented in the upper right portion of the left presentation field or in the upper left portion of the right presentation field. The size of left and right presentation fields was about 33.92 × 33.92 degrees. Each presentation field was located 6.01 degrees from the center of the monitor. Half of infants were familiarized with the shading figures and the other half were familiarized with the cast-shadow figures. If the target side was left in the first trial, it was right in the second trial. The order of trials was counterbalanced across infants.

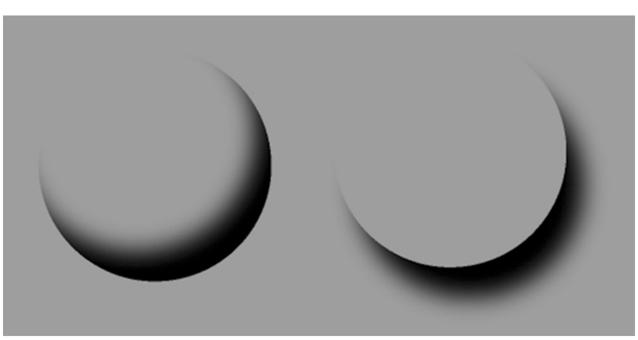

Fig. 1 Shading figure (left) and cast-shadow figure (right)

We reasoned that if infants could differentiate the single shading figure from the cast-shadow figures and vice versa, they would show a novelty preference for the target side after the familiarization phase.

Data coding One observer, who had no access to the stimuli the infants were viewing, measured each infant's looking time to the right or left presentation field from the video recordings. To calculate interobserver agreement, a second observer's measurement of the infants' looking time was obtained from 25 % of all trials. Interobserver agreements were $r = 0.90$ in the prefamiliarization test, $r = 0.97$ in the familiarization test, and $r = 0.93$ in the postfamiliarization test.

Results

Familiarization Trials

For the familiarization phase, individual looking times were averaged across the first three and the last three trials. The mean total looking times of each age group were 10.28 s for infants age 5 to 6 months, and 11.99 s for infants age 7 to 8 months in the first three familiarization trials. In the last three familiarization trials, the mean total looking time of each group was 9.32 s for infants age 5 to 6 months, and 10.13 s for infants age 7 to 8 months.

We performed a 2 × 2 × 2 ANOVA for the looking times, with (i) trial (the first three, the last three) as an intraparticipant factor, (ii) the type of familiarized figure (shading vs. cast shadow), and (iii) age group (younger group vs. older group) as interparticipant factors. The ANOVA revealed a significant main effect of trial, $F(1, 28) = 7.28$, $p < .01$, $\eta_p^2 = 0.20$, which reflects a decrease in looking times over the trials. No other effects were reliable, all *ns*, $p > .05$. These results showed that participants in each age group were familiarized with the shading and cast-shadow figures and that there was no significant difference in the decrease in looking times between age groups.

Test Trials

We calculated the preference score for the target side based on the looking times of each infant. The preference score was the ratio of the looking times for the target side to the total looking times for both the target side and the nontarget side. The preference scores were 51.43 % (SE = 2.47) in the prefamiliarization test and 48.58 % (SE = 4.37) in the postfamiliarization test for 5- to 6- month-old infants. For the 7- to 8-month-old infants, the preference scores were

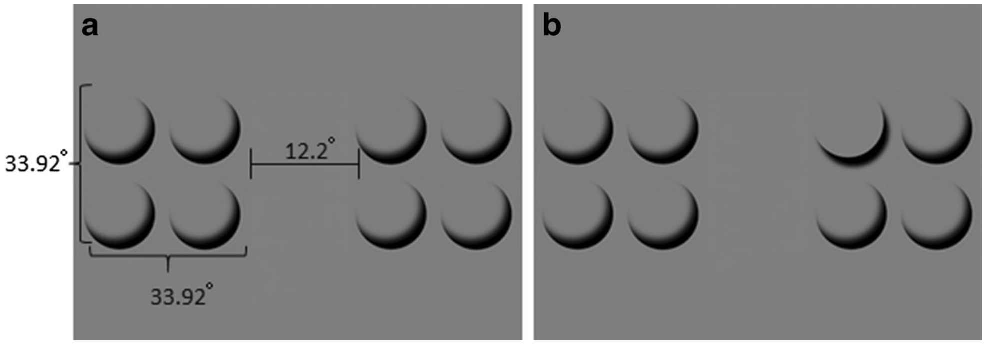

Fig. 2 (a) Example of the familiarization phase. The same four figures were presented in both the left and right presentation fields. (b) Example of the test phase. The nonfamiliarized figure was presented at upper right in the left presentation field or at upper left in the right presentation field (target side). The figures are not to scale

47.14 % (*SE* = 2.36) in the prefamiliarization test and 58.26 % (*SE* = 3.06) in the postfamiliarization test. The mean total looking times in the prefamiliarization test were 17.37 s for the younger group and 18.17 s for the older group. In the postfamiliarization test, the mean total looking times were 12.68 s for the younger infants and 14.41 s for the older infants.

To examine whether infants looked longer at the target side in the postfamiliarization test than in the prefamiliarization test, a 2 × 2 × 2 ANOVA was performed on preference scores, with (i) test (prefamiliarization test vs. postfamiliarization test) as a within-participants factor, (ii) age group (5 to 6 months vs. 7 to 8 months), and (iii) figure type of target (shading vs. cast shadow) as between-participants factors. The only statistically significant outcome was for the interaction of test and age, $F(1, 28) = 4.30$, $p = .047$, $\eta_p^2 = 0.13$ (all other *p*s > .05). To explore what drove this interaction, we performed post hoc analysis. The simple effects analyses showed that the preference scores of the 7- to 8-month-olds were significantly different between the postfamiliarization test and the prefamiliarization test, $F(1, 14) = 6.541$, $p = .02$, $\eta_p^2 = 0.32$. The 7- to 8-month-olds looked longer at the target side in the postfamiliarization test than in the prefamiliarization test. In contrast, the 5- to 6-month-old infants' looking times were not significantly different between the pre- and postfamiliarization tests, $F(1, 14) = 6.541$, $p = .51.$, $\eta_p^2 = 0.32$. The post hoc power analysis ($\alpha = .05$, $1 - \beta = 0.95$) was done using G-Power 3.1 (Faul, Erdfelder, Buchner, & Lang, 2009). No other effects were reliable ($p > .05$).

We also examined the preference for the target side in each age group and figure type by conducting a two-tailed *t* test versus chance (50 %). First, we tested the preference for the target side in each age group. In the postfamiliarization test, the 7- to 8-month-olds showed a significant preference for the target side, $t(15) = 2.72$, $p = .02$, $r = 0.58$, but the 5- to 6-month-old infants did not, $t(15) = 0.33$, *ns*, $r = 0.09$. In the prefamiliarization test, neither age group showed a significant preference for the target, 5–6 months: $t(15) = 0.58$, *ns*, $r = .15$; 7–8 months: $t(15) = 1.21$, *ns*, $r = .30$. Second, we tested the preference for the target side in each figure type. No significant preference was shown in the prefamiliarization test, shading group: $t(16) = 0.86$, *ns*, $r = 0.21$; cast-shadow group: $t(14) = 1.50$, *ns*, $r = 0.37$, or in the postfamiliarization test, shading group: $t(16) = 1.25$, *ns*, $r = 0.30$; cast-shadow group: $t(14) = 0.36$, *ns*, $r = .10$.

In Experiment 1, we found that only the 7- to 8-month-old infants showed the novelty preference for the target side, which included a nonfamiliarized figure; this group was the only one that could differentiate this unfamiliar shape from its familiar cohort shapes. In Experiment 2, we used contrast-reversed shadows, which violate Cavanagh and Leclerc's (1989) first requirement for perceiving shadows. The objective was to test whether contrast-reversed figures would interfere with the perception of shadows and render infants unable to discriminate these figures, as Elder et al. (2004) have documented in adult participants.

Experiment 2

In Experiment 2, we examined the possibility that infants could not discriminate contrast-reversed figures.

Method

Participants Participants were 16 infants age 7 to 8 months (9 males, mean age 226.0 days, range 165 to 253 days). An additional six infants were tested in this experiment but were excluded from analysis because of fussiness.

Stimuli To reduce the perceptual appearance of the shadows, we inverted the contrast polarity of shading and cast-shadow figures in Experiment 1 by using Adobe Photoshop (see Fig. 3). The background of the images was gray (luminance = 14.8 cd/m^2) and the crescents were white (luminance =

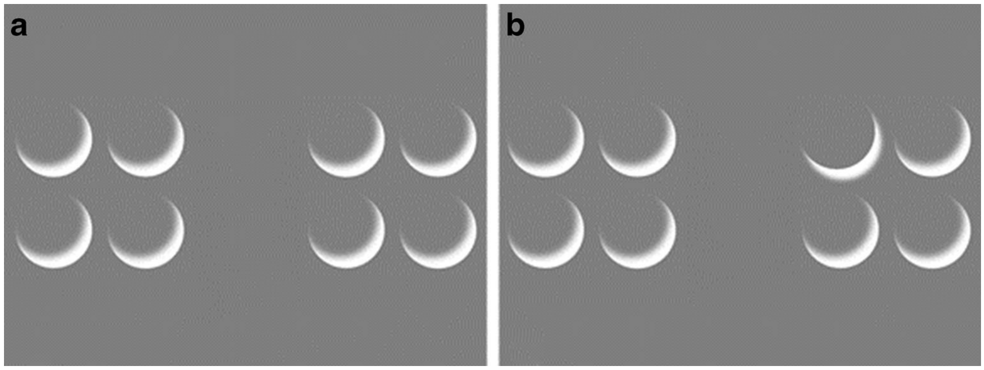

Fig. 3 (a) Example of the familiarization phase. The same four figures were presented in both the left and right presentation fields. (b) Example of the test phase. One nonfamiliarized figure was presented at upper right in the left presentation field or at upper left in the right presentation field (target side). The figures are not to scale

93.9 cd/m^2). The sizes of the presentation field and figures were the same as in Experiment 1.

Apparatus, data coding, and procedure The apparatus and procedure were the same as in Experiment 1. Interobserver agreement of Experiment 2 was r = 0.93 in the prefamiliarization test, r = 0.97 in the familiarization, and r = 0.95 in the postfamiliarization test.

Results

Familiarization trials For the familiarization phase, individual looking times were averaged across the first three and the last three trials. The mean total looking times of all participants were 12.01 s in the first three familiarization trials and 11.09 s in the last three familiarization trials.

We performed a two-way ANOVA on looking times, with (i) trial (first three, last three) as a within-participants factor, and (ii) the type of familiarized figure (shading, cast shadow) as an interparticipants factor. A significant main effect of trial emerged, $F(1, 14) = 43.12$, $p < .001$, $\eta_p^2 = 0.75$; looking times decreased over the trials. No other effects were reliable ($p > .05$). These results showed that participants were successfully familiarized with the shading and cast-shadow figures.

Test trials The mean total looking time was 16.56 s and 11.93 s in the prefamiliarization and postfamiliarization tests, respectively. The preference scores were 50.71 % (SE = 1.87) in the prefamiliarization test and 48.00 % (SE = 3.09) in the postfamiliarization test.

To examine whether infants looked longer at the target side in the postfamiliarization test than in the prefamiliarization test, a two-way ANOVA was performed on preference scores, with (i) test (prefamiliarization vs. postfamiliarization) as a within-participants factor and (ii) figure type (shading vs. cast shadow) as a between-participants factor. The ANOVA showed no significant difference in preference scores. These results indicate that 7- to 8-month-old infants could not discriminate the contrast-reversed shading and cast-shadow figures.

Again, we examined the preference for the target side using a two-tailed t test versus chance (50 %). First, we tested the preference for the target side in each figure type. No infants showed significant preference in the prefamiliarization test, shading group: $t(16) = 0.86$, ns, $r = 0.21$; cast-shadow group: $t(14) = 1.50$, ns, $r = 0.37$, or the postfamiliarization test, shading group: $t(16) = 1.25$, ns, $r = 0.30$; cast-shadow group: $t(14) = 0.36$, ns, $r = .10$. Second, we tested all infants' preference for the target side, and there was no significant preference in the in the prefamiliarization test, shading group: $t(16) = 0.86$, ns, $r = 0.21$; cast-shadow group: $t(14) = 1.50$, ns, $r = 0.37$, or in the postfamiliarization test, shading group: $t(16) = 1.25$, ns, $r = 0.30$; cast-shadow group: $t(14) = 0.36$, ns, $r = .10$.

In the pre- and postfamiliarization tests, infants showed no significant preference for target, prefamiliarization: $t(15) = 0.38$, ns, $r = .10$; postfamiliarization: $t(15) = 0.65$, ns, $r = .17$.

Additionally, we examined whether a significant difference existed in the preference for the incongruent figure across the two experiments. A three-way ANOVA was performed with test (prefamiliarization test, postfamiliarization test) as a within-participants Factor × Experiment (Experiment 1, Experiment 2) as a between-participants Factor × Target Type (shading, cast shadow), as a between-participants factor. In this analysis, we used the preference scores of 7- to 8-month-old infants from both experiments because only 7- to 8-month-old infants participated in Experiment 2. The ANOVA indicated a significant two-way interaction of Experiment × Test, $F(1, 63) = 5.05$, $p = .03$, $\eta_p^2 = 0.15$. The simple-effect analysis showed that preference scores in the postfamiliarization test were significantly different between Experiment 1 and Experiment 2: $F(1, 28) = 4.66$, $p = .04$, $\eta_p^2 = 0.14$. Also, preference scores in Experiment 1 were significantly different between the prefamiliarization test and the postfamiliarization test, $F(1, 14) = 4.77$, $p = .046$, $\eta_p^2 = 0.25$. No other effects were reliable: all ns, $p > .05$. These results indicated that 7- to 8-month-old infants could discriminate the shading and cast-shadow figures but not the contrast-reversed figures.

Discussion

In this study, we explored whether infants have sensitivities to shading and cast shadows. We also confirmed that contrast polarity plays an important role in infants' perception of shadows.

Our Experiment 1 data showed that only 7- to 8-month-old infants could differentiate a shaded figure from one with a cast shadow (and vice versa) when the shadows were darker than the background. In Experiment 2, when the contrast polarity of figures in Experiment 1 was reversed, infants could not discriminate these figures. Taken together, our results suggest that 7- to 8-month-old infants but not 5- to 6-month-old infants can discriminate between different visual cues such as shading and cast shadow.

Some of our findings were new. First, we revealed that 7- to 8-month-old infants showed a preference for a pattern that contained a single different shape depicted by shading or cast shadow. This preference for a pattern with a discrepant element has been shown in previous studies where orientation was depicted by shading. In Bhatt and his colleagues and Shirai et al. (2005), infants showed a preference for patterns of shapes that contained a single item in a discrepant orientation. In this study, our results revealed that infants could detect a shading from cast shadows, and vice versa. These results reflect the infants' ability to discriminate shapes from a shading and a cast shadow, which were perceived as different 3-D shapes by adults. However, we must limit the interpretation of our results; that is, they did not directly confirm that 5- to 6-month old infants cannot perceive shading and cast shadow. There is a possibility that extending the familiarization time would increase the performance of 5- to 6-month-old infants.

Many previous studies have explored infants' perception of 3-D shapes, and these have suggested that infants as young as 7 months could perceive 3-D shapes from pictorial depth cues. Yonas and colleague reported that 7-month-old infants could perceive depth from shading (Granrud et al., 1985) and from cast shadows (Yonas & Granrud, 2006) but that 5-month-old infants could not. They documented that 7-month-old infants preferred to reach for the object that was perceived from shadings or cast shadows as being nearer. Additionally, a previous study used looking behavior to show that 6- to 7-month-old infants can represent 3-D shapes from pictorial depth cues (i.e., shadings; Tsuruhara et al., 2010; Tsuruhara, Sawada, Kanazawa, Yamaguchi, & Yonas, 2009). Tsuruhara and her colleagues used a transfer-across-cue paradigm to test infants' ability to represent 3-D shapes. They discovered that after familiarizing themselves with a 3-D shape with some pictorial depth cues (shading, texture, and line junction), 6- to 7-month-old infants could identify the 3-D shapes depicted by those cues, but 4- to 5-month-old infants could not. These studies converge on the conclusion that around 7 months is an important developmental period for perceiving 3-D shapes using 2-D depth cues. Our results showed that 7- to 8-month-old infants could discriminate a shading from a cast shadow; however, the results do not directory indicate that the infants perceived 3-D shapes from the shadows. To clarify such an open question, additional experiments (i.e., transfer-across-cues experiments, as in previous studies) are needed.

Our results suggest that contrast polarity of shadows was important for perceiving the shadows. With contrast-reversed figures, infants could not differentiate shape on the basis of shadows. In fact, in Experiment 2, 7- to 8-month-old infants could not perceive shapes from the contrast-reversed shading and cast-shadow figures from Experiment 1. The importance of contrast polarity on the perception of shadows (and the perception of shapes from shadows) had already been revealed by Cavanagh and Leclerc (1989), who argued that adults' perception of shadows conforms to the two following requirements: (i) shadows must be darker than the nonshadow area (i.e., the background of the shadows), and (ii) the order of lightness along the borders of shadows should be consistent. Only a few studies have sought to determine when infants begin to utilize cues according to these two requirements. Our previous study revealed that infants as young as 7 months already utilize the second requirement (Sato et al., 2015), but this result in the present study showed that the contrast polarity along the shadow border plays an important role in 7- to 8-month-old infants' perception of cast shadows. As far as we know, the first requirement (that shadows be darker than nonshadow backgrounds) has not previously been explored with infants. Our study revealed that infants could use the first requirement.

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