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Young infants' perception of illusory contours in dynamic displays

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Abstract. Ninety-six 4-month-old infants were habituated to one of three computer-generated displays depicting two rod parts above and below an occluding box. In the first display, the surfaces and boundaries of the rod and box were specified by dense surface texture. Their depth segregation was specified by accretion and deletion of background texture and motion shear. In the second display, the unity of the rod parts and box, and their depth segregation, were specified only by illusory contours. In the third display, the boundaries of the rod and box were specified by illusory contours, perceptible only via spatiotemporal integration of accretion and deletion of sparse-background-texture elements. Infants appeared to perceive object unity, and segregate the rod and box surfaces, in all three displays, indicating use of illusory contours to perceive bounded surfaces in depth. The results suggest a cognitive contribution to perception of some illusory contours, abilities which seem to be present by at least 4 months of age.

1 Introduction

Since the pioneering studies of Fantz (1961, 1964), research on young infants' perceptual skills has revealed remarkable levels of competence on many visual tasks. Although infants' perceptual abilities undergo considerable development over the first few postnatal months (see Johnson, in press), early skills often can be appropriately characterised as organised, rather than reflecting the 'blooming, buzzing confusion' espoused by James (1890).

Evidence for perceptual organisation in infants comes from a variety of domains. For example, young infants appear to perceive structure in illusory-contour displays. In the display depicted in figure 1a, most adults report the percept of a white square in front of four smaller circles, one at each corner (Kanizsa 1979). The contours of the square are illusory, in that they are not specified by discontinuities in luminance, colour, texture, motion, or depth at the perceived locations of the boundaries, unlike most perceptible boundaries among real objects. Young infants have also been demonstrated

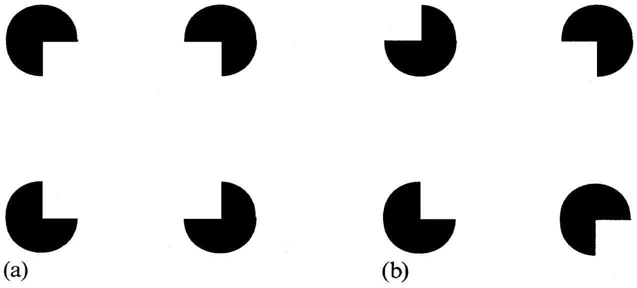

Figure 1. (a) An illusory-contour display used in studies of young infants' perceptual organisation. After habituation to a real square, infants preferred a display with inducing elements at varying orientations (b) over the illusory-contour display (a), suggesting that the infants perceived the illusory square (Ghim 1990).

to perceive the illusory contours in this stimulus (Ghim 1990). After habituation to a dark square against a light background, infants 3 and 4 months old looked less at an illusory square (figure 1a) relative to a display in which the 'inducing elements' (the 3/4 circles) were arranged in different orientations, as depicted in figure 1b. Given that infants tend to look longer at novel compared to familiar displays after habituation (Bornstein 1985), these results suggest that the infants perceived the illusory square.

Many instances of illusory contour involve processes of both 'modal' and 'amodal' completion (Petry and Meyer 1987). Modal completion refers to perception of a coherent (but illusory) surface in front of another, whereas amodal completion refers to perceptual completion of the far surface. In the case of the illusory square of figure 1a, perception of the square is an example of modal completion. Perception of four partly occluded circles, as opposed to four circles with parts missing, is an instance of amodal completion.

Ghim (1990) provided evidence of modal completion in the infants she observed. Evidence of amodal completion has been reported in studies of young infants' perception of the coherence of partly occluded objects (Kellman and Spelke 1983). Infants aged 4 months were habituated to a rod-and-box display such as depicted in figure 2a, and subsequently presented with complete-rod and broken-rod test displays (figures 2b and 2c, respectively). The infants consistently looked longer at the broken-rod display, suggesting perception of a complete rod behind the box in the habituation (rod-and-box) display. Thus the infants appeared to infer the hidden region of the rod.

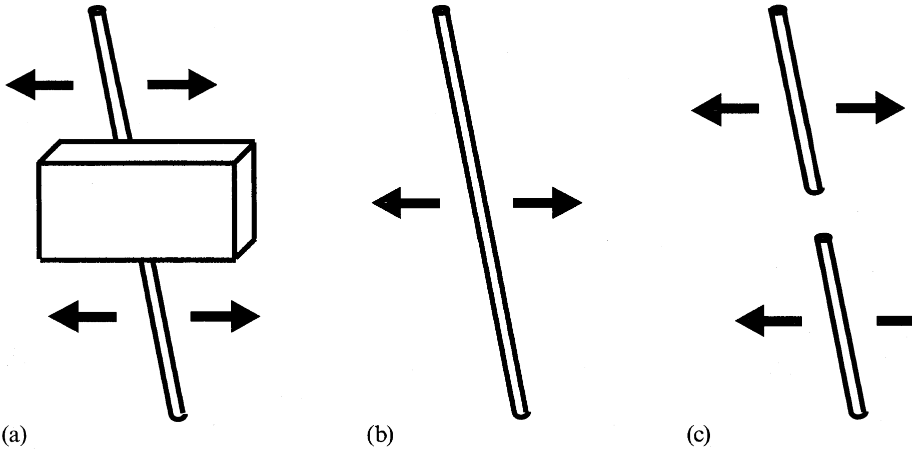

Figure 2. (a) Rod-and-box display used in studies of infants' perception of object unity. The two aligned rod parts underwent common motion, above and below the box. (b) Complete-rod test display. (c) Broken-rod test display. After habituation to (a), infants looked longer at (c) than at (b), implying amodal completion of the rod behind the box in (a) (Kellman and Spelke 1983).

Each of these examples involves infants' perception of visual structure that is incompletely specified. However, the precise nature of the infants' representation of such underspecified structures remains unclear from these studies. For example, in Kellman and Spelke's (1983) object-unity task, 4-month-old infants appeared to perceive the unity of the two rod parts in the rod-and-box display, but this result does not necessarily imply representation of the shape of the hidden region. [Craton (1996) habituated older infants to displays in which a horizontally oriented rectangle occluded the centre of a vertically oriented rectangle, followed by rectangle and cross test displays, both consistent with the visible portions of the occluded surface in the habituation display. Craton reported that infants younger than 8 months do not appear to maintain a representation of the shape of the hidden region of a partly occluded object.] Likewise, it is unclear if infants' abstraction of the two-dimensional square shape in Ghim's

(1990) study of illusory contours was accompanied by perception of the apparent-depth ordering of the individual surfaces (the square in front of the inducing elements), such as reported by adults (Kanizsa 1979). Indeed, it is unclear if the infants perceived separate surfaces at all in this two-dimensional display. That is, it is possible that shape perception occurred in the absence of perception of occlusion.

The goal of the present study was to explore young infants' perception of surfaces in depth that were visually underspecified. This was accomplished by presenting 4-month-old infants with computer-generated two-dimensional displays in which surface segregation was defined by illusory contours. Because there was no actual depth difference between the shapes, infants' perception of surfaces in depth would imply utilisation of illusory contours as information for surface boundaries and occlusion. In each of the two experiments, the object-unity paradigm was employed (Kellman and Spelke 1983).

2 Experiment 1

2.1 *Introduction*

In experiment 1, 4-month-olds' perception of surfaces in depth in illusory-contour displays was investigated with the no-surface-texture (NST) display, depicted in figure 3a. This consisted of a black rod and black box, moving back and forth out-of-phase relative to one another, against a random-dot-textured background. After habituation to the NST display the infants were presented with black complete-rod and broken-rod test displays, moving in the same manner as the rod parts in the habituation display, against the same background. We reasoned that longer looking at the broken rod after habituation would imply perception of the unity of the rod, and thereby demonstrate the contribution of illusory contours to the perceptual completion process. This logic stems from the lack of boundary information at the intersection of the rod and box in the NST display. As a result of the lack of texture, there was no direct information for depth ordering, nor occlusion, and perception of complete box and rod shapes would depend on perceiving the connectedness of the separated box and rod parts across the intersection. This connectedness was given only by illusory contours. (Note that perception of the coherence of the rod and box depends on both modal and amodal completion.)

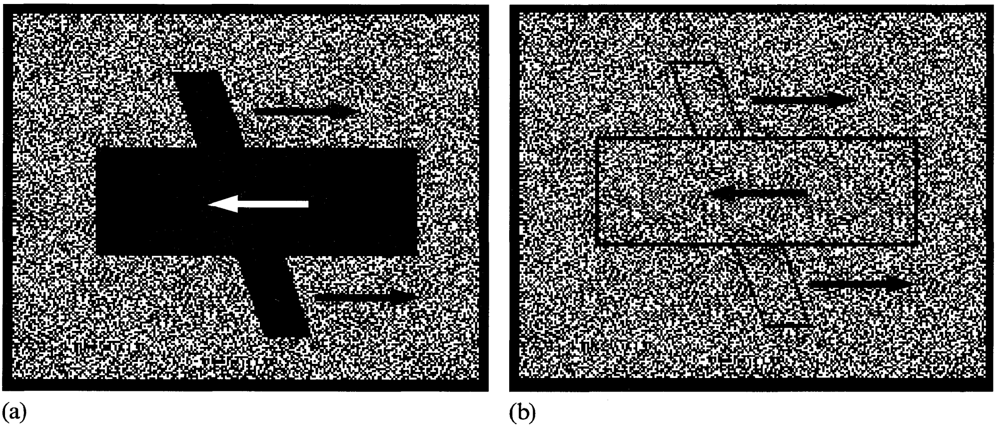
(a) (b)

Figure 3. Displays presented to infants in experiment 1. (a) No-surface-texture (NST) display. (b) Dense-surface-texture (DST) display. Both displays consisted of two rod parts undergoing common motion above and below a box. The rod and box moved back and forth out-of-phase relative to one another, against a textured background. Note that information for depth ordering in the DST display was given by motion shear at the intersection of the rod and box. There is no such information in the NST display—perception of the segregation of the rod and box depends on connecting modal and amodal illusory contours. (The arrows and outlines are provided here for illustrative purposes only, and were not present in the displays themselves.)

We also asked if the illusory contours in the NST display would support perception of unity as effectively as a display in which there was information for occlusion and depth ordering at the intersection of the rod and box. A second group of infants was habituated to the dense-surface-texture (DST) display, depicted in figure 3b. This display was identical to the NST display in dimensions and motion, but the rod and box were both covered in the dense random-dot texture. Information for the depth ordering of the rod behind the box was given at their intersection, via motion shear at the boundaries of the box.

The DST display is rich in texture cues. Infants aged 5 months have been found to be sensitive to accretion and deletion of texture (the progressive covering and uncovering of background by a near surface) as information for depth (Granrud et al 1984), and 3-month-olds have been shown to recover shape information in dynamic displays that consisted entirely of random-element texture (Kaufman-Hayoz et al 1986). Motion-based surface segmentation has been reported for infants as young as 2 months (Wattam-Bell 1991, 1992). Thus the 4-month-olds in the present study who viewed the DST display were predicted to be able to distinguish the rod and box shapes and their depth ordering, and perceive the rod's unity.

Both the rod and the box moved back and forth in the DST display, in contrast to displays used in past studies of infants' perception of object unity, in which a rod moved behind a stationary box (Kellman and Spelke 1983; Johnson and Náñez 1995; Johnson and Aslin 1996). Motion of both surfaces was necessary in the DST display; otherwise, the box would be undefined because it was camouflaged by the background. Both rod and box surfaces moved in the same manner also in the NST display. Although it is unclear what the contribution might be of this type of surface motion to infants' perception of illusory contours (and such motion is not necessary to distinguish the rod and box against the background), the motion was included in the NST display for two reasons. First, because the surface motion was identical in both the DST and NST displays, we could be more confident that any differences in infants' responses to each display would reflect the differences in surface textures and, more importantly, actual vs illusory contours. Second, 4-month-old infants have been found to perceive unity in rod-and-box displays in which the rod moves relative to the box, but not when the rod and box are stationary (Kellman and Spelke 1983).

2.2 *Method*

2.2.1 *Subjects.* Sixty-four full-term infants (thirty-two female) comprised the final sample (mean age = 124 days, range = 107 – 133 days). Five additional infants were observed but not included in the sample because of excessive fussiness (three) or sleepiness (two). The infants were recruited by letter and telephone from hospital records and birth announcements in the local newspaper. The majority of the infants were from Caucasian middle-class families. Parents were paid a nominal sum for their participation.

2.2.2 *Apparatus.* An Amiga 3000 computer and an 80 cm Sony colour monitor were used to generate the displays. Two observers viewed the infant through small peepholes cut into two black panels 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 mouse port. Both observers were blind to the stimulus on the screen at any given time. The second observer had never been allowed to view the displays, and was naive to the hypotheses under investigation.

2.2.3 *Stimuli.* The DST display consisted of a 40.6 cm × 44.5 cm array of 45 549 dots (in a 189 × 241 array), subtending 18.0 deg × 19.6 deg visual angle at the infant's 125 cm viewing distance. Half the dots were black and half were white, randomly distributed over the array. This produced a dense random-dot texture. A 4 s animation (30 frames s^{-1}) depicted a rod and box, both covered by dense random-dot texture, moving out-of-phase 24.8 cm (11.2 deg) laterally across the screen, at a rate of 6.2 cm s^{-1} (2.8 deg s^{-1}). The rod measured 4.4 cm × 30.5 cm (2.0 deg × 13.7 deg), and was oriented 25° counterclockwise from the vertical. The box measured 11.4 cm × 30.5 cm (5.2 deg × 13.7 deg). A DST baseline (DSTB) display was also employed, to assess baseline posthabituation preferences and thereby control for the possibility that there might be an intrinsic preference for the broken rod over the complete rod. In the DSTB display, the bottom rod part lagged behind the top rod part by 1 s, thus appearing unconnected to the top rod part. DST test displays consisted of a broken rod and a complete rod, each moving in the same manner as the rod parts in the habituation displays (the rod parts in the broken-rod display moved together). Infants in both the DST and DSTB conditions viewed these same test displays. The NST and NSTB displays (including test displays) were identical to the DST and DSTB (and test) displays, respectively, except the surfaces of the rod and box were black.

Sixty-four infants were habituated to one of four displays: DST, DSTB, NST, or NSTB. In each group of sixteen infants, eight viewed the broken rod first after habituation, and eight viewed the complete rod first (order was determined randomly by the computer).

2.2.4 *Procedure.* The infants were tested individually, each placed in an infant seat approximately 125 cm from the display monitor. The habituation display was presented until the infant met the habituation criterion. This criterion was defined according to the common 'infant-control' procedure (Horowitz et al 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. If the total looking time during the first three trials was less than 12 s, the criterion was based on the first three subsequent trials for which looking time totalled 12 s or more.

Timing of each trial, during both habituation and test, 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. The two test displays were seen three times each in alternation, for a total of six posthabituation trials.

2.3 *Results and discussion*

Each infant contributed six posthabituation looking times to the analyses, three for the broken rod and three for the complete rod. Looking times were calculated by averaging the two observers' judgments for each test trial. Interobserver agreement was high for each condition (Pearson $r = 0.89$ or higher). Both parametric and nonparametric analyses were conducted on the data (see Siegel and Castellan 1988).

Figures 4a and 4b show the average looking times for infants who viewed the DST and DSTB displays, respectively. Infants in the experimental condition (those habituated to the DST display) looked longer at the broken rod, whereas those in the baseline condition (habituated to the DSTB display) looked about equally at the two test displays. Comparisons of looking times to the test displays were conducted with a 2 (Condition: experimental vs baseline) × 2 (Display: broken vs complete rod) × 2 (Order:

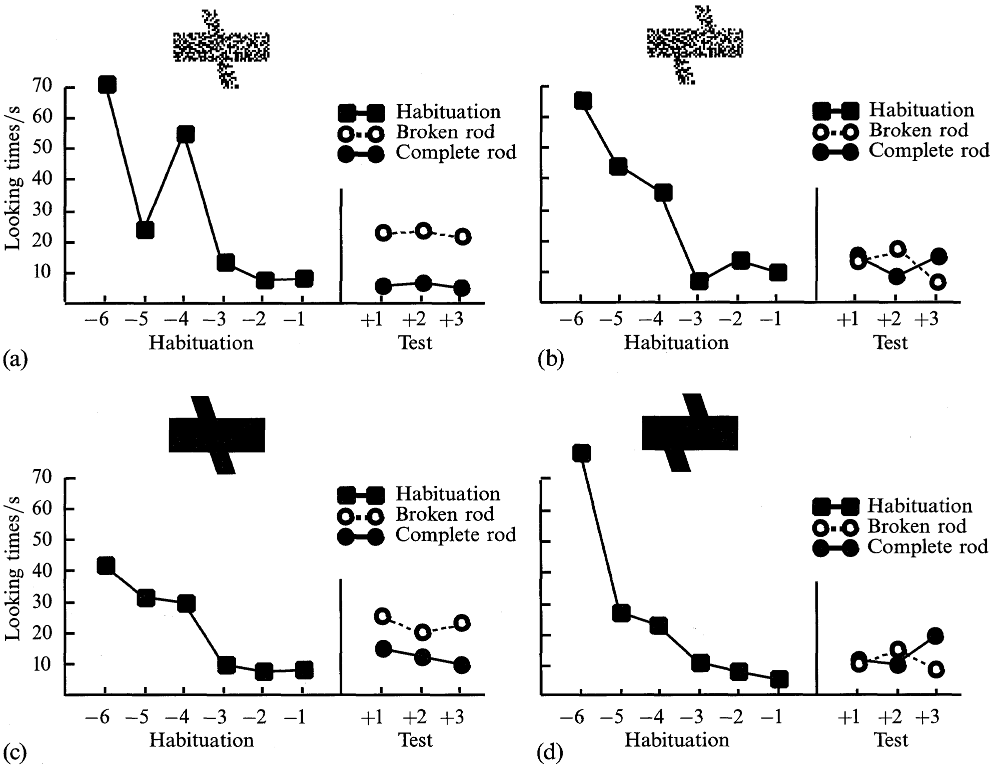

Figure 4. Looking-time results of experiment 1. (a) DST condition. (b) DSTB (baseline) condition. (c) NST condition. (d) NSTB (baseline) condition. Note the consistent preference for the broken rod after habituation to the DST and NST displays, suggesting perceptual completion in both displays. This implies perception of illusory contours in the NST display.

broken vs complete rod first after habituation) × 3 (Trial: first, second, or third block of test trials) mixed ANOVA. There was a significant effect of Display, $F_{1,28} = 9.69$, $p < 0.01$, due to greater looking time overall at the broken rod (mean = 18.49 s, SD = 20.19) than at the complete rod (mean = 11.43 s, SD = 18.97). There was also a significant interaction between Condition and Display, $F_{1,28} = 13.09$, $p < 0.01$; and a significant interaction between Condition, Display, and Order, $F_{1,28} = 6.46$, $p < 0.05$ (the source of this three-way interaction is unclear, as neither the experimental nor the baseline group's analysis revealed a significant Display × Order interaction). There were no other significant effects. The Condition × Display interaction was due to greater looking time at the broken rod (mean = 22.58 s, SD = 21.61) than at the complete rod (mean = 7.32 s, SD = 5.90) by infants in the experimental group, $F_{1,15} = 16.69$, $p < 0.01$. In contrast, infants in the baseline group looked about equally at the broken rod (mean = 14.41 s, SD = 17.98) and at the complete rod (mean = 15.55 s, SD = 25.65), $F_{1,15} = 0.14$, ns. Infants in the experimental group looked longer at the broken rod than did infants in the baseline group, $t_{30} = 1.76$, $p < 0.05$ (one-tailed).

Nonparametric analyses performed on test display preferences confirmed these conclusions. Infants in the experimental condition showed significantly greater preference for the broken rod than did infants in the baseline condition, Wilcoxon–Mann–Whitney test, $z = 3.02$, $p < 0.01$. Infants in the experimental condition preferred the broken rod, Wilcoxon signed-ranks test, $z = 2.74$, $p < 0.01$; whereas infants in the baseline condition showed no test display preference, $z = 0.21$, ns.

Figures 4c and 4d show looking times to the NST and NSTB displays, respectively. In like manner to the DST conditions, infants in the experimental condition looked longer at the broken rod, whereas those in the baseline condition looked about equally at the two test displays. A Condition × Display × Order × Trial mixed ANOVA revealed a marginally significant Condition × Display interaction, $F_{1,28} = 3.59$, $p < 0.07$, and no other significant effects. This interaction was due to greater looking time at the broken rod (mean = 21.36 s, SD = 27.80) than at the complete rod (mean = 12.46 s, SD = 12.65) by infants in the experimental group, $F_{1,15} = 3.62$, $p < 0.08$. In contrast, infants in the control group looked about equally at the broken rod (mean = 11.84 s, SD = 13.22) and at the complete rod (mean = 14.08 s, SD = 22.87), $F_{1,15} = 0.36$, ns. Infants in the experimental group looked longer at the broken rod than did infants in the baseline group, $t_{30} = 1.70$, $p < 0.05$ (one-tailed).

Nonparametric analyses confirmed these conclusions. Infants in the experimental condition showed significantly greater preference for the broken rod than did infants in the baseline condition, $z = 2.83$, $p < 0.01$. Infants in the experimental condition preferred the broken rod, $z = 2.07$, $p < 0.05$; whereas infants in the baseline condition showed no test display preference, $z = 0.31$, ns.

To compare the performance of the infants who viewed the DST and NST (experimental) displays, a 2 (Group: DST vs NST) × 2 (Display: broken vs complete rod) mixed ANOVA was conducted on the looking-time data. The only significant effect was a main effect of Display, $F_{1,30} = 11.75$, $p < 0.01$, due to greater looking time overall at the broken rod. The Group × Display interaction failed to reach significance. That is, any difference in posthabituation preference between infants who viewed the DST and NST displays was not statistically significant. Although the broken-rod preference by the NST infants fell just short of significance in the parametric analysis, the overall pattern of results provides convincing evidence that illusory contours contribute to 4-month-olds' perception of surfaces in (unordered) depth. [It is unclear how depth ordering of the rod and box may have been resolved by the infants. The NST display provides no cues as to depth ordering of these two surfaces, and is thus similar to the 'spontaneously splitting figure' discussed by Kellman and Shipley (1991) that reverses in depth with prolonged viewing.]

3 Experiment 2

3.1 *Introduction*

In experiment 2, we employed a display in which surface boundaries were specified by kinetic illusory contours (illusory contours given by motion; see Kellman and Cohen 1984; Kellman and Loukides 1987). The sparse-surface-texture (SST) display is depicted in figure 5, and consisted of a sparse-texture-covered rod and box, presented against a sparse-texture background. Boundaries at the top and bottom edges of the rod parts and box were given by motion shear of nearby surface and background dots;

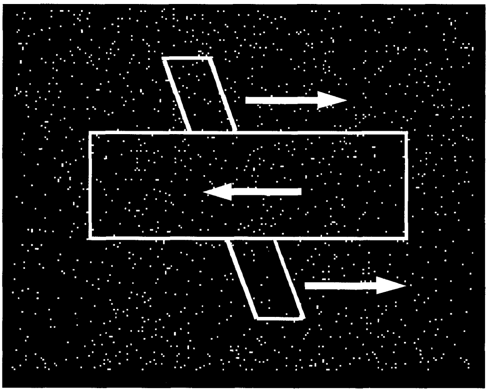

Figure 5. Sparse-surface-texture (SST) display presented to infants in experiment 2. The boundaries of the rod and box are illusory, given by instances of accretion and deletion of background texture over time and motion shear separated from the illusory contours. (The arrows and outlines are provided here for illustrative purposes only, and were not present in the displays themselves.)

note that there were no texture elements at the edges themselves (thus edges were not physically present). Boundaries at the left and right edges of the rod parts and box were given by accretion and deletion of background texture elements while the surfaces moved back and forth in like manner to the DST and NST displays. Like the vertical edges, these horizontal edges were not physically present.

The boundaries of the rod and box in the SST display were underspecified in two ways. First, there were no discontinuities at the edges of the rod and box surfaces in any static view; thus recovery of surface shape could only occur when the surfaces moved. Second, accretion and deletion of individual background elements at the horizontal edges of the rod and box was fragmented across space and time. Only by integration (across space and over time) of successive distinct appearances and disappearances of these elements would it be possible to perceive these edges. Therefore perception of segregated surfaces in depth would seem to depend on the ability to integrate these events. Past research has provided evidence for young infants' spatiotemporal integration abilities (Johnson and Aslin 1995; Smith et al 1996), but not in the perception of illusory contours.

3.2 *Method*

3.2.1 *Subjects.* Thirty-two full-term infants (sixteen female) comprised the final sample (mean age = 115 days, range = 97 – 134 days). Two additional infants were observed but not included in the sample because of excessive fussiness. The infants were recruited from the same subject pool as those in experiment 1.

3.2.2 *Apparatus and procedure.* The apparatus and procedure were the same as those in experiment 1.

3.2.3 *Stimuli.* The SST display consisted of a 40.6 cm × 44.5 cm array of 45 549 dots (in a 189 × 241 array), subtending 18.0 deg × 19.6 deg visual angle at the infant's 125 cm viewing distance. In contrast to the dense (50% white, 50% black) texture in the DST display used in experiment 1, the majority of the dots (97%) in the SST display were black and the rest (3%) were white, randomly distributed over the array. This arrangement produced a background composed of sparse random-dot texture. The rod and box also were covered by sparse random-dot texture. A SST baseline (SSTB) display, like that used in the NST and DST conditions of experiment 1, was also employed to assess infants' preferences for a broken rod after exposure to a rod-and-box display in which the rod parts did not appear connected. Except for the background and surface texture, the SST and SSTB displays (and test displays) were identical to the displays described in experiment 1.

Sixteen infants were habituated to each display: SST or SSTB. In each group of sixteen infants, eight viewed the broken rod first after habituation, and eight viewed the complete rod first (order was determined randomly by the computer).

3.3 *Results and discussion*

Each infant contributed six posthabituation looking times to the analyses, three for the broken rod and three for the complete rod. Looking times were calculated by averaging the two observers' judgments for each test trial. Interobserver agreement was again high (Pearson $r = 0.92$ or higher). Again, both parametric and nonparametric analyses were conducted.

Figures 6a and 6b show the average looking times for infants who viewed the SST and SSTB displays, respectively. Infants in the experimental condition looked longer at the broken rod, whereas those in the baseline condition looked about equally at the two test displays. A Condition × Display × Order × Trial mixed ANOVA revealed a significant effect of Condition, $F_{1,28} = 7.24$, $p < 0.05$, due to greater looking time overall by the experimental group (mean = 29.61 s, SD = 40.87) than by the baseline

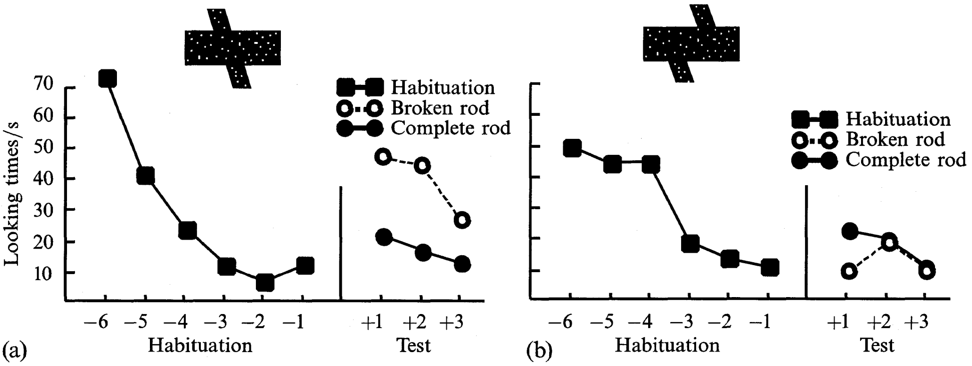

Figure 6. Looking-time results of experiment 2. (a) SST condition. (b) SSTB (baseline) condition. Infants consistently preferred the broken rod after habituation to the SST display, implying perception of the illusory boundaries of the rod and box.

group (mean = 16.69 s, SD = 20.25). There was a significant effect of Order, $F_{1,28} = 4.92$, $p < 0.05$, due to greater looking time overall by infants who were habituated to the complete rod first (mean = 28.48 s, SD = 36.45) than by infants who viewed the broken rod first (mean = 17.82 s, SD = 27.90). There was also a significant interaction between Condition and Display, $F_{1,28} = 7.07$, $p < 0.05$, and no other significant effects. The Condition × Display interaction was due to significantly longer looking at the broken rod (mean = 40.48 s, SD = 46.87) than at the complete rod (mean = 18.74 s, SD = 30.62) by infants in the experimental group, $F_{1,15} = 6.67$, $p < 0.05$. In contrast, infants in the baseline group looked about equally at the broken rod (mean = 14.74 s, SD = 18.75) and at the complete rod (mean = 18.63 s, SD = 21.67), $F_{1,15} = 0.93$, ns. Infants in the experimental group looked longer at the broken rod than did infants in the baseline group, $t_{30} = 3.50$, $p < 0.01$ (two-tailed).

Nonparametric analyses confirmed these conclusions. Infants in the experimental condition showed significantly greater preference for the broken rod than did infants in the baseline condition, $z = 3.20$, $p < 0.01$. Infants in the experimental condition preferred the broken rod, $z = 2.59$, $p < 0.01$; whereas infants in the baseline condition showed no test display preference, $z = 0.83$, ns.

Performance of the infants who viewed the SST and DST (experimental) displays was compared to examine whether the illusory contours specifying the boundaries of the rod and box in the SST display attenuated the infants' perception of the surfaces in this display. A Group × Display mixed ANOVA revealed a significant main effect of Group, $F_{1,30} = 6.41$, $p < 0.05$, due to greater looking time overall by infants in the SST group; and a significant main effect of Display, $F_{1,30} = 13.89$, $p < 0.001$, due to greater looking time overall at the broken rod. As in experiment 1, the Group × Display interaction was not significant. This indicates that, in like manner to the DST display, infants had little difficulty in appropriately segregating the rod and box surfaces in the SST display, even though the surface boundaries were underspecified.

4 General discussion

The results of the present study suggest that young infants perceive the segregation in depth of surfaces whose individual unity (experiment 1) or boundaries (experiment 2) are given by illusory contours. These findings are consistent with studies demonstrating young infants' perception of illusory contours (Bertenthal et al 1980; Ghim 1990; Colombo et al 1996) and young infants' perception of three-dimensional structure in two-dimensional displays (Kellman 1984; Schmuckler and Proffitt 1994; Johnson and Aslin 1995). A common feature of these studies is that they demonstrate infants' ability to go beyond the information directly available at the retinal image.

That is, visual scenes were interpreted in accord with their distal, rather than proximal, characteristics. One question raised by these studies concerns the origins of perceptual organisation in infancy. Is perceptual organisation an unlearned (perhaps innate) set of skills, or are its origins best accounted for by developmental processes, such as maturation of the visual system, and/or experience viewing objects in the world?

Perceptual organisation has been reported in infants even younger than the 4-month-olds observed in the present experiments. Slater (1995) reviewed studies in which neonates display various visual preferences, such as moving vs stationary stimuli, three-dimensional vs two-dimensional patterns, and several others. The implication of such findings is clear: Human visual perception is at least partially organised from birth, in the absence of any visual experience. However, this does not necessarily mean that perceptual organisation does not undergo development from birth. Although the results of the present study are suggestive, they do not provide evidence that infants younger than 4 months perceive illusory contours, and at this time there are no other studies in the literature bringing evidence to bear on this issue.

An example of the development of perceptual organisation can be found in studies of young infants' perception of object unity. Perception of object unity by 4-month-olds has been demonstrated in a variety of studies (Kellman and Spelke 1983; Slater et al 1990; Johnson and Náñez 1995; Johnson and Aslin 1996). However, at present there is no available evidence of unity perception in infants younger than 2 months (Johnson and Aslin 1995). Neonates appear to respond to the rod parts in rod-and-box displays as separate (Slater et al 1990, 1996). It is currently unknown how this particular ability develops, but we have speculated on the emergence of young infants' inferential skills as an important consideration (Johnson 1997).

How, then, can the results of the present study be accounted for? Theories of perception of illusory contours can be divided into three groups: high-level, top–down, or cognitive theories; intermediate-level theories; and low-level, bottom–up, or neurophysiological theories.

High-level theories consider perception of illusory contours as akin to problem-solving (for example Gregory 1972; Rock 1983). The interpretation of illusory contours, according to such theories, requires 'postulating' the existence of boundaries of near surfaces that partly occlude far surfaces. This involves assessing the probability that the appearance of the far objects is best accounted for by occlusion or not. In the case of the illusory square, the interpretation of a square, partly occluding four circles, is preferred over the interpretation of four partial circles [see the discussion in Nakayama and Shimojo (1990) on real-world occlusion constraints].

Intermediate-level theories emphasise the importance of inherent propensities or tendencies in the visual system that govern perceptual processes. The best known example is Gestalt theory (Koffka 1935; Kanizsa 1979). According to Gestalt theory, the visual system forces organisation of proximal stimuli in accord with the simplest possible distal form. These forces are independent of visual experience. Most stimuli we encounter will be interpreted as consistent with Gestalt principles such as simplicity, good form, symmetry, good continuation, proximity, and common fate. Perception of most illusory contours follows principles of good form, simplicity, good continuation, and perhaps others. Another intermediate-level theory (Kellman and Shipley 1991) accounts for illusory contours in terms of 'interpolation' (perceptual extension) of the edges of the inducing elements into homogeneous regions of the stimulus, to connect with neighbouring inducing elements.

Low-level theories stress the contributions of neural mechanisms to perception of illusory contours. According to some low-level theories, hierarchies of neural circuits are organised in successive stages, the lower stages responsible for identifying contour orientation, and the higher stages responsible for integrating these inputs (Grossberg and Mingolla 1985; Peterhans and von der Heydt 1991). Because the higher stages have access to the global context of visual scenes, endpoints of inducing elements can be incorporated into the inputs to the higher stages, and images comprising illusory contours are built up from isolated stimulus features. Intriguing support for low-level theories comes from studies reporting sensitivity to illusory contours of individual neurons in areas V2 (von der Heydt et al 1984) and V1 (Grosof et al 1993) of the macaque monkey's visual cortex.

How well do these theories account for infants' perceptual organisation in general, and the present study in particular? Intermediate-level theories have been found inadequate to account for many infant perceptual phenomena. For example, Gestalt theory would predict perception of object unity in neonates, because Gestalt principles operate independently of experience. However, as we have seen, neonates do not appear to perceive unity (Slater et al 1990, 1996). Gestalt theory would also have difficulty explaining why 4-month-olds' unity perception seems to rely heavily on common fate, but not good continuation, good form, or other Gestalt principles (Kellman and Spelke 1983). Interpolation theory, likewise, is inadequate to account for 4-month-olds' failure to perceive unity in some displays (Johnson and Aslin 1996). Although the results of experiment 1 of the present study fit with these views, in that the illusory contours in the NST display are consistent with both Gestalt principles and interpolation theory, the kinetic illusory contours of experiment 2 would be more difficult to reconcile with these accounts. This is because there were no inducing elements per se in the SST display, and therefore no opportunity for the operation of good continuation or visual interpolation between elements. Rather, the illusory contours in the SST display were elicited by inducing events: instances of occlusion and revealing of background dots, separated over space and time (vertical edges), and lateral dot motion (horizontal edges).

There is currently much controversy concerning the contribution of high-level (cognitive) skills to perceptual organisation in infancy. Attempts have been made to account for neonates' visual preferences entirely in terms of subcortical mechanisms, with some, but not universal, success (Banks and Salapatek 1981; M H Johnson 1990; see Slater 1995 for discussion). The debate seems to rest on one's criteria for using the term 'cognitive' to describe a particular skill or ability.

At the present time, no specific neurophysiological mechanisms, operational in young infants, have been identified that would support perception of illusory contours, although such mechanisms are certainly plausible. We would argue for an account of the present results that recognises the contribution of cognitive skills to the use of illusory contours in surface segregation and unity perception. This is especially true of experiment 2. In order to perceive object unity in the two-dimensional SST display, the infant would necessarily infer the existence of separate objects (the rod and box), whose surfaces were defined by a sparse scattering of dots, whose vertical edges were defined by repeated occurrences of discrete appearances and disappearances of other (ie background) dots, and whose horizontal edges were given by motion shear of dots separated by some distance from the edges themselves. Thus there seem to be at least three kinds of cognitive-activity-involved spatiotemporal integration of the appearance/disappearance events, inferring the depth ordering of the rod and box, and inferring the existence of the hidden portion of the rod. This seems a remarkable achievement, especially considering they were occurring simultaneously.

In order to probe further questions of the development of perceptual organisation, it might be useful to show SST displays to younger infants, in a simple shape-perception task. If neonates were successful at discriminating a shape defined by illusory contours in this type of display, it would provide evidence for spatiotemporal integration as part of those perceptual skills that are organised at birth.

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