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Infants' Perception of Transparency

Scott P. Johnson
Cornell University

Richard N. Aslin
University of Rochester

Four- and 7-month-old infants' perception of transparency was investigated with computer-generated achromatic or color displays depicting a semitransparent box occluding the center of a rod. Following habituation, infants viewed test displays consisting of either a two-color rod (corresponding to the habituation display's proximal characteristics) or a solid rod (corresponding to the distal characteristics of the event depicted by the habituation display). Looking-time results from 4-month-olds suggested perception of transparency in color displays but not in an achromatic display. An additional condition indicated that transparency perception may rely on the visibility of background texture through the transparent surface. Seven-month-olds, in contrast, provided some evidence of transparency perception in the achromatic display. Implications for the development of infants' responses to object properties and perceptual segregation are discussed.

A central task of vision is to segment the optic array, with the goal of obtaining veridical perception of objects and surfaces at various distances. This process is challenged by the fact that many objects are only partially visible, being partly occluded by other, nearer objects or surfaces. Yet perception of bounded, coherent, segregated objects under conditions of partial occlusion seems to pose little difficulty for the mature visual system.

Research on the development of these skills has revealed that veridical surface segregation in occlusion displays (i.e., responding to partly occluded objects as consisting of both visible and occluded parts) is often accomplished by even very young infants (Johnson, 2000). Some studies have focused on the specific visual information used by young infants to perceive the continuation and connectedness of two visible object parts behind a nearer, occluding object. For example, Kellman and Spelke (1983) found that 4-month-olds perceived the unity of a center-occluded rod when the two visible parts of the rod, above and below an occluding box, underwent common translatory motion. Their method capitalized on the tendency of young infants to prefer novel displays over familiar displays following a period of habituation to a single stimulus (Bornstein, 1985; Spelke, 1985). After habituation to the rod-and-box display, the infants in the Kellman and Spelke study viewed test displays consisting of a complete rod and a "broken" rod, the previously visible parts of which appeared with a gap between them. Both test displays were consistent with the visible portions of the rod in the habituation display, but the infants looked longer at the broken rod. Control experiments provided evidence that infants had no inherent preference for a broken rod relative to a complete rod (see Kellman & Spelke, 1983).

Further experiments revealed that 4-month-olds perceived object unity when the rod parts moved vertically or in depth, or when a rod part moved conjointly with a dissimilar surface, but not when the rod was stationary (Kellman & Spelke, 1983; Kellman, Spelke, & Short, 1986). These results led to the conclusion that young infants rely on motion to segregate surfaces, to the exclusion of other potential information such as edge and surface configuration and surface appearance (see Kellman, 1996). More recent research has revealed, however, that young infants exploit a variety of visual cues in addition to motion in order to segregate surfaces in partial occlusion displays. For example, we previously reported (Johnson & Aslin, 1996) that 4-month-olds appeared to use accretion and deletion of background texture (a depth cue) and edge orientation to perceive object unity.

In the present experiments we continued this line of inquiry by exploring infants' perception of transparency. Our goals were (a) to investigate the visual information that infants use to segregate a semitransparent surface from an occluded opaque surface and background and (b) to reveal developmental changes in sensitivity to this information. Research with adults has identified the conditions under which perception of transparency will be reliably supported. First, there must be at least three surface layers in the scene: a background, an opaque surface against the background, and a transparent layer over both of these surfaces (Metelli, 1974). Second, there must be an *X-junction* (see Figure 1) at the intersection of the three layers, and the luminances and/or colors of the visible regions across this junction must satisfy certain constraints (Anderson, 1997; Beck, Prazdny, & Ivry, 1984; D'Zmura, Colantoni, Knoblauch, & Laget, 1997; Metelli, 1974; but see Watanabe & Cavanaugh, 1993). Perceptual *scission*, or decomposition of the scene into its constituent layers, often obtains when these conditions have been met.

Scott P. Johnson, Department of Psychology, Cornell University; Richard N. Aslin, Center for Visual Science and Department of Brain and Cognitive Sciences, University of Rochester.

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Correspondence concerning this article should be addressed to Scott P. Johnson, Department of Psychology, Uris Hall, Cornell University, Ithaca, New York 14853. Electronic mail may be sent to sj75@cornell.edu.

Transparency perception in adults is remarkably robust. Perceptual scission and shape recognition in transparency displays have been found to occur for adults after only 60 ms of exposure (Watanabe & Cavanaugh, 1992), implying that transparency is

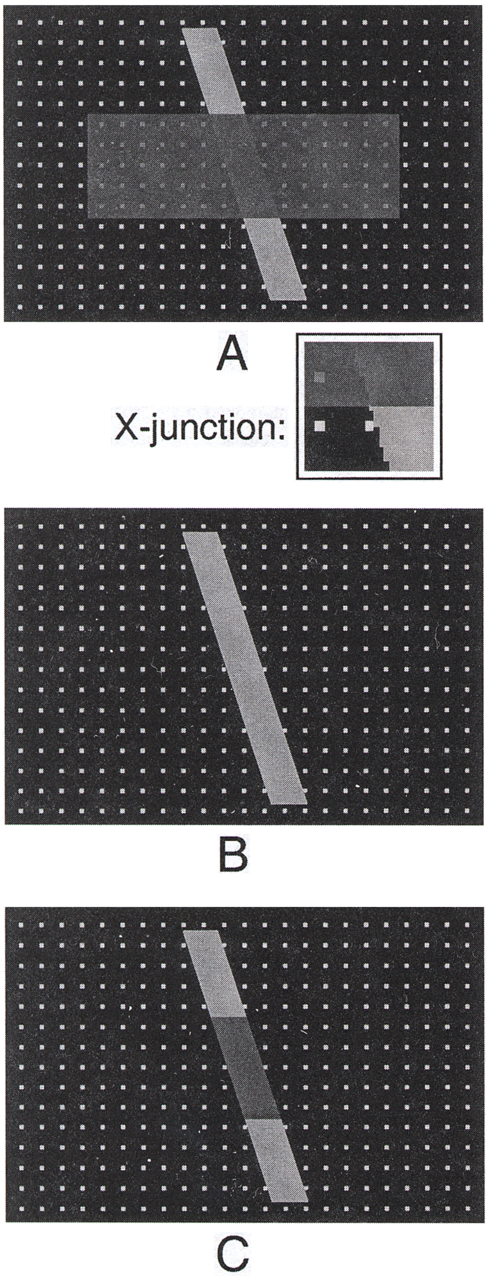

Figure 1. A: The gray rod transparency display shown to the infants in Experiments 1 and 4. The rod and box surfaces underwent out-of-phase translatory motion. This display, and the color displays depicted in Figure 2, provided a convincing appearance of transparency for adults. See text for details. Inset: A close-up of an X-junction in the transparency display. Note that across the junction, say from right to left, the luminance ratios are maintained (i.e., the background appears dark to the left of the rod both uncovered and covered by the transparent box). B: Solid rod. C: Two-color rod.

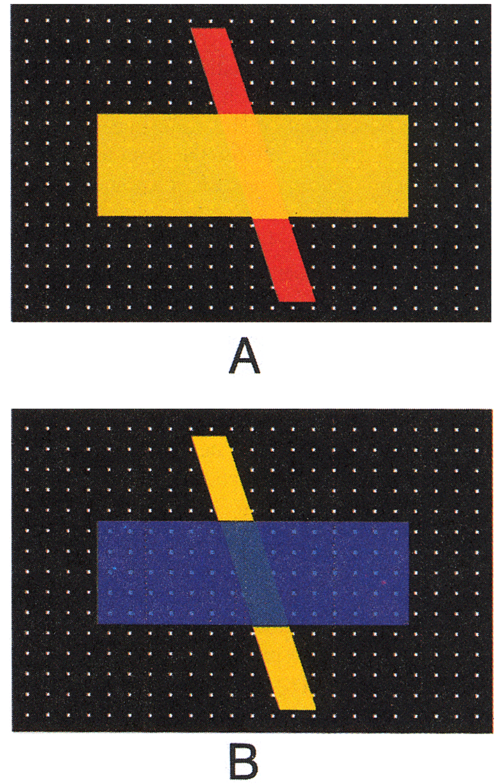

Figure 2. The red rod and yellow rod shown to the infants in Experiment 1. These displays were similar to the gray rod display except for the colors of the rods, the boxes, the rod–box intersections, and the background dots "behind" the boxes.

represented relatively early in the cortical processing stream (Nakayama, He, & Shimojo, 1996; Sajda & Finkel, 1995). Scission can occur even if there is no actual transparency in the display, as Metelli (1974) demonstrated with suitable colors of opaque paper cut into precise shapes (forming X-junctions). Scission can also be achieved with computer-generated displays depicting apparently transparent surfaces that cannot be physically realized with real objects (D'Zmura et al., 1997).

We investigated transparency perception in young infants with displays depicting two surfaces in front of a background (see Figure 1A). In each display, a transparent rectangular box overlapped the center of a rod, whose uncovered ends protruded above and below the box. (We use the term *transparent* throughout this article, but the box surfaces were actually semitransparent, appearing to be tinted.) The rod and box moved laterally, out of phase with each other. These displays provided a convincing appearance of transparency to adults.[1] In Experiment 1, we habituated three groups of 4-month-olds to transparency displays that were either achromatic (see Figure 1A) or colored (see Figure 2). Following habituation, the infants were presented with two test displays. One

[1] Ten undergraduates were shown the three transparency displays from Experiment 1. All reported spontaneously, and without instruction, that each display appeared to consist of a transparent object (i.e., the box) in front of an opaque object with a solid surface (the rod).

consisted of a single-luminance or single-color (*solid*) rod (see Figure 1B), its entire surface corresponding to the surface of the protruding rod ends in the habituation display. The second test display consisted of a rod in which the luminance or color of its center portion corresponded to the luminance or color of the central rod portion overlapped by the box in the habituation display, and the luminance or color of its top and bottom portions corresponded to the luminance or color of the protruding ends of the rod in the habituation display (*two-color* rod; see Figure 1C). We reasoned that if the infants perceived transparency, they would perceive a solid rod behind the box and would subsequently look longer at the two-color rod because it would be relatively novel compared with the habituation stimulus and the solid rod. On the other hand, if the infants did not perceive transparency but rather responded only to the physical properties of the displays, they should prefer the solid rod because the two-color rod more closely resembled the appearance of the rod in the habituation display. Experiment 2 consisted of several control conditions designed to rule out alternative explanations for the results of Experiment 1. In Experiment 3, we explored the role of texture cues in 4-month-olds' perception of transparency with a condition in which background texture elements were not visible through the box surface. Finally, in Experiment 4, we probed 7-month-olds' perception of transparency. Taken together, the results suggest a gradual emergence of veridical responses to transparency over the first several postnatal months.

Experiment 1

Method

Participants. Forty-eight full-term infants (26 girls) composed the final sample (mean age = 122 days, range = 106–141 days). An additional 5 infants were observed but not included in the sample because of excessive fussiness (3 infants) or sleepiness (2 infants). The infants were recruited by telephone from hospital records, birth announcements in the local newspaper, or hospital visits. The majority of the infants were from Caucasian, middle-class families. Parents were paid a nominal sum for their participation.

Apparatus and stimuli. An Amiga 3000 computer and an 80-cm color monitor were used to generate the displays. Two observers viewed the infant through small peepholes cut into either side of a black panel that extended 47 cm from the sides of the monitor.

The computer presented the stimulus displays, stored each observer's data, calculated the habituation criterion for each infant, and changed displays after the criterion was met. The computer also recorded how long the infant looked at each display according to the observers' judgments. These judgments were entered via two hand-held microswitches connected to the computer's mouse port. The displays were not visible from the observers' vantage points. One observer had never been allowed to view the displays and was naive to the hypotheses under investigation.

There were three transparency displays shown during habituation, one display to each of three separate groups of 16 infants: a gray rod (GR; see Figure 1A), a red rod (RR; see Figure 2A), and a yellow rod (YR; see Figure 2B). Each display consisted of a 3.2 × 27.9 cm (1.5° × 12.6°) of visual angle) light gray, red, or yellow rod oriented 15° counterclockwise from the vertical and a 10.2 × 27.9 cm (4.7° × 12.6° of visual angle) dark gray, yellow, or blue box. The intersection of the rod and box was either an intermediate gray (GR display), orange (RR display), or turquoise green (YR display). A 4-s animation (30 frames per second), run as a loop, depicted the rod and box undergoing out-of-phase lateral translation, with each surface moving 24.8 cm (11.2°) across the screen at a rate of 6.2 cm/s (2.8°/s). The rod and box were presented against a black background on which a 15 × 23 grid of white dots, serving as texture elements, was superimposed. The dots appeared to be visible through the box, becoming darker or colored when "covered," and white again when "uncovered," by the box. The dots were completely occluded and disoccluded by the rod.[2]

The two-color test displays were identical to the rod portion of the habituation displays except for the absence of the box (i.e., rods with either a light gray top and bottom and an intermediate gray center, a red top and bottom with an orange center, or a yellow top and bottom with a turquoise green center; see Figure 1C). The solid test displays consisted of rods whose entire surface was light gray, red, or yellow (see Figure 1B). Test display rods moved laterally against a dot background, occluding and disoccluding the background dots, as in the habituation displays.

Procedure. Each infant was placed in an infant seat approximately 125 cm from the display monitor. The GR, RR, or YR display was presented until each infant met the habituation criterion, defined according to the common infant-control procedure (Horowitz, Paden, Bhana, & Self, 1972) as a decline in looking time during three consecutive trials adding up to less than half the total looking time during the first three trials. Timing of each trial began when the infant fixated the screen after display onset. Each observer independently indicated how long the infant looked at the display by pressing a separate microswitch as long as the infant fixated the screen and releasing it when the infant looked away. An individual trial was terminated when both observers released their microswitches for 2 overlapping seconds. At this point, the screen was turned off by the computer, and the next display appeared 2 s later. When looking times to the habituation display declined to criterion, the computer changed from habituation to test displays on the subsequent test trials. The two test displays (solid rod and two-color rod) were seen three times each in alternation, for a total of six posthabituation trials. The order of test display presentation was counterbalanced.

Results and Discussion

Looking times were calculated by averaging the two observers' judgments for each test trial. Interobserver agreement was high (mean Pearson r = .98 across all experiments reported in the present article). Because some of the cells were characterized by positively skewed distributions, data were log-transformed prior to parametric analyses (the data in Table 1 represent raw scores). In addition, nonparametric analyses were performed on raw data (we used Wilcoxon signed rank tests on individual conditions and Mann–Whitney tests on comparisons across conditions, which

[2] The displays were prepared with Deluxe Paint software. The color and luminance of individual regions of the display were determined by R, G, and B (red, green, and blue) controls, each with settings from 0 to 15. For all displays, the black background settings were [0, 0, 0 (values of the R, G, and B controls, respectively)] with luminance of 0.4 cd/m^2 and Uniform Chromaticity Scale values of u′ = .04 and v′ = .48; the white background dot settings were [15, 15, 15], 49.1 cd/m^2, u′ = .19, v′ = .47. For the GR display, the settings were as follows: box, [6, 6, 6], 8.5 cd/m^2, u′ = .16, v′ = .47; dots seen through the box, [12, 12, 12], 31.6 cd/m^2, u′ = .18, v′ = .47; rod, [11, 11, 11], 26.7 cd/m^2, u′ = .18, v′ = .47; rod center seen through the box, [9, 9, 9], 17.7 cd/m^2, u′ = .15, v′ = .47. For the RR display, the settings were as follows: box, [11, 11, 0], 24.4 cd/m^2, u′ = .17, v′ = .56; dots seen through the box, [13, 13, 0], 34.1 cd/m^2, u′ = .18, v′ = .56; rod, [15, 0, 0], 9.8 cd/m^2, u′ = .38, v′ = .54; rod center seen through the box, [14, 11, 0], 28.0 cd/m^2, u′ = .20, v′ = .56. For the YR display, the settings were as follows: box, [6, 5, 15], 9.8 cd/m^2, u′ = .16, v′ = .29; dots seen through the box, [10, 10, 15], 24.0 cd/m^2, u′ = .17, v′ = .40; rod, [12, 13, 0], 33.0 cd/m^2, u′ = .17, v′ = .56; rod center seen through the box, [0, 10, 11], 17.3 cd/m^2, u′ = .11, v′ = .44.

Table 1
Means of Infants' Looking Times (in Seconds) During the Last Habituation Trial and Test Trials

Experiment and habituation display	Last habituation trial		Two-color rod		Solid rod	
Experiment 1						
Gray rod	8.41	(1.93)	12.51	(2.42)	12.45	(2.02)
Red rod	7.17	(1.68)	17.39*	(5.57)	9.08	(2.14)
Yellow rod	9.22	(2.68)	18.89*	(2.70)	12.48	(2.49)
Experiment 2						
Red rod, control	12.67	(2.89)	11.58	(2.60)	15.20	(4.09)
Yellow rod, control	8.67	(1.65)	11.18	(2.58)	11.01	(2.27)
Experiment 3						
Yellow rod, no texture	8.78	(1.38)	10.99	(1.71)	16.52**	(2.37)
Experiment 4						
Gray rod, older infants	4.92	(0.66)	14.56*	(2.17)	9.20	(1.53)

Note. Numbers represent raw scores. (Analyses reported in the text were computed on log-transformed scores.) Standard errors are shown in parentheses.
* Significantly greater looking than both on the last habituation trial and at the solid rod, $ps < .05$.
** Significantly greater looking than both on the last habituation trial and at the two-color rod, $ps < .05$.

incorporate information about both the direction and the magnitude of individual differences in test display preference).

As can be seen in Table 1, the infants in the GR group did not exhibit a strong preference for either test display (7 of the 16 infants looked longer at the two-color rod, $z = 0.26$, *ns*). In contrast, infants in the RR group looked longer at the two-color rod test display (12 of the 16 infants looked longer at the two-color rod, $z = 2.48$, $p < .05$, a significant difference relative to the GR group, $z = 2.19$, $p < .05$). Infants in the YR group also looked longer at the two-color rod test display (12 of the 16 infants looked longer at the two-color rod, $z = 2.28$, $p < .05$, a significant difference relative to the GR group, $z = 2.00$, $p < .05$). This conclusion was confirmed by the parametric analyses. A 3 (group: GR, RR, or YR habituation display) × 2 (order: two-color vs. solid rod first after habituation) × 2 (display: solid vs. two-color rod) × 3 (trial: first, second, or third block of test trials) analysis of variance (ANOVA) yielded significant main effects of order, $F(1, 42) = 5.97$, $p < .05$, resulting from longer looking overall by infants who first viewed the solid rod (the reasons for this effect are unclear), and of display, $F(1, 42) = 11.82$, $p < .01$, the result of longer looking overall at the two-color rods. There was also a significant Group × Trial interaction, $F(4, 84) = 3.42$, $p < .05$, that was due to a decline in looking times across trials by infants in the GR and RR groups along with a slight increase in looking by infants in the YR group. More important, the Group × Display interaction was significant, $F(2, 42) = 3.50$, $p < .05$. Analyses of simple effects revealed significantly longer looking at the two-color rod by infants in both the RR group, $F(1, 42) = 5.73$, $p < .05$, and the YR group, $F(1, 42) = 13.10$, $p < .001$. In contrast, infants in the GR group did not exhibit a significant looking-time preference during test, $F(1, 42) = 0.003$, *ns*.

Analyses were also conducted on the infants' recovery of looking at the two test displays relative to looking times during the last habituation trial (see Table 1).[3] Infants in the GR group did not recover interest to either the two-color or the solid test display, $ts(15) = 1.35$ and 1.54, respectively, *ns*. Infants in the RR group recovered interest to the two-color rod, $t(15) = 4.10$, $p < .01$, but not to the solid rod, $t(15) = 1.66$, *ns*. Likewise, infants in the YR group recovered interest to the two-color rod, $t(15) = 3.75$, $p < .01$, but not to the solid rod, $t(15) = 1.42$, *ns*.

These results begin to provide evidence that the infants who viewed the RR and YR displays perceived a transparent, colored surface (the box) that partly occluded an opaque surface (the rod) and a background. In contrast, the infants did not appear to perceive transparency in the GR display. Possible accounts for this discrepancy are considered in Experiment 4 and the General Discussion.

Experiment 2

An alternative interpretation of the results of Experiment 1 is that the infants looked longer at the two-color displays for some reason unrelated to perception of transparency, perhaps because the two-color test rods were inherently more interesting than the solid test rods. This possibility was addressed in Experiment 2, in which 4-month-olds were habituated to rod-and-box displays that were identical to the RR and YR displays except for the color of the rod–box intersection. In the RR/C and YR/C (red rod / control and yellow rod / control) habituation displays, the intersections were colored blue and red, respectively, which abolished adults' percept of a transparent box overlapping an opaque rod.[4] After habituation to one of these displays, the infants in Experiment 2 were presented with the same two-color and solid rod test displays viewed by the infants in Experiment 1.

[3] The recovery analyses should be interpreted with caution, because habituation was defined according to a criterion and we had no measure of spontaneous recovery (i.e., some of the infants might have met the criterion by chance). Nevertheless, the recovery analyses are consistent with the suggestion that the infants generalized habituation to the solid rods in the color displays and perceived the two-color rods as relatively novel.

[4] When shown the control displays from Experiment 2, 8 of 10 adult participants reported that a rod consisting of three colored sections appeared in front of the box in both displays, and 2 participants reported that they were unsure about the depth ordering or the appearance of the rod in the displays. None of the adults reported that the box appeared as a transparent surface in front of an opaque, solid rod.

Method

Participants. Thirty-two full-term infants (10 girls) composed the final sample (mean age = 122 days, range = 102–139 days). An additional 4 infants were observed but not included in the sample because of excessive fussiness. The infants were recruited from the same participant pool as in Experiment 1.

Apparatus, stimuli, and procedure. The apparatus and procedure were identical to those used in Experiment 1. The stimuli were identical as well except that infants in the RR/C group were habituated to a rod-and-box display in which the intersection of the rod and box was colored blue and infants in the YR/C group were habituated to a display in which the intersection was red.[5] Following habituation, the infants in the RR/C and YR/C groups viewed the same (solid rod and two-color rod) test displays as did infants in the RR and YR groups, respectively. Specifically, infants in the RR/C group viewed a solid red rod and a two-color red rod with an orange midsection during test. Infants in the YR/C group viewed a solid yellow rod and a two-color yellow rod with a turquoise-green midsection during test. Note that the midsections of the two-color test rods in the RR/C and YR/C groups differed from the midsection of the rod in the habituation display, which was blue or red, respectively.

Results and Discussion

As can be seen in Table 1, the infants in the RR/C and YR/C groups looked about equally long at the two-color and solid rod test displays (13 of the 32 infants looked longer at the two-color rod, $z = 1.23$, *ns*, a significant difference relative to the RR and YR groups, $z = 3.63$, $p < .001$). This conclusion was confirmed by the parametric analyses. A 2 (condition: experimental vs. control) × 2 (group: RR [or RR/C] vs. YR [or YR/C] habituation display) × 2 (order) × 2 (display) × 3 (trial) ANOVA yielded a significant interaction between condition and display, $F(1, 56) = 18.46$, $p < .001$, and no other significant effects. Analyses of simple effects revealed significantly longer looking at the two-color rod by infants in the two experimental conditions of Experiment 1, $F(1, 56) = 17.96$, $p < .001$. In contrast, infants in the two control conditions of Experiment 2 looked slightly longer at the solid rod during test, $F(1, 56) = 3.38$, $p = .07$. These infants in the RR/C and YR/C groups did not recover interest to either test display (all $ts < 1.10$, *ns*).

These results suggest that the longer looking times to the two-color test rod in Experiment 1 were not the result of an inherent preference for two-color rods over solid rods. However, as an additional check on this possibility, we presented three groups of 8 four-month-olds (11 girls; mean age = 123 days, range = 114–140 days; 1 additional fussy and 2 sleepy infants were observed but were not included in the sample) with the GR, RR, and YR solid and two-color test displays with no prior habituation experience. Other aspects of the experimental design were identical to those described previously. There were no significant differences in looking time to either test display by any of the three groups (GR solid rod mean looking time = 17.14 s, *SEM* = 4.06; GR two-color rod mean looking time = 15.96 s, *SEM* = 3.60; RR solid rod mean looking time = 27.02 s, *SEM* = 5.89; RR two-color rod mean looking time = 31.50 s, *SEM* = 7.16; YR solid rod mean looking time = 25.59 s, *SEM* = 4.64; YR two-color rod mean looking time = 25.21 s, *SEM* = 6.69; all $ts < 0.95$, *ns*).

The difference in performance between the infants in Experiments 1 and 2, therefore, most likely resulted from some aspect of the RR or YR displays during habituation. One possibility is that the infants in Experiment 1 perceived the rod as a solid-color rod that was partly occluded by a transparent box despite the proximal characteristics indicative of a two-color rod, a percept consistent with greater looking at the two-color rod during test. In contrast, the infants in Experiment 2, habituated to a control display or having no habituation experience, exhibited no consistent test display preference, which suggests that there was no inherent preference for the two-color rod.

Experiment 3

Because the predictions and results of Experiment 2 involved null findings, its outcome might be considered equivocal. Experiment 3 was designed to address this concern by habituating 4-month-olds to a display that was predicted to lead to a looking-time preference opposite that of Experiment 1: longer looking at the solid rod. The infants viewed a rod-and-box display in which background texture was not visible through the box (the YR/NT display [yellow rod / no texture]). This background texture, which was present in the GR, RR, and YR displays of Experiment 1, may have contributed to perception of a transparent box by the change in color of the texture elements as the box moved back and forth across the display. Young infants are sensitive to texture as information necessary for the perception of object shape (Johnson & Aslin, 1998; Kaufman-Hayoz, Kaufman, & Stucki, 1986), and they use accretion and deletion of texture as a cue for relative depth (Johnson & Aslin, 1996). We reasoned that without texture, infants would not perceive the box as transparent in the YR/NT display and might not segregate the rod and box surfaces in the same way as did the infants in Experiment 1. We hypothesized, therefore, that the infants would perceive a two-color rod in front of the box in the habituation display. In this case, we expected the infants to look longer at the apparently novel solid rod than at the two-color rod during test.

Method

Participants. Sixteen full-term infants (8 girls) composed the final sample (mean age = 126 days, range = 116–158 days). An additional 4 infants were observed but not included in the sample because of excessive fussiness. The infants were recruited from the same participant pool as in Experiments 1 and 2.

Apparatus, stimuli, and procedure. The apparatus and procedure were identical to those used in Experiments 1 and 2. The stimuli were identical to those viewed by the YR group except that the infants in the YR/NT group were habituated to a display in which the background dots were not visible through the box surface and thus supported the perception of an opaque box that occluded the background texture. Following habituation, the infants in the YR/NT group viewed the same (two-color and solid rod) test displays as did infants in the YR group.

Results and Discussion

As can be seen in Table 1, the infants in the YR/NT group looked longer at the solid rod test display (11 of the 16 infants looked longer at the solid rod, $z = 2.38$, $p < .05$, a significant

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[5] For the RR/C display, the settings for the rod center (blue) were [0, 0, 14], 3.1 cd/m^2, $u' = .17$, $v' = .16$. For the YR/C display, the settings for the rod center (red) were [14,5,5], 12.3 cd/m^2, $u' = .26$, $v' = .50$.

difference relative to the YR group, $z = 3.17$, $p < .01$). This conclusion was confirmed by the parametric analyses. A 2 (group: YR/NY vs. YR habituation display) × 2 (order) × 2 (display) × 3 (trial) ANOVA yielded significant interactions between order and trial, $F(2, 56) = 4.60$, $p < .05$, and among group, order, and trial, $F(2, 56) = 5.51$, $p < .01$. These interactions were due to a decrease in looking across test trials by infants who viewed the two-color rod first, accompanied by an increase in looking by infants who viewed the solid rod first, a pattern that was pronounced in the YR/NT group (the reasons for these effects are unclear). More important, there was a significant Group × Display interaction, $F(1, 28) = 14.22$, $p < .001$. Analyses of simple effects revealed a marginally significant preference for the solid rod by infants in the YR/NT group, $F(1, 28) = 3.94$, $p = .057$. In contrast, infants in the YR group looked longer at the two-color rod, $F(1, 28) = 11.21$, $p < .01$. Infants in the YR/NT group recovered interest to the solid rod, $t(15) = 3.25$, $p < .01$, but not to the two-color rod, $t(15) = 1.32$, *ns*.

The results of Experiment 3 confirm and extend the conclusions of Experiments 1 and 2 by providing further evidence that post-habituation test display preference is a function of habituation experience and by providing evidence for the role of texture in infants' transparency perception. When infants viewed the RR and YR transparency displays, they apparently responded to the appearance of transparency in the displays and dishabituated to a novel stimulus on the basis of the habituation displays' distal, rather than proximal, characteristics. Without the availability of background texture visible through the box in the YR/NT display, however, there was less visual information in support of perceptual scission. In this case, the infants appeared to respond on the basis of the display's proximal characteristics and may have perceived a two-color rod in front of the box.

Interestingly, 10 undergraduates who viewed the YR/NT display (a different group than the one that viewed the displays from Experiments 1 and 2) all reported a convincing percept of transparency, a yellow rod behind a tinted blue box. The adults, therefore, did not appear to use texture information in the same manner as did the infants. This result corroborates the outcome of an earlier experiment of ours (Johnson & Aslin, 1996) in which we found that adults perceived object unity in a two-dimensional display without background texture, whereas 4-month-olds appeared unable to achieve perceptual completion of the visible rod segments unless texture elements, which perhaps facilitated segregation of the rod parts and box into their constituent depth planes, were present.

Experiment 4

The final experiment was undertaken to probe possible reasons for the apparent failure of 4-month-olds in the GR condition of Experiment 1 to perceive transparency, a surprising finding considering the robust performance in the two-color transparency conditions. We considered two potential reasons for this negative result. First, it may be that the information available in the color conditions is more accessible to young infants than is the information in the achromatic display. Second, there might be unforeseen problems with the achromatic display itself such that it is an inappropriate test of transparency perception in infants. To distinguish between these possibilities, we tested 7-month-olds' responses to transparency in the GR display (the GR/O group [gray rod / older infants]). This procedure enabled us to contrast the performance of the 7-month-olds with that of the 4-month-olds in the GR group of Experiment 1 without altering the stimulus parameters of the GR display.

Method

Participants. Sixteen full-term infants (6 girls) composed the final sample (mean age = 217 days, range = 207–236 days). An additional 2 infants were observed but not included in the sample because of excessive fussiness (1) or persistent inattention to the display (1). The infants were recruited from the same participant pool as in Experiments 1–3.

Apparatus, stimuli, and procedure. The apparatus and procedure were identical to those used in Experiments 1–3. The infants were habituated to the GR display and were subsequently presented with the GR two-color and solid rod test displays.

Results and Discussion

As can be seen in Table 1, the infants in the GR/O group looked longer at the two-color rod test display (13 of the 16 infants looked longer at the two-color rod, $z = 2.90$, $p < .01$, a significant difference relative to the GR group, $z = 2.07$, $p < .05$). This conclusion was confirmed by the parametric analyses. A 2 (group: GR/O vs. GR) × 2 (order) × 2 (display) × 3 (trial) ANOVA yielded a significant main effect of order, $F(1, 28) = 12.36$, $p < .01$, and a significant Order × Trial interaction, $F(2, 56) = 3.66$, $p < .05$, effects that resulted from a decrease in looking across trials by infants who viewed the two-color rod first along with a slight increase in looking by infants who viewed the solid rod first (the reasons for these effects are unclear). The Group × Display interaction was marginally significant, $F(1, 28) = 3.46$, $p = .073$. Analyses of simple effects revealed significantly longer looking at the two-color rod by infants in the GR/O group, $F(1, 28) = 6.61$, $p < .05$. In contrast, there was no significant difference in preference among infants in the GR group, $F(1, 30) = 0.12$, *ns*. Infants in the GR/O group showed recovery of interest to the solid rod, $t(15) = 3.69$, $p < .01$, but much stronger recovery to the two-color rod, $t(15) = 7.09$, $p < .00001$.

Experiment 4 provides some evidence that the 7-month-olds, in contrast to the 4-month-olds, may have perceived transparency in the achromatic GR display. Nevertheless, this interpretation should be viewed cautiously. The difference in performance between the 4- and 7-month-olds was not statistically robust, and the 7-month-olds in Experiment 4 appeared to find both test displays novel (albeit recovery was stronger to the two-color rod), leaving open the possibility that the achromatic condition did not furnish unambiguous information in support of transparency perception for either age group. The evidence, therefore, appears to reflect a developmental trend toward veridical perceptual scission with age in achromatic displays, either because transparency in achromatic displays is more difficult to perceive or because color displays more effectively engage infant attention toward information needed for the perception of transparency. This process may not yet be complete by 7 months.

General Discussion

Evidence was obtained for veridical perception of transparency in infants, and evidence was obtained for important limitations of this ability. Four-month-olds appeared to perceive transparency in color displays but not in an achromatic display. The importance of background texture in support of infants' transparency perception was highlighted as well: In the absence of texture visible through a box that appeared transparent to adults, 4-month-olds' perceptual segregation seemed to be organized according to what was directly visible in the display rather than according to its distal characteristics. Finally, we obtained evidence (though not unequivocal) that by 7 months, infants achieved perceptual scission even in the achromatic display.

How was perceptual scission achieved by the infants? In a transparency display, there are lawful relations between the luminances and colors of each region that are based on the physics of transparency. There is some disagreement concerning precisely how these relations should be modeled in the case of achromatic displays (Masin, 1997; Metelli, da Pos, & Cavedon, 1985), but the GR achromatic display used in Experiments 1 and 4 met both the Masin and the Metelli et al. criteria for transparency perception (which are based on the luminance ratios of each region of the display). In color displays, Beck (1978; cf. Metelli, 1974) hypothesized that the visual system encodes a stimulus color depending both on its wavelength and on the wavelengths of other simultaneously presented colors and that it will compute transparency if stimulus conditions warrant application of a "correction" to the perceived wavelength (e.g., in the case of an overlying filter). The infants who viewed the RR and YR displays may have relied on the colors of the rod and box to "infer" that the appearance of the two-color rod's center region was due to a mixture of the two colors. That is, simultaneous color contrast (which contributes to surface color percepts that are based on the surrounding color context) was modified by transparency perception. Such a correction process might be related to color constancy, which imparts the perception of stable object color despite changes in the spectral characteristics of reflected light (i.e., color constancy may evince a correction to wavelength that is based on recovery of the illuminant's chromaticity). Color constancy may be at least partially operational by 4–5 months of age (Dannemiller, 1989; Dannemiller & Hanko, 1987), although little is known about the mechanisms of its development (see Dannemiller, 1989).

Why did the 4-month-olds not respond to transparency in the achromatic display? It may be that the GR display did not furnish sufficient visual information to support young infants' transparency perception. For example, the index of transparency, as calculated using the Metelli et al. (1985) formula, was .28. This may have been too low (i.e., too nearly opaque) to appear unambiguously transparent to the 4-month-olds. By 7 months, gains in contrast sensitivity may have led to an improvement in perceptual scission that was based on luminance information. Alternatively (or in addition), the color in the RR and YR displays may have provided additional necessary visual information in support of transparency perception. Precisely how might color have been involved? One possibility considers the relation between early object perception skills and infant looking times. It might be that early in the ontogeny of transparency perception, infants require more time to abstract this particular object property from a visual display (cf. Johnson, 1996). In the present experiments, the infants who were habituated to the RR and YR displays looked significantly longer during habituation (M = 218.35 s, SD = 123.79) than did the infants who viewed the GR display (M = 146.78 s, SD = 59.73), $t(46) = 2.18$, $p < .05$.[6] This result suggests that when infants first develop competence at transparency perception, they look longer at displays in which information for this object property is enhanced (i.e., the color displays) than at displays in which the information is available but perhaps more difficult to access (i.e., the achromatic displays). (We have no evidence, however, that younger infants do not perceive transparency.) On the other hand, it might be that the contribution of color to infants' transparency perception lies mainly in its salience. The infants thus may have responded to the segregation of the rod and box surfaces in the color displays because longer looking assured sufficient time to encode the relevant stimulus information in support of transparency.

An alternative viewpoint considers the development of visual processing streams in infancy. Our results are consistent with the possibility that the parvocellular stream matures prior to the magnocellular stream. This notion is based on the early emergence in infancy of such visual functions as orientation sensitivity and shape discrimination, thought to be subserved by the parvocellular system, relative to such functions as direction sensitivity and stereopsis, thought to be subserved by the magnocellular system (see Atkinson, 1992). Perceptual scission in the RR and YR displays is most likely dependent on chromatic sensitivity, a parvocellular function, whereas scission in the GR display relies on contrast sensitivity, a magnocellular function (see Schiller & Logothetis, 1990).

The rod and box surfaces in the present experiments were moved out of phase because we thought it unlikely that the infants would segregate the rod and box surfaces in static displays. Not only do infants rely on object motion as an important cue for surface segregation (Kellman, 1996), but motion also attracts young infants' attention. Thus, in the present context, we hypothesized that the infants might fail to attend to the relevant stimulus variables in each display unless the display's elements moved. Although we have no direct evidence that motion was involved in the infants' responses to transparency, we know that motion is strongly related to transparency perception in adults. Kersten, Bülthoff, Schwartz, and Kurtz (1992) found that two overlapping squares undergoing a rigid rotation could be perceived in reversed depth order depending on the luminance of the two-color region (i.e., whether it was consistent with transparency or occlusion) and in fact could be perceived to undergo nonrigid motion. That is, transparency perception was found to override the visual system's tendency toward perception of rigid motion (Wallach & O'Connell, 1953). Plummer and Ramachandran (1993) reported that two moving gratings at different orientations could be seen as either a single pattern or as orthogonal components, depending on the luminances of the gratings' intersections. When the intersections' luminances were consistent with transparency, the gratings

[6] It is important to note, however, that habituation looking times to the GR display were comparable to looking times to color displays in which 4-month-olds responded to object unity, as reported by Johnson and Náñez (1995) and Johnson and Aslin (1996). Therefore, it is not always the case that color displays will capture infants' attention longer than will achromatic displays. Nor is it necessarily true that 4-month-olds have difficulty responding to object properties in achromatic displays: We have found previously (Johnson & Aslin, 1998) that 4-month-olds perceive object unity in achromatic displays.

were perceived as separate, with orthogonal trajectories; when the intersections were darkened (i.e., inconsistent with transparency), the gratings cohered and appeared to move as a unit. Thus transparency influenced the perceived global motion of the pattern. The specific role of motion in infants' transparency perception remains a question for future research.

A final question concerns previous experiments that have probed older infants' manual responses to transparent surfaces and that have suggested that infants have difficulty with transparency. For example, Butterworth (1977) tested search abilities in 9-month-olds with opaque and transparent covers on the hiding locations of an attractive toy. Lockman (1984) investigated detour abilities in 8–12-month-olds using opaque and transparent barriers. Diamond and Gilbert (1989) explored reaching for a toy in opaque and transparent boxes by 7–11-month-olds. All of these researchers reported that the infants had greater difficulty with transparent barriers or covers than with opaque barriers: The infants often attempted to reach directly for the toys "through" the transparent surface but readily reached around an opaque surface. This response pattern is likely due not to an inability to detect the presence of the transparent covers but rather to a misinterpretation of the implications of transparency for reaching behaviors. Yates and Bremner (1988) found that such misinterpretations are eliminated when 9-month-olds are provided with the opportunity to play with the transparent covers. These infants consistently moved aside the covers to obtain a toy in a subsequent reaching task.

If 4-month-olds are capable of perceptual scission in some transparency displays, why would older infants exhibit apparent confusion with transparency in reaching tasks? The answer is unclear at present. This question recalls discrepancies between claims of object permanence in young infants when visual preference paradigms are used (e.g., Baillargeon, Spelke, & Wasserman, 1985) and when reports are based on reaching as the dependent measure (Piaget, 1954). Various accounts of this apparent developmental décalage (i.e., competence at a task along with failure at a second task that seems logically equivalent) have focused on neurophysiological development (Bertenthal, 1996) and on developing infant knowledge as consisting of "graded representations" (Munakata, McClelland, Johnson, & Siegler, 1997). The results of the present studies suggest that infants may perceive some transparent surfaces in displays that are rich in visual information (e.g., motion, color, and texture) and that can be inspected at length. However, when a transparent barrier impedes acquisition of a desired toy (which might be reached for quickly, without adequate scrutiny of the barrier), an infant may not encode transparency sufficiently to guide appropriate reaches. Consistent with this notion are the results of the present Experiments 1–4, which suggest that the developmental trajectory of transparency perception extends through the first postnatal year.

It might be that infants detect transparency at an early age on the basis of extensive perceptual (passive) exposure to transparent *surfaces* from birth (e.g., water in the bath). However, completely veridical percepts of transparency may require additional perceptual–motor (active) experience to learn about the properties of transparent *objects* (e.g., glass containers), such as solidity (cf. Titzer, 1995). This view is consistent with a growing body of evidence suggesting that the development of object perception proceeds with input from multiple sources of information, including sensitivity to and utilization of a variety of visual cues (e.g., orientation, motion, color, luminance, texture, and depth; see Eizenman & Bertenthal, 1998; Johnson, 1997, 2000), alongside experience and attendant knowledge of objects' physical properties (see Needham, Baillargeon, & Kaufman, 1997).

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