ELSEVIER

Cognition 71 (1999) 257–288

COGNITION

Synchronous change and perception of object unity: evidence from adults and infants

Peter W. Jusczyk[a,*], Scott P. Johnson[b], Elizabeth S. Spelke[c], Lori J. Kennedy[d]

[a]*Department of Psychology, Johns Hopkins University, 3400 North Charles Street, Baltimore, MD 21218-2685, USA*
[b]*Cornell University, Ithaca, New York, USA*
[c]*Massachusetts Institute of Technology, Cambridge, MA, USA*
[d]*University of Oregon, Eugene, OR, USA*

Received 18 June 1998; accepted 13 April 1999

Abstract

Adults and infants display a robust ability to perceive the unity of a center-occluded object when the visible ends of the object undergo common motion (e.g. Kellman, P.J., Spelke, E.S., 1983. Perception of partly occluded objects in infancy. Cognitive Psychology 15, 483–524). Ecologically oriented accounts of this ability focus on the primacy of motion in the perception of segregated objects, but Gestalt theory suggests a broader possibility: observers may perceive object unity by detecting patterns of synchronous change, of which common motion is a special case. We investigated this possibility with observations of adults and 4-month-old infants. Participants viewed a center-occluded object whose visible surfaces were either misaligned or aligned, stationary or moving, and unchanging or synchronously changing in color or brightness in various temporal patterns (e.g. flashing). Both alignment and common motion contributed to adults' perception of object unity, but synchronous color changes did not. For infants, motion was an important determinant of object unity, but other synchronous changes and edge alignment were not. When a stationary object with aligned edges underwent synchronous changes in color or brightness, infants showed high levels of attention to the object, but their perception of its unity appeared to be indeterminate. An inherent preference for fast over slow flash rates, and a novelty preference elicited by a change in rate, both indicated that infants detected the synchronous changes, although they failed to use them as information for object unity. These findings favor ecologically oriented accounts of object perception in which surface motion plays a privileged role. © 1999 Elsevier Science B.V. All rights reserved

Keywords: Object perception; Object unity; Gestalt versus ecological theories; Infant perception; Synchronous change

* Corresponding author. Tel.: +1-410-5167055; fax: +1-410-5164478;
E-mail address: jusczyk@jhu.edu (P.W. Jusczyk)

PII: S0010-0277(99)00026-8

1. Introduction

> Margaret, are you grieving over Goldengrove unleaving? (Gerard Manley Hopkins, 'Spring and Fall').

Although the visual world is filled with objects that partly occlude other objects, we experience our surroundings as a layout of bodies whose surfaces continue beyond the point where they are directly visible. Adults rely on a variety of sources of visual information in perceiving objects, including the motion, contour, texture and depth of visible surfaces (e.g. Papathomas et al., 1995). How is this information integrated to yield experiences of stable, coherent and bounded objects?

Visual organization has been a topic of interest at least since von Helmholtz (1925) and James (1890), and traditionally it has been explained in two general ways. According to the Gestalt psychologists, visual organization follows from a general law of Prägnanz, whereby visual experience is organized into the simplest and most regular units (Koffka, 1935). This law is the source of the well-known Gestalt principles of good continuation, good form, similarity and common fate, which serve to form units that are maximally smooth, regular and homogeneous in their properties and transformations. According to a contrasting ecological tradition that includes von Helmholtz (1925), Brunswik (1956) and Gibson (1979), visual organization results from sensitivity to information of high 'ecological validity' in the optic array: information that reliably specifies whether surfaces lie on the same or different objects. If perceivers follow Gestalt principles, on the ecological view, it is because those principles are useful predictors of object boundaries (see Brunswik and Kamiya, 1953), and because perceivers have either evolved or learned to use them.[1]

A wealth of research on object perception and perceptual organization in adults has attempted to distinguish these possibilities, with inconclusive results. Although adults have been found to perceive objects in accord with all the Gestalt principles of organization, these findings are equally consistent with both Gestalt and ecological theories. Further research has found that adults' organization of visual scenes is affected in some ways by learned processes of object recognition (e.g. Wallach et al., 1953; Peterson and Gibson, 1994), but this finding too can be encompassed by either theory: learning either may modulate the perceptions that result from an inherent Prägnanz principle, or it may modify the ecological validities assigned to particular information sources. For these reasons, some investigators have turned to studies of human infants.

Young infants' object perception has been assessed by means of preferential looking methods that rely on the tendency of infants to decrease their looking

[1]Some ecologically oriented theorists propose that perceivers learn the ecological validities of different sources of information for object boundaries (e.g. von Helmholtz, 1925; Brunswik and Kamiya, 1953). Other theorists propose that perceptual systems have evolved so as to capitalize on the information of highest validity (e.g. Gibson, 1979; Kellman, 1993). We return to this distinction.

time to successive presentations of a visual display, and then to look longer at subsequent displays that are perceived as more different from the familiar one (Bornstein, 1985; Spelke, 1985). For example, Kellman and Spelke (1983) presented infants with a display in which the two visible ends of a rod underwent common, lateral motion behind a central occluder (Fig. 1a). After habituation to this display, the infants were shown two test displays consisting of a complete rod (Fig. 1b) and a 'broken' rod whose previously visible parts now appeared with a gap between them (Fig. 1c). 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. The results of control experiments provided evidence that infants had no inherent preference for the broken rod, and that habituation to a

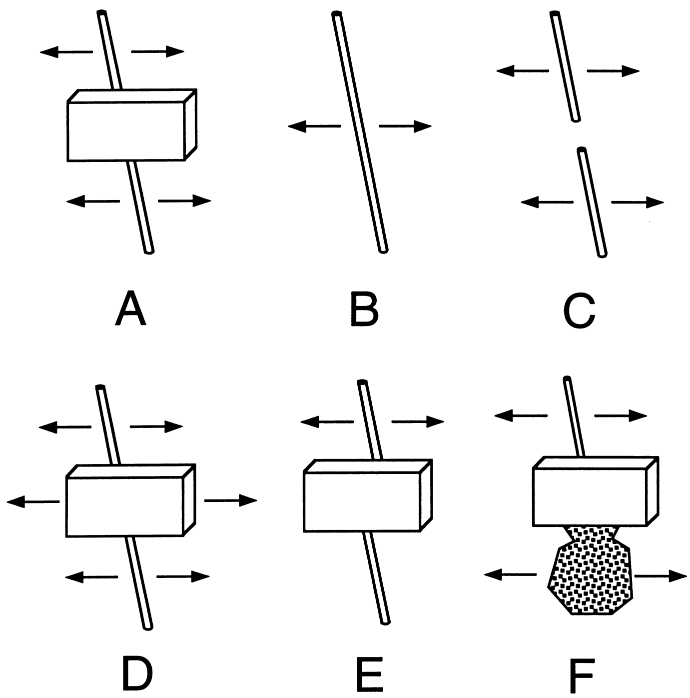

Fig. 1. Displays employed in past research to investigate the visual information used by adults and infants in perception of object unity (Kellman and Spelke, 1983). (A) Partial occlusion display in which two rod parts move relative to a stationary occluder. (B) Complete rod. (C) Broken rod. After habituation to (A), infants showed a reliable preference for (C) relative to (B), implying perception of the rod's unity in (A). (D) Partial occluder display in which rod and occluder surfaces move concurrently. (E) Partial occlusion display in which only the top rod part moves, as the bottom part and occluder remain stationary. (F) Partial occlusion display in which a rod and dissimilar surface move concurrently relative to a stationary occluder. The infants appeared to perceive unity only in (A) and (F), indicating the importance of object motion, relative to stationary surroundings, in young infants' perception of object unity. Adults perceived unity in (A) and (D), implying that with development, stationary configurational information sources contribute to object perception, in addition to motion.

partially occluded rod was followed, after removal of the occluder, by longer looking at a visibly changed rod display (a novelty preference) than at an unchanged rod display (a familiarity preference) (see Kellman and Spelke, 1983). These results provide evidence that the infants perceived the connectedness of the rod in the habituation display.

A variety of experiments have attempted to specify the conditions under which young infants perceive object unity by varying the motion and the stationary configurational properties of the occlusion display. Four-month-old infants appear to perceive the unity of a center-occluded object that moves laterally, vertically or in depth (Kellman et al., 1986), but not an object that moves jointly with its occluder (Kellman and Spelke, 1983) (see Fig. 1d), that is composed of one moving and one stationary part (Kellman and Spelke, 1983; Johnson and Náñez, 1995) (see Fig. 1e), or that remains stationary during motion of the occluder (Kellman and Spelke, 1983) or of the infant (Kellman et al., 1987). Perception of object unity also is affected by information for a difference in depth between the object and occluder: Although young infants appear to perceive the unity of a center-occluded object in two-dimensional displays in which a form moves in front of a textured background surface, occluding the surface as it moves (Johnson and Náñez, 1995; Johnson and Aslin, 1996; Johnson and Aslin, 1998a), they do not perceive object unity in a two-dimensional display lacking background texture (Johnson and Aslin, 1996), or in a three-dimensional display in which the rod parts are closer to the infant than the occluder so that the gap between them is directly visible (Kellman and Spelke, 1983).

Finally, young infants' perception of object unity is not strongly affected by some stationary configurational properties of a display such as the similarity of an object's visible surfaces in color or texture or the simplicity of the object's overall form (Kellman and Spelke, 1983; but see Craton, 1996; Needham, 1998). Four-month-old infants were found to perceive the unity of a moving, center-occluded object not only when the ends of the object were aligned and similar, but also when they formed two misaligned and dissimilar shapes (Kellman and Spelke, 1983; compare Figs. 1a,f). Young infants also failed to perceive the unity of center-occluded objects in stationary displays, even when the ends could be smoothly connected to form simple and homogeneous forms (Kellman and Spelke, 1983).

All these findings appear to cast doubt on the Gestalt view. Gestalt theory predicts that infants, like adults, will organize visual displays in accordance with all principles of organization, but infants favor motion over other Gestalt relations. Moreover, Gestalt theory should predict that subject-relative and object-relative motion will have equivalent effects on perception, but infants perceive object unity from the latter motion relationships alone (Kellman et al., 1987). Kellman (1993) suggests that these findings favor an ecological approach to object perception: Object-relative motion provides the most reliable information for object unity and boundaries, and infants' perception reflects this fact of our visual ecology.

Recent research nevertheless calls this conclusion into question, by providing evidence that infants' perception of object unity is influenced by the alignment and relatability of the object's visible edges when they view moving displays. When the two visible ends of a center-occluded object move together, infants have a stronger perception of object unity when the ends are aligned than when they are misaligned, and perception of the unity of the object is abolished altogether when the visible ends are not relatable (Johnson and Aslin, 1996; see also Needham and Baillargeon, 1997). These findings raise the possibility that infants perceive objects in accordance with all the configurational relationships that are effective for adults, just as the Gestalt psychologists predicted. Infants' failure to use these relationships in stationary displays may stem from their reduced attention to displays that undergo no motion or change.

In brief, neither studies of adults nor studies of infants have clarified the core processes giving rise to object perception. Although both infants and adults use common motion to perceive object boundaries, this finding can be encompassed within either ecological or Gestalt approaches to perception. In the present experiments, we investigate adults' and infants' perception of displays for which the predictions of the two approaches diverge: displays in which two visible, partly occluded surfaces undergo synchronous changes in brightness or color rather than synchronous changes in position.

Although synchronous changes in surface coloration have received little attention from students of visual organization, these changes provide a potential source of visual information of interest for distinguishing between Gestalt and ecological approaches. Common motion can be viewed as a special case of synchronous change, in which surfaces undergo simultaneous, parallel changes in position and velocity. In the original discussion of the principle of 'common fate' of Wertheimer (1958) indeed, common motion was seen as one of many ways in which two visual elements can change in concert. When an object is uniformly colored, moreover, synchronous changes in color and brightness conform to the Gestalt law of Prägnanz in a further way, by emphasizing the object's homogeneity of surface appearance. According to Gestalt theory, therefore, observers should use synchronized color change as information for object unity.

Unlike other Gestalt relationships, however, synchronous color and brightness changes are not reliable sources of information for object boundaries. Most brightness changes stem from changes in illumination, whose incidence on surfaces depends on surface orientation, reflectance and curvature, but not on object unity or boundaries. Other kinds of synchronous change, such as changes in the colors of leaves during autumn, do depend on the internal composition of objects, but these changes also are of questionable validity as information for object boundaries. Changes in objects' composition tend to occur very gradually, to occur asynchronously within a single object (e.g. the edges of a leaf may yellow before its interior) and to occur at roughly the same times in distinct objects (in a given scene, for example, different leaves will tend to change color at about the same time). According to ecological theorists, therefore, synchronous color and brightness changes should be less effective than synchronous motion at specifying object boundaries, both for adults and for infants.

Investigations of infants' perception of stationary, synchronously changing objects are of interest for a further reason. Like position changes, color and brightness changes are highly potent elicitors of visual attention in infants (Maurer and Lewis, 1998). An infant who views a stationary, synchronously changing object, therefore, should attend to that object as much as to a moving object. Infants' perception of such objects thus should cast further light on their sensitivity to the stationary Gestalt relationships of good continuation, good form and color similarity. If the infants in previous research failed to use such relationships to specify the unity of stationary objects because they were insufficiently attentive to those objects, then they might succeed at using those relationships in synchronously changing displays.

Accordingly, we investigated perception of center-occluded objects in synchronously changing displays. We begin by presenting a study of adults' perception of these displays, and then we turn to infants.

2. Experiment 1

In Experiment 1, we presented a group of adults with computer-generated displays in which two rod parts extended from behind an occluding box (Fig. 2). In different displays, the two visible surfaces of the rod were either aligned or misaligned, moving or stationary, and synchronously changing or constant in bright-ness and color. Adults' ratings of these displays were compared to investigate both the effectiveness of each source of information and the interactions among different sources. If the Gestalt law of Prägnanz governs adults' perception, then all three kinds of information should have influenced adults' ratings and different information sources should have interacted in common ways. If a principle of ecological validity governs adults' perception, then edge alignment and common motion should have influenced adults' perception but synchronous color changes should not.

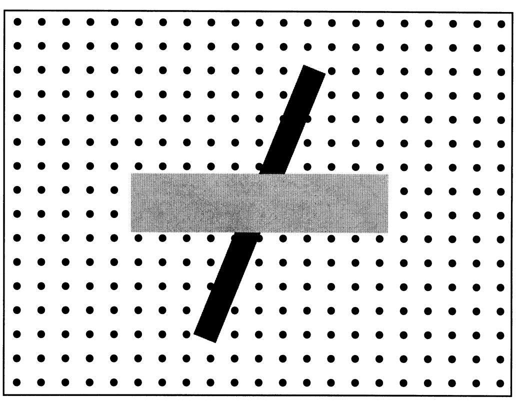

Fig. 2. Example of a rod-and-occluder display used in the present research. See text for details.

2.1. Materials and methods

2.1.1. Participants

Twenty undergraduate students, all with normal color vision and normal or corrected-to-normal acuity, received partial course credit for participation.

2.1.2. Apparatus and stimuli

An Amiga 3000 computer and an 80 cm, Barco color monitor were used to generate the displays. Eight displays were individually presented to each participant in a different random order. Each stimulus contained a 15.0 × 3.6 cm yellow occluder (18.4×4.6° at the observers' 45-cm-viewing distance), oriented with its long axis horizontal. The background consisted of a 16 × 21 grid of black dots against a 30.8 × 25.2 cm (34.4×29.2°) white field. The aligned/stationary/one-color display contained a blue 18.5×1.8 cm (22.3 × 2.3°) rod, oriented 22.5° clockwise from the vertical (see Fig. 2). The aligned/stationary/color-change display was identical to this display, except the rod surfaces underwent a uniform, gradual and repeated color change from red to purple, to blue and back to red. Each complete cycle of this change lasted 2 s. The aligned/moving/one-color and aligned/moving/color-change displays were identical to the two previously-described displays, respectively, except the rod parts underwent lateral translation at a constant rate of 5.4 cm/s (6.8°/s) behind the occluder. Each cycle of motion lasted 4 s; thus the rod moved 10.8 cm (13.6°) back and forth. There were also four displays in which the top rod part was oriented 22.5° clockwise from the vertical but the bottom rod part was oriented vertically. The edges of the two rod parts were relatable (Kellman and Shipley, 1991), such that they would join if extended in a straight path behind the occluder, comprising a single, bent, partly occluded surface. (A pair of edges leading behind an occluder that are relatable, but not collinear, may not be as likely as aligned edges to be perceived as contiguous) (see Kellman and Shipley, 1991). Thus there were four bent-rod displays: bent/stationary/one-color, bent/stationary/color-change, bent/moving/one-color and bent/moving/color-change.

2.2. Procedure

Participants were first shown a pencil whose ends protruded from behind an envelope as an example of a partly occluded object. They were then told that they would view a series of displays and asked to rate how likely it was that the two visible surfaces in each display were connected behind the occluder. This was done by means of a scale from 0 to 100, 0 indicating a high degree of confidence that the two surfaces were not connected behind the occluder, and 100 indicating a high degree of confidence that the two surfaces were connected. Participants were instructed that any number between (and including) 0 and 100 was permissible, depending on the strength of their impression of connectedness. All participants agreed that the pencil/envelope arrangement would merit a high number (at least 90). After these instructions, the lights were dimmed and the displays were presented one at a time. Participants were allowed to view each display as long as he or she wished (usually no longer than 10 s). A connectedness rating was given for each display prior to the next one being shown.

2.3. Results

Fig. 3 presents the connectedness ratings for each of the eight displays. Displays in which the rod parts were aligned received high ratings, regardless of whether or not common motion or synchronous color-change was available. Displays in which the rod parts were stationary and not aligned received low ratings, and displays in which the rod parts moved together and were not aligned received intermediate ratings.

The connectedness ratings were subjected to a 2(alignment: aligned vs. bent rod parts) × 2(motion: stationary vs. moving rod parts) × 2(color: one-color vs. synchronous color-change) within-subjects ANOVA. There was a significant effect of alignment, $F(1,19) = 37.05$, $P < 0.00001$, reflecting higher ratings of connectedness in displays with aligned rod parts. There was also a significant alignment × motion interaction, $F(1,19) = 18.21$, $P < 0.001$. No other main effects or interactions reached significance. Posthoc (Newman–Keuls) tests revealed that there were no significant differences among aligned-rod displays, which were all rated significantly higher in connectedness than bent-rod displays, Ps < 0.001. Among bent-rod displays, motion displays were rated significantly higher than stationary displays, Ps < 0.001.

2.4. Discussion

The findings of Experiment 1 provide evidence that the primary information determining perception of object unity was alignment of the rod parts: Connected-

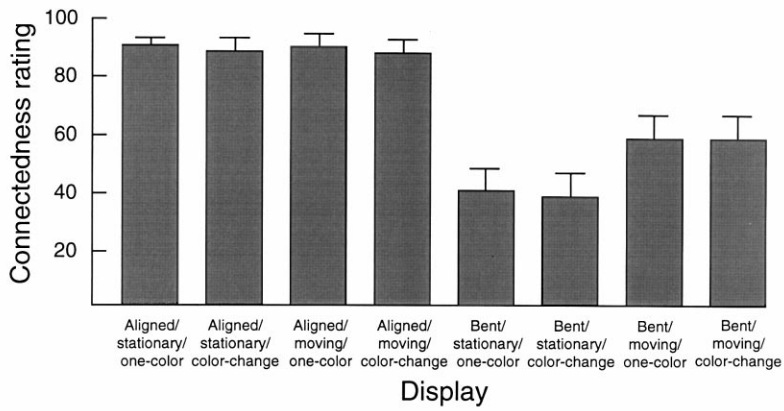

Fig. 3. Connectedness ratings from Experiment 1. Adults rated displays high in the likelihood of connectedness only when the rod parts were aligned, regardless of whether the rod parts moved or underwent synchronous color-change. Motion also contributed to perception of unity, however, in that ratings were higher in bent-rod displays when the rod parts moved together. Synchronous color change did not appear to contribute in any important way to perception of object unity.

ness ratings were near ceiling in each of the four alignment displays. A second effective information source was common motion: Although the connectedness ratings for aligned displays were at ceiling with or without motion, common motion influenced participants' ratings of bent-rod displays by shifting their perceptions toward connectedness. In striking contrast to these findings, synchronous color-change provided no contribution to judgments of object unity: Even with displays rated low in connectedness, such as the bent/stationary displays, participants showed no shift toward perception of connectedness in the presence of synchronous color-changes.

The primacy of alignment over common motion was unanticipated, and it conflicts with the findings from similar experiments conducted with three-dimensional objects (Kellman and Spelke, 1983; Smith et al., in preparation). When adults view a three-dimensional, center-occluded rod whose visible surfaces move together, they tend to perceive the surfaces as connected even when they are strongly misaligned. Two features of the present displays may account for this difference. First, the present displays were entirely two-dimensional and so may have failed to induce strong perceptions of surfaces in motion. Second, the displays used a computer-generated, constant velocity motion with sudden reversals of direction at its endpoints, whereas previous studies have used manually produced motions that decelerated before changing direction. Constant velocity motions and reversals are dynamically implausible and give rise to perceptual illusions (Runeson, 1974) which may attenuate their effectiveness as information for object unity. Whatever the reason for the greater effect of alignment, however, the present findings agree with other studies in providing information that both edge alignment and common motion specify object unity for adults.

The most important feature of the present findings is the absence of an effect of synchronous color change on adults' perception of object unity. This finding is at odds with the account of perceptual organization of Wertheimer (1958) and casts doubt on the thesis that a Gestalt law of Prägnanz governs adults' perception of objects. Nevertheless, Gestalt theory can be amended, without serious revision, to encompass this finding. Perhaps the law of Prägnanz operates in a simple way to govern object perception early in ontogeny, but it operates in a more complex way later in development, as perception is increasingly modulated by experience. Children may initially group surfaces into objects consistent with a general Prägnanz principle, assembling surfaces into units with the simplest motions, color changes, edges and the like. With development, however, children may learn that motion relationships are more informative than other synchronous changes. Although adults do not employ synchronous color changes to perceive object unity, therefore, any kind of detectable synchronous change may specify object unity for young infants.

The next experiments tested this possibility by investigating 4-month-old infants' perception of object unity in displays in which a center-occluded object synchronously changed in brightness or color. In all, we report six further experiments, in which a total of 112 infants was presented with either moving or stationary objects undergoing synchronous patterns of change in color or brightness, and in which the infants' perception of object unity was assessed. When the object was presented in motion (Experiment 3), the infants' looking patterns provided evidence that they perceived its unity. In contrast, none of the experiments provided evidence for perception of object unity when the object was stationary, regardless of the synchronous changes that were presented (Experiments 2 and 4–7). To investigate whether infants' failure to perceive object unity from synchronous changes in brightness or color stemmed from a failure to discriminate those changes, a final experiment assessed both infants' perception of object unity and the discriminability of the non-motion changes employed in our studies. Experiment 7 provided evidence that infants detected the changes in brightness and color of a stationary, center-occluded object, but that they failed to use these changes as information for object unity.

3. Experiment 2

Our first infant experiment was based on studies by Kellman and Spelke (1983) and Johnson and Náñez (1995). Four-month-old infants were habituated to the two-dimensional stationary display (identical to the aligned/stationary/color-change display described in Experiment 1; see Fig. 2). After habituation, the infants viewed stationary complete and broken rod test displays containing the same color changes as seen during habituation. We reasoned that if young infants are able to utilize common color change as information for object unity, there would be a reliable preference for the broken rod during testing.[2]

3.1. Materials and methods

3.1.1. Participants

The final sample consisted of 16 full-term infants (seven female; mean age = 121 days, SD = 10.7). Six additional infants were observed but not included in the sample due to excessive fussiness. The infants were recruited by hospital visits and follow-up telephone calls. The majority of the infants were from Caucasian, middle-class families. Parents were paid a nominal sum for their participation.

3.1.2. Apparatus and stimuli

The same computer and monitor as described in Experiment 1 were used to

[2] The possibility that infants would look longer at a broken rod because of an intrinsic preference for that display (e.g. a preference for two objects rather than one) was addressed by means of two control experiments, in which the broken and complete rods were presented either after no habituation (n=12) or after habituation to stationary rod-and-occluder displays with non-synchronous color or brightness changes in the top and bottom rod parts (n=16). In neither of these experiments was there any preference for the broken rod test display; nor was there a preference for the complete rod. These findings are consistent with the results of control conditions across a wide variety of object unity experiments (Kellman and Spelke, 1983; Kellman et al., 1987; Slater et al., 1990; Johnson and Aslin, 1995; Johnson and Náñez, 1995; Johnson and Aslin, 1996; Johnson and Aslin, 1998a) also demonstrating a lack of an intrinsic preference for either test display.

generate and present the displays. 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 hand-held microswitches, connected to the computer's mouse port. Observers were blind to the stimulus on the screen at any given time.

After habituation to the two-dimensional stationary display, the infants viewed stationary broken and complete rod test displays, undergoing the same color change as in the habituation display, presented three times each in alternation. Eight infants viewed the broken rod first after habituation, and eight viewed the complete rod first (order was determined randomly by the computer).

3.1.3. Procedure and analyses

The infants were tested individually in a darkened room. Each infant was placed in a car seat approximately 45 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. The computer program was designed to terminate the habituation phase after 15 trials or 15 min of total looking. However, all infants met the habituation criterion within these limits.

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 when the infant looked away. An individual trial was terminated when both observers released their microswitches for 2 overlapping s. 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 post-habituation trials.

Looking times were calculated by averaging the two observers' judgments for each test trial. Interobserver agreement was high (mean Pearson $r = 0.95$, calculated by comparing the two observer's judgments for each trial). The looking-time data across cells were heterogeneous, perhaps due to occasional 'sticky fixation', or prolonged gaze toward a visual stimulus (Hood, 1995). Therefore, data in this and all subsequent experiments were log-transformed prior to analysis. (Analyses were also conducted with non-transformed data, resulting in outcomes with similar interpretations, but with some tests of significance only reaching more marginal levels.)

3.2. Results

Fig. 4 presents the mean looking times on the last six habituation trials and on the

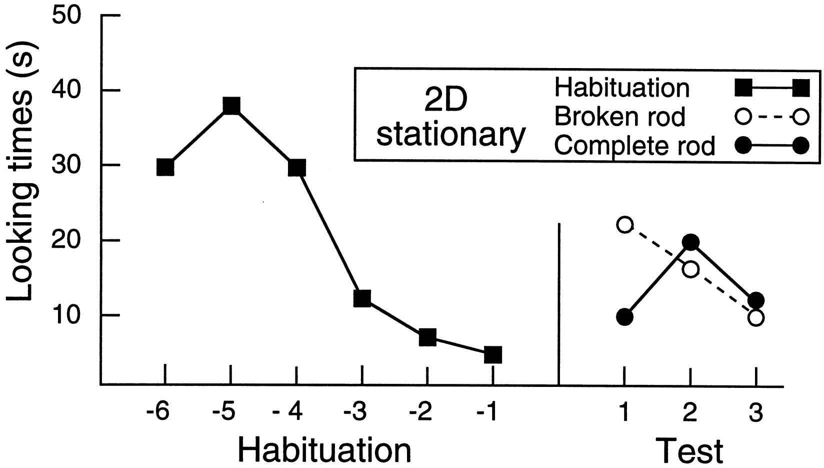

Fig. 4. Looking times during habituation and test from the 2D stationary condition in Experiment 2. Note that there was a preference for the broken rod during the first test-trial pair. However, analyses revealed that this preference was not reliable across test-trial pairs, thus providing no strong evidence for perception of object unity in the 2D stationary condition.

six test trials. On the early habituation trials, infants showed high levels of looking at the occlusion display, and looking subsequently declined. During the test, looking levels were comparable to those obtained in previous research with moving objects (Johnson and Náñez, 1995), but the infants did not demonstrate a consistent test display preference across trials (overall mean looking at broken rod=16.69 s, SD=23.74; mean looking at complete rod=14.65 s, SD=18.29). Preliminary ANOVAs including sex and order revealed no significant main effects or interactions, and data were collapsed across these variables for subsequent analyses. Looking times during the six posthabituation test trials were examined with a 2(display: broken vs. complete rod during test)×3 (trial block: first, second or third pair of test displays) ANOVA. There were no significant effects.

The infants in the two-dimensional stationary condition appeared to recover interest to the broken rod display during the first test trial pair, but not to the complete rod display. Recovery of looking to the broken rod (assessed relative to the last habituation stimulus) was marginally significant, $t(15)=2.10$, $P=0.053$ (two-tailed test). Recovery to the complete rod failed to reach significance, $t(15) = 1.84$, ns. The difference in recovery to the two test displays also was not significant ($t=1.11$, ns).

3.3. Discussion

The findings of Experiment 2 provide no clear evidence that infants perceive a stationary, center-occluded object undergoing synchronous changes in color as a unitary, connected body. After habituation to this display, infants showed no differential looking to complete and broken rod displays. Infants did show marginally significant recovery of looking time to the broken rod, a result that could suggest some perception of the object's unity. This suggestion is weakened, however, by the absence of a reliable difference in dishabituation to the two test displays. Infants' marginal recovery of looking time to the broken test display therefore might stem primarily from dishabituation to the removal of the occluder rather than from dishabituation to any perceived change in the rod.

When considered in light of the robust performance of the infants observed by Kellman and Spelke (1983) and Johnson and Náñez (1995), the findings of Experiment 2 suggest that synchronous color changes do not provide sufficient visual information to support strong and reliable perception of the rod's unity for infants. Because looking times were as high in the present experiments as in previous research with moving objects, this finding is not likely due to any lack of attention to the present displays. Nevertheless, it is possible that the absence of reliable test preferences stemmed from other non-specific factors. In particular, infants may show inconsistent looking patterns when they are presented with two-dimensional displays that change in color, and these inconsistencies might mask their perception of object unity. Experiment 3 tested this possibility by presenting infants with the same two-dimensional displays, except that the object appeared in motion.

4. Experiment 3

The infants in Experiment 3 were presented with a two-dimensional moving display, identical to the aligned/moving/color-change display described in Experiment 1. Based on the findings of Kellman and Spelke (1983) and Johnson and Náñez (1995), we hypothesized that after habituation to this display, the infants would subsequently show a consistent preference for a broken rod relative to a complete rod, thereby providing evidence for perception of object unity in the motion display.

4.1. Materials and methods

4.1.1. Participants

The final sample consisted of 16 full-term infants (seven female; mean age=124 days, SD=9.0). Five additional infants were observed but not included in the sample due to excessive fussiness. The infants were recruited from a similar population, and in the same manner, as in Experiment 2.

4.1.2. Apparatus, stimuli and procedure

The apparatus, stimuli and procedure were identical to those described in Experiment 2, except the infants were habituated to the two-dimensional moving display. The broken and complete rod test displays moved in an identical manner. The rod parts in all displays also underwent the same cyclical color change as employed in Experiments 1 and 2.

4.2. Results

Looking times again were calculated by averaging the two observers' judgments for each test trial, and interobserver agreement was again high (mean Pearson $r = 0.97$). As seen in Fig. 5, infants who were habituated to the two-dimensional moving display showed slightly higher initial levels of looking at the display than were those habituated to the two-dimensional stationary display in Experiment 2. By the end of habituation and throughout the test sequence, however, looking levels in the two experiments were very similar. During the test, the infants in Experiment 3 looked longer overall at the broken rod relative to the complete rod (mean looking at broken rod = 16.66 s, SD = 18.11; mean looking at complete rod = 10.88 s, SD = 12.31). Preliminary ANOVAs including sex and order, revealed no significant main effects or interactions, and data were collapsed across these variables for subsequent analyses. Looking times during the six posthabituation test trials were examined with a 2(display: broken vs. complete rod during test) × 3(trial block: first, second or third pair of test displays) ANOVA. The only significant effect was one of display, $F(1,15) = 10.36$, $P < 0.01$, the result of greater looking at the broken rod during test.

In order to investigate the contribution of motion to perception of object unity above and beyond the information present in both the two-dimensional stationary and two-dimensional motion displays (e.g. synchronous color change), the looking time data from Experiment 3 were compared with the those of Experiment 2 with a 2(condition: two-dimensional motion vs. two-dimensional stationary) × 2(display: broken vs. complete rod during test) × 3(trial block: first, second or third pair of test displays) mixed ANOVA. The only (marginally) significant effect was an interac-

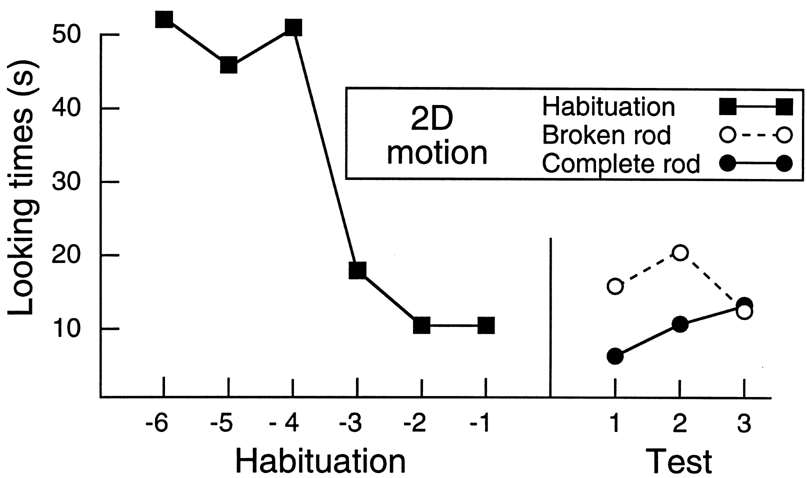

Fig. 5. Looking times during habituation and test from the 2D moving condition in Experiment 3. Note the overall preference for the broken rod during test, implying perception of object unity when the rod parts underwent common motion.

tion of condition and display, $F(1,30) = 3.91$, $P=0.057$. Posthoc comparisons revealed that infants in the two-dimensional motion condition looked significantly longer at the broken rod than at the complete rod, $P < 0.05$, whereas this difference failed to reach significance for infants in the two-dimensional stationary condition, $P > 0.80$. Infants in the two-dimensional stationary condition looked marginally longer at the complete rod than did infants in the two-dimensional motion condition, $P = 0.065$.

4.3. Discussion

Infants who were habituated to a moving, center-occluded rod subsequently looked longer at a broken rod than at a complete rod. This result is unlikely to have stemmed from an intrinsic preference for a broken rod, because no such preference was obtained in Experiment 2, in two baseline experiments in which infants viewed fully visible broken and complete rods changing in color with no prior habituation, or in a further experiment with habituation to an asynchronously changing object (see footnote 2). This preference also cannot be attributed to perception of the moving, occlusion display as a broken rod and to a preference for the more familiar rod display, for three reasons. First, a large body of evidence over four decades indicates that habituation is followed by a preference for a novel object over a familiar one (e.g. Bornstein, 1985; Spelke, 1985). Second, previous research using this method and similar partial occlusion displays provides strong and consistent evidence that infants who are habituated to a center-occluded object subsequently look longer at a novel than at a familiar object (Kellman and Spelke, 1983; Kellman et al., 1986; Kellman et al., 1987; Slater et al., 1990; Johnson and Aslin, 1995, 1996, 1998a,b; Johnson and Náñez, 1995).[3] Third, a comparison of Experiments 2 and 3 reveals a preference for the broken test display after habituation to the moving rod but not after habituation to the stationary rod. These findings would make no sense on the assumption that infants show a familiarity preference on posthabituation trials: In that case, one would be forced to conclude that common motion has the

[3]There is one exception to this generalization, reported in a recent paper by Bogartz and Shinskey (1998). After habituation to a moving, center-occluded rod, a group of 6-month-old infants was found to look modestly longer at a broken rod display, relative to a complete rod (Bogartz and Shinskey did not report whether this difference was statistically significant). This looking preference cannot be attributed to habituation, however, because of the preferences shown by two further groups of 6-month-old infants who were given an habituation sequence with a moving, fully visible rod that was either complete or broken. Preferences for the broken rod were slightly larger in the control group that was habituated to the broken rod (again, Bogartz and Shinskey did not report whether this difference was significant), suggesting that this particular looking time procedure did not produce stimulus-specific habituation and dishabituation. The failure to obtain habituation and novelty preferences with fully visible objects contradicts a large literature on visual discrimination and memory in infants (e.g. Bornstein, 1985). It also contradicts the findings of experiments by Kellman and Spelke (1983), in which infants showed reliably longer looking to a visibly changed rod after habituation to a rod-and-occluder display. We do not know why Bogartz and Shinskey failed to obtain consistent novelty preferences in their experiments. Given that they did not obtain such preferences with fully visible objects, it is not clear whether their use of this method to investigate infants' perception of occlusion provides any useful insights or interpretations.

opposite effect for the infants in Experiment 3 than it had for the adults in Experiment 1 (see also Wertheimer, 1958), for the infants in previous experiments (e.g. Kellman and Spelke, 1983), or for animals (e.g. Lea et al., 1996; Sato et al., 1997), and an effect opposite to that which would be predicted from our visual ecology (see Kellman, 1993). In contrast, the findings do make sense on the assumption that infants show a novelty preference on posthabituation trials, and that common motion of the center-occluded rod enhances perception of its unity.

The findings of Experiment 3 therefore add to the large body of evidence that 4-month-old infants perceive the unity of a center-occluded object whose visible ends are presented in motion. Moreover, the present experiments extend this evidence in two respects. First, previous research comparing infants' reactions to moving and to stationary center-occluded objects have generally found that infants look longer at moving than at stationary displays. This difference raised the possibility that motion enhances perception of object unity because of an interaction of motion with other Gestalt relationships such as color similarity and alignment: motion may enhance infants' attention to a partly occluded object, leading infants to perceive the object's unity by analyzing stationary Gestalt relationships (although see Kellman and Spelke, 1983). Experiment 2 provides evidence against this possibility, however, because infants looked at least as long at the stationary rod as infants in previous experiments have looked at moving rods. Moreover, looking times at the test displays of Experiment 3 were no higher, in general, than those for Experiment 2. Motion, therefore, did not appear to enhance infants' attention to stationary Gestalt relationships in these experiments, but rather specifically provided infants with information about object unity.

Second, as noted previously, past research was consistent with two general accounts of infants' perception of object unity: infants might have perceived object unity either by detecting synchronous patterns of motion or by detecting a larger class of synchronous patterns of change. Experiments 2 and 3 begin to distinguish these possibilities. These experiments provide evidence that motion, but not other kinds of synchronous change (such as color change), support perception of object unity in 4-month-old infants. Like the findings with adults, these findings cast doubt on the Gestalt psychologists' approach to object perception and favor an ecological approach in which motion plays a privileged role.

5. Experiment 4

Although the results of Experiments 2 and 3 provide no evidence that infants perceive object unity from synchronous changes in color, we cannot conclude that synchronous changes in color play no role in young infants' object perception. It is possible that in conjunction with other information, synchronous color change would influence infants' perception of object unity. In particular, the two-dimensional stationary display employed in Experiment 2 may have contained too little visual information to allow a response to object unity to emerge in the 4-month-olds we observed. Johnson and Aslin (1996) and Johnson (1997) proposed a threshold model, according to which veridical object perception occurs when two conditions are met: first, the display must encompass sufficient visual information, in order to support the perceptual completion and appropriate depth ordering of partly occluded and fully visible surfaces (Nakayama et al., 1996). One way in which this might be realized is by the number of information sources available that are consistent with a particular depth ordering of the display. Second, the observer must be capable of attending to, and using, the available information, and veridical object perception in young infants is potentially compromised due to limitations in their use of multiple information sources. Johnson and Aslin found support for the threshold model in studies of 4-month-old infants' perception of object unity in a series of two-dimensional displays in which the availability of different information sources was manipulated. They found that the infants appeared to perceive unity in displays containing common motion of the rod parts, background texture, and alignment of the rod parts' edges. However, in the absence of background texture or edge alignment, perception of object unity appeared to be disrupted.

We hypothesized that in Experiment 2 of the present study, the two-dimensional stationary display may have contained insufficient visual information to support young infants' perception of object unity. It might be that in three-dimensional displays, the addition of depth information (from binocular disparity, motion parallax and accommodation and convergence of the eyes), along with synchronous color change, would be sufficient to meet the threshold of information required for veridical perception of object unity in 4-month olds. This possibility was explored in Experiment 4 by habituating infants to a three-dimensional stationary rod-and-occluder display in which the visible rod parts underwent a color change similar to that in the displays employed in Experiments 2 and 3. This was accomplished by embedding small Christmas lights along the length of a translucent rod.

5.1. Materials and methods

5.1.1. Participants

The final sample consisted of 16 full-term infants (nine female; mean age=122 days, SD=6.7). Thirteen additional infants were observed but not included in the sample due to excessive fussiness (eight), experimenter error (four), or insufficient attention to the display (defined as failure to look longer than 12 s on three consecutive habituation trials) (one). The infants were recruited from a similar population as described in Experiments 2 and 3 via public birth announcements.

5.1.2. Apparatus and stimuli

The habituation stimulus consisted of a 25.0×13.0 cm yellow occluder (14.7×7.8° at the infant's 95-cm-viewing distance) and a complete or broken rod, oriented 22.5° clockwise from the vertical behind the occluder. The complete rod measured 53.0×1.3 cm (29.2×0.8°). The broken rod was similar in dimensions but contained a 10-cm gap in its center. The rods were made of Plexiglas and had alternating miniature red and blue Christmas lights inserted at 2.5 cm intervals for their entire lengths. As in Experiments 2 and 3, the rods underwent a uniform, gradual and repeated color change from red to blue and back again, each cycle of which lasted 2 s. During a cycle, the red lights began at full intensity and the blue lights at 0 intensity; the red lights were gradually dimmed to 0 intensity as the blue lights were brightened to full intensity. The rods were mounted on a 100×100 cm (46.5°) white pegboard panel, such that the center of the complete rod, and the gap in the broken rod, were hidden behind the occluder. The two display panels were attached via standard door hinges to the rear of a 100×100×30 cm display box. The box was lit from above by a 15 W fluorescent bulb within a translucent plastic panel. A weighted heavy white cotton curtain was dropped over the front of the box between trials. Black curtains surrounded the display box and shielded the rest of the room from the infant's view. As in Experiments 2 and 3, the test displays consisted of the connected and broken rods undergoing the same color changes at the same rates as during habituation, but with no occluder. Order of initial presentation was counterbalanced across subjects.

5.1.3. Procedure and analyses

The infants were placed in an infant seat. The first habituation trial began with the raising of the curtain. As in Experiment 2, the trial continued until the infant looked away for 2 s continuously. At the end of each trial, the curtain was lowered, and the next trial begun by raising the curtain after 6 s. The infants were habituated according to the same criterion as described in Experiment 2. Before the first test trial, the occluder was removed and the panel containing the fully visible complete or broken rod was swung into the display. During the intertrial interval between successive test trials, the rear panel in place during the previous trial was swung away and the panel with the other display was swung into place.

The single observer coded the infant's looking time by looking through one of the pegholes in the back panel and pressing a response key attached to a timer. The observer could not see the display from her vantage point, was never informed about the nature of the two displays, and dropped to the floor between test trials while the panels were prepared and positioned. A second assistant was seated at the table with the timer; she recorded the looking times on each trial and calculated the criterion looking decrement. A third person was responsible for raising and lowering the curtain and for changing the displays between trials. As in Experiments 2 and 3, when looking times to the habituation display declined to criterion, the infant viewed the test displays. The two test displays were seen three times each in alternation, for a total of six posthabituation trials.

Looking times on the test trials were analyzed as in Experiments 2 and 3, in order to determine whether infants showed any reliable preference for the broken rod display over the complete display. In addition, the test trial looking times in Experiment 4 were compared to those in Experiment 2, to determine if the use of three-dimensional displays enhanced infants' response to the color-change information. Finally, the test trial looking times in Experiment 4 were compared to those in Experiment 3, to assess the relative contributions of 2D motion information and 3D depth information to infants' perception of objects.

5.2. Results

As seen in Fig. 6a, the infants who were habituated to the three-dimensional stationary display subsequently showed no consistent preference for either test dis-

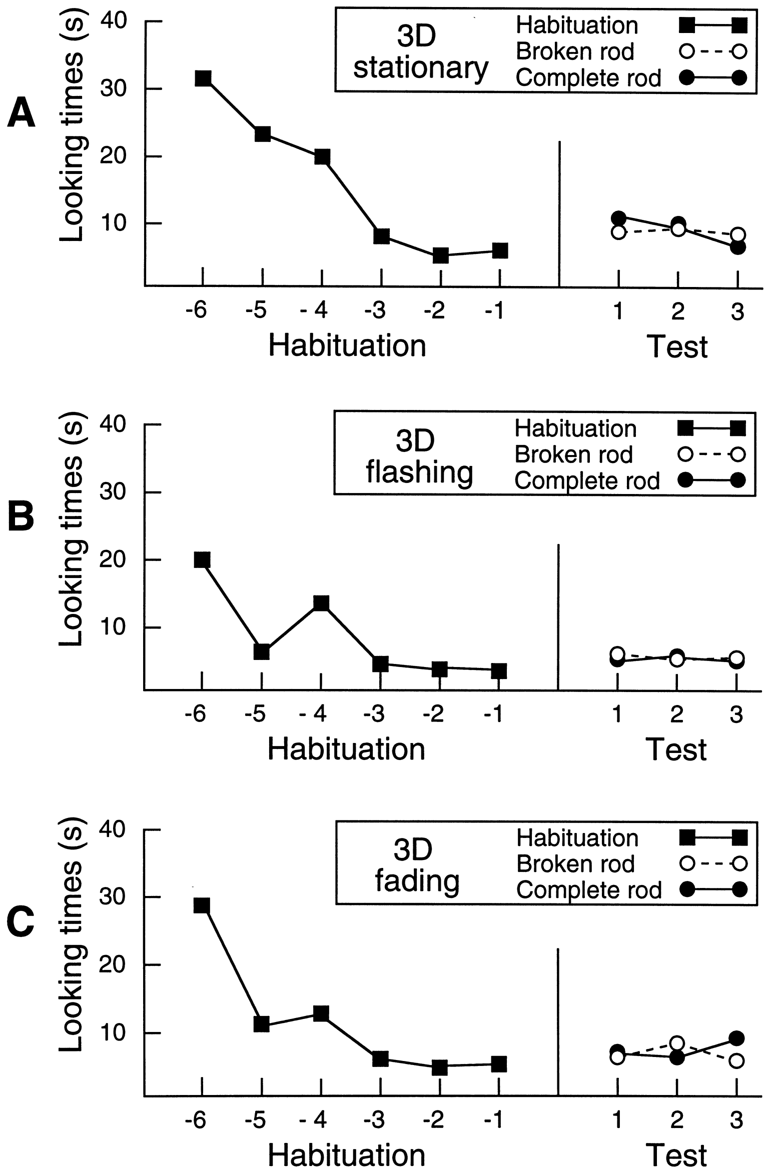

Fig. 6. Looking times during habituation and test from Experiments 2–6. (A) 3D stationary condition. (B) 3D flashing condition. (C) 3D fading condition. In none of these conditions did the infants demonstrate a clear preference for the broken rod, suggesting ambiguity regarding the rod parts' unity.

play (mean looking at broken rod=8.85 s, SD=8.93; mean looking at complete rod=9.51 s, SD=10.38). A display×trial ANOVA revealed no significant effects. A condition×display×trial ANOVA comparing infants' looking patterns in Experiment 4 to those in Experiment 2 (the two-dimensional stationary condition) likewise revealed no significant effects. However, a condition×display×trial ANOVA comparing the two-dimensional motion (Experiment 3) and three-dimensional stationary (Experiment 4) conditions yielded a significant interaction between condition and display, $F(1,30) = 6.77$, $P < 0.05$. Posthoc comparisons revealed that infants in the two-dimensional motion condition looked longer overall than those in the three-dimensional stationary condition, and that infants in the two-dimensional motion condition looked longer at the broken rod than at the complete rod (Ps < 0.01).

5.3. Discussion

Infants who viewed a three-dimensional, partly occluded stationary rod whose visible ends underwent a synchronous color change showed no evidence of perceiving the rod's unity. Their looking patterns differed reliably from those of infants who viewed a two-dimensional partly occluded moving rod (Experiment 3), providing further evidence that synchronous motion, but not other synchronous changes, specifies object unity. This experiment thus failed to support the threshold model, because the addition of three-dimensional depth information to a color-change rod display did not allow a veridical percept to emerge. Along with the results of the two-dimensional stationary condition, this experiment suggests that young infants do not use synchronous color changes as information for object unity under the present conditions.

6. Experiment 5

Although Experiments 2 and 4 provided no evidence that young infants perceive object unity by detecting synchronous changes in the ends of a stationary object, these experiments can be criticized in two ways. First, although the rods changed in color, they underwent little change in brightness. Psychophysical and physiological studies demonstrate that transient mechanisms in the visual system are more sensitive to changes in brightness than to changes in hue (e.g. Ramachandran and Gregory, 1978). It is possible, therefore, that synchronous changes in brightness would be more detectable by young infants and thereby more informative about object unity. Second, the rods in Experiments 2 and 4 changed color gradually. Some research suggests, however, that objects are better segregated by the visual system in the presence of more abrupt changes in visual onset (e.g. Yantis and Jonides, 1984; Jonides and Yantis, 1988). Synchronous, abrupt onsets of illumination may therefore provide infants with superior information about object unity.

In Experiment 5, we continued to test the effects of synchronous change on young infants' object perception by modifying the display of Experiment 4 in two respects.

First, instead of changing in color from red to blue, the rod in Experiment 5 changed in brightness from on, when the internal red lights were illuminated, to off. Second, this change was made abruptly: Instead of fading the red lights in and out, the lights were flashed on and off. Responses to the complete and broken rods in this three-dimensional flashing condition were compared to those in Experiment 2 (to assess the combined effects of brightness changes, abrupt onsets, and depth information on infants' perception of object unity) and Experiment 3 (to compare the combined effects of these sources of information to the effect of motion).

6.1. Materials and methods

6.1.1. Participants

The final sample consisted of 16 full-term infants (four female; mean age = 124 days, SD = 7.5). Two additional infants were observed but not included in the sample due to excessive fussiness (one) or insufficient attention to the display (one). The infants were recruited from a similar population as described in Experiments 2–4, via public birth announcements.

6.1.2. Apparatus, stimuli and procedure

The apparatus, stimuli and procedure were identical to those described in Experiment 4, with the following exceptions: only the red lights inside the rod were illuminated; during each cycle the lights were on for 0.5 s and then extinguished for 0.5 s, for a flashing rate of 1 Hz.

6.2. Results

As seen in Fig. 6b, the infants who were habituated to the three-dimensional flashing display subsequently showed no consistent preference for either test display (mean looking at broken rod = 5.63 s, SD = 3.80; mean looking at complete rod = 5.43 s, SD = 4.09). A display×trial ANOVA revealed no significant effects. A condition×display×trial ANOVA comparing the test trial looking preferences in Experiment 5 (three-dimensional flashing condition) to those in Experiment 2 (two-dimensional stationary condition) revealed a significant effect of condition, $F(1,30) = 17.30$, $P < 0.01$, due to greater looking overall by infants in the two-dimensional stationary condition. There was also a significant interaction between condition, display and trial, $F(2,60) = 3.21$, $P < 0.05$ (inspection of the data suggests that this effect reflects spurious fluctuations in stimulus preferences over trials – an effect that does not bear on the hypotheses under investigation). A condition × display × trial ANOVA comparing test trial looking preferences in Experiment 5 (three-dimensional flashing condition) and Experiment 3 (two-dimensional motion condition) revealed significant effects of condition, $F(1,30) = 7.18$, $P < 0.05$, resulting from greater looking overall by infants in the two-dimensional motion condition, and display, $F(1,30) = 8.37$, $P < 0.01$, qualified by a significant interaction between condition and display, $F(1,30) = 4.64$, $P < 0.05$. Posthoc comparisons revealed significantly greater looking at the broken rod by infants in the two-dimensional motion condition relative to looking at the complete rod, and greater than looking at either rod by infants in the three-dimensional flashing condition (Ps < 0.01).

6.3. Discussion

Experiment 5, like the stationary conditions in Experiments 2 and 4, provided no evidence that young infants perceived the stationary partly occluded object in the habituation display as connected behind the occluder. The infants showed reliably less preference for a broken rod after habituation to a center-occluded stationary rod undergoing synchronous, abrupt-onset changes in brightness (Experiment 5) than after habituation to a center-occluded moving rod (Experiment 3). The introduction of brightness changes evidently did not influence infants' perception of the unity of the center-occluded object.

The findings of Experiment 5, like those of Experiments 2 and 4, therefore, suggest that infants do not perceive object unity via synchronous changes in a stationary object. Nevertheless, it is possible that the stationary displays in Experiments 2, 4 and 5 failed to evoke perception of object unity because of their unnaturalness.[4] Few objects, other than neon signs and Christmas lights, undergo repeated, cyclical changes in illumination. Instead, natural objects that undergo changes tend to do so only once during any given episode. For example, people who blush do not continuously alternate between a flushed face and a pale face over a short period of time; when ice melts, it melts slowly rather than going through a rapid series of alternations between a solid and a liquid state. Accordingly, the next experiment investigated infants' perception of a center-occluded object that underwent a single, synchronous, gradual change in color.

7. Experiment 6

In Experiment 6, infants were presented with a three-dimensional center-occluded object that changed its color just once during each trial (the three-dimensional fading condition). On each habituation and test trial, infants viewed a rod that changed from red to blue and then remained blue throughout the rest of the trial. Other aspects of the experimental design and method remained the same as in Experiments 2–5.

7.1. Materials and methods

7.1.1. Participants

The final sample consisted of 16 full-term infants (four female; mean age=121 days, SD=6.3). Five additional infants were observed but not included in the sample due to excessive fussiness (three), experimenter error (one), or insufficient attention

[4]We thank Tom Bever for these observations and for suggesting this experiment.

to the display (one). The infants were recruited from a similar population as described in Experiments 2–5, via public birth announcements.

7.1.2. Apparatus, stimuli and procedure

The apparatus, stimuli and procedure were identical to those described in Experiments 4 and 5, with the following exceptions: at the start of each habituation and test trial, the rod was presented with all the red lights illuminated; it changed from red to blue over a 2 s period, and then remained blue throughout the rest of the trial.

7.2. Results

As seen in Fig. 6c, the infants who were habituated to the three-dimensional fading display subsequently showed no consistent preference for either test display (mean looking at broken rod = 7.05 s, SD = 7.06; mean looking at complete rod = 7.66 s, SD = 6.12). A display×trial ANOVA revealed no significant effects. A condition×display×trial ANOVA comparing looking preferences in Experiment 6 (three-dimensional fading condition) to those in Experiment 2 (two-dimensional stationary condition) yielded a significant effect of condition, $F(1,30) = 8.44$, $P < 0.01$, due to greater looking overall by infants in the two-dimensional stationary condition. There was also a significant interaction between display and trial, $F(2,60) = 4.06$, $P < 0.05$ (suggesting spurious fluctuations in stimulus preferences not relevant to the hypothesis under investigation). A condition × display × trial ANOVA comparing looking preferences in Experiment 6 (three-dimensional fading condition) to those in Experiment 3 (two-dimensional motion condition) revealed only a significant interaction between condition and display, $F(1,30) = 9.88$, $P < 0.01$. Posthoc comparisons revealed significantly greater looking at the broken rod relative to the complete rod by infants in the two-dimensional motion condition, and greater looking than at either rod by infants in the three-dimensional fading condition (Ps < 0.01).

7.3. Discussion

Experiment 6 provided no evidence that young infants utilize synchronous change, even this naturalistic change, in perception of partly occluded objects. The comparison of looking preferences in Experiments 6 and 2 indicated that the introduction of a naturalistic change in a three-dimensional display did not enhance infants' perception of object unity; the comparison of preferences in Experiments 6 and 3 revealed again that motion provides more effective information for object unity than do other types of synchronous change.

Experiments 2–6 tested infants' perception of object unity in five different displays in which the ends of the object underwent synchronous changes. The rate of change varied from instantaneous (the flashing change in Experiment 5), to gradual and cyclic (Experiments 2–4), to once per trial (the fading change in Experiment 6). All the stationary conditions yielded the same negative finding: infants' looking times to fully visible complete and broken displays provided no evidence that they perceived a unitary, connected object behind the central occluder. Only when the rod underwent concurrent synchronous changes in position (Experiment 3) did the infants appear to perceive its unity.

8. Experiment 7

The final experiment in this series was undertaken for two purposes. First, it explored the central issue of young infants' perception of object unity by using a greater variety of patterns of synchronous change. Infants viewed a center-occluded object that flashed synchronously at either a faster or a slower rate than in Experiment 5, in order to test whether either, or both, of these rates would increase the effectiveness of synchronous changes as information for object unity. Second, Experiment 7 investigated whether the infants in Experiments 2–6 were able to detect the temporal changes used in the previous experiments. We think it is likely that the infants were sensitive to these changes, because past research has demonstrated young infants' sensitivity to color and brightness (see Teller and Bornstein, 1987) and the variety of rates that were employed in the present research lie well within the range of infants' temporal resolution (e.g. Balaban and Dannemiller, 1992). Moreover, young infants have been found to discriminate between rates like those in Experiments 2–6 in audio-visual displays (e.g. Spelke, 1979; Lewkowicz, 1992). Because spectral sensitivity, contrast sensitivity, temporal resolution and rate discrimination have not been tested with the present displays, however, it remains conceivable that the color and brightness changes were not detected by the infants in Experiments 2–6.

As in Experiment 6, the infants in Experiment 7 were habituated to a center-occluded rod whose visible portions flashed in synchrony, and then were tested with complete and broken rod displays. For the infants in the three-dimensional fast-flash condition, the occluded rod flashed faster than in all the previous experiments: 4 cycles/s. For the infants in the three-dimensional slow-flash condition, the occluded rod flashed slower than in Experiment 5: 0.5 cycle/s. Infants in both conditions viewed test displays that flashed either at the same rate seen during habituation, or the other rate (i.e. fast vs. slow).

To investigate both perception of object unity and discrimination between different rates of change, the test trial looking times of the infants in the two conditions were compared so as to distinguish between three possibilities. First, if infants failed to perceive a unitary object and failed to discriminate the two rates of change, then infants in the two conditions should show equivalent looking times across the two test display rod types (broken vs. complete) and flash rates (fast vs. slow). Second, if infants failed to perceive a unitary object but successfully discriminated the two flash rates, then infants should show no preferences between the two test rods, but they would show a reliable preference between the two test rates. Infants might show a preference for the novel rate, or they might have an intrinsic preference for either the fast or slow flash rate. Third, if infants were able to perceive object unity based on one or both of the new flash rates in Experiment 7 and they discriminated between the flash rates, then these two effects should be discernible in the test trial looking times: Infants in one or both conditions should prefer the broken rod, and a flash rate preference should also be evident.

8.1. Materials and methods

8.1.1. Participants

The final sample consisted of 32 full-term infants (16 female; mean age = 131 days, SD = 7.4). Eleven additional infants were observed but not included in the sample due to excessive fussiness (six), experimenter error (four), or insufficient attention to the display (one). The infants were recruited from a similar population as described in Experiments 2–6, via public birth announcements.

8.1.2. Apparatus and stimuli

The apparatus and stimuli were identical to those described in Experiments 4–6, with the following exceptions: the red lights in the habituation and test rods flashed at either a fast rate (4 cycles/s) or a slow rate (0.5 cycle/s).

8.1.3. Design and procedure

Among the 32 infants who participated in the experiment, 16 were habituated to the fast flash rate and the remaining 16 were habituated to the slow flash rate. All infants subsequently viewed the fully visible complete and broken rods on six alternating test trials (as in Experiments 2–6). For half the infants habituated to each flash rate, the complete rod flashed at the fast rate and the broken rod flashed at the slow rate. For the other infants, the pairing of rod displays and flash rates was reversed. Each infant therefore viewed one novel and one familiar flash rate during test.

8.2. Results

The data from Experiment 7 were subjected to two independent analyses. First, patterns of looking at the two rod types (broken vs. complete) were assessed. Second, patterns of looking at the two flash rates (fast vs. slow) were analyzed. (Because the design of Experiment 7 did not permit the inclusion of infants in each of the possible conditions (two possible flash rates for the habituation display and each of the two test displays), an omnibus ANOVA was not possible.)

8.2.1. Analyses of rod type preferences

As seen in Fig. 7, the infants who were habituated to the three-dimensional, fast flash (Fig. 7a) and three-dimensional, slow flash (Fig. 7b) displays, subsequently showed no consistent preference for either test display. For infants in the three-dimensional, fast flash condition, mean looking at broken rod = 2.79 s, SD = 2.34; mean looking at complete rod = 3.47 s, SD = 4.66. For infants in the three-dimensional, slow flash condition, mean looking at broken rod = 4.49 s, SD = 3.88; mean looking at complete rod = 5.69 s, SD = 6.57. A condition (three-dimensional, fast

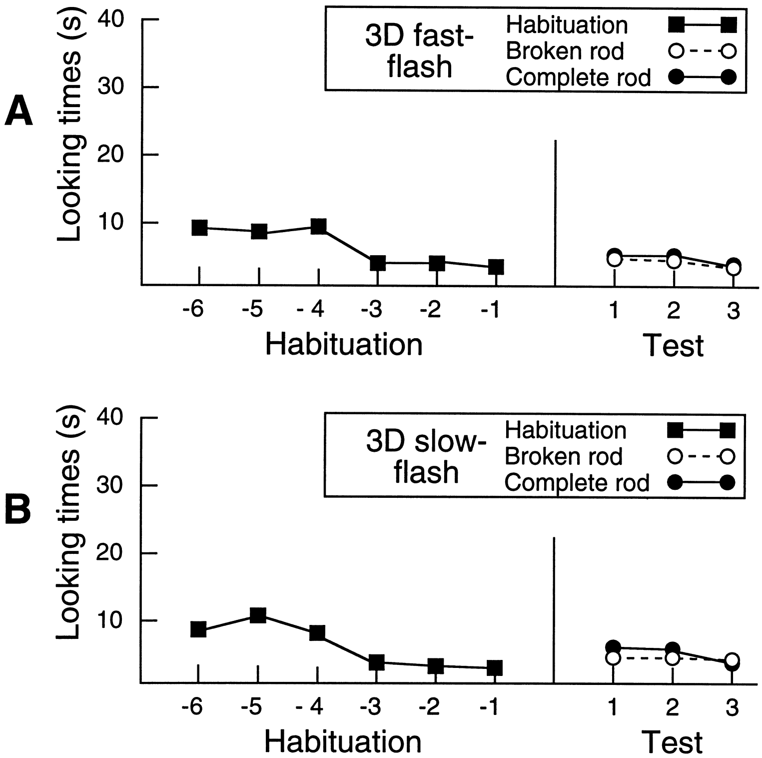

Fig. 7. Looking times during habituation and test from Experiment 7. Posthabituation data show looking at the two test rod types (i.e. broken vs. complete). (A) 3D fast-flash condition. (B) 3D slow-flash condition. In neither condition did the infants demonstrate a clear preference for the broken rod, again providing no evidence for perception of object unity.

flash vs. three-dimensional, slow flash)×display×trial ANOVA yielded a significant effect of condition, $F(1,30) = 6.75$, $P < 0.05$, the result of greater looking overall during test by infants in the three-dimensional, slow flash condition (mean = 5.09 s, SD = 5.40) relative to infants in the three-dimensional, fast flash condition (mean = 3.13 s, SD = 3.69). (This effect is explored further in analyses outlined in the next section.) There was also a main effect of trial, $F(2,60) = 12.03$, $P < 0.01$, the result of a decline in looking across the three test trials, and a significant interaction between condition, display and trial, $F(2,60) = 4.45$, $P < 0.05$ (again suggesting spurious fluctuations in stimulus preferences not relevant to the hypothesis under investigation).

8.2.2. Analyses of flash rate preferences

As seen in Fig. 8, infants in both the three-dimensional, fast flash (Fig. 8a) and three-dimensional, slow flash (Fig. 8b) conditions looked longer at the test displays with the faster flash rate (mean looking at the fast rate = 5.04, SD = 5.80; mean looking at the slow rate = 3.18 s, SD = 3.05). A condition×display×trial ANOVA revealed a significant effect of condition (discussed in the previous section), due to greater looking overall during test by infants in the three-dimensional, slow flash condition: a preference for the novel rate.

There was also an effect of display, $F(2,30) = 12.59$, $P < 0.01$, due to the preference for the fast flash rate, an effect of trial, $F(2,60) = 12.02$, $P < 0.001$, resulting from a decline in looking across the three test trial pairs, and an interaction between display and trial, $F(2,60) = 3.90$, $P < 0.05$, due to the greater magnitude of preference for the fast rate during the first test trial pair relative to subsequent pairs (see Fig. 8).

8.3. Discussion

As in the previous stationary color and brightness change conditions, Experiment 7 provided no evidence that the changes in flash rate we tested contributed to 4-month-old infants' perception of object unity. However, the results of Experiment 7

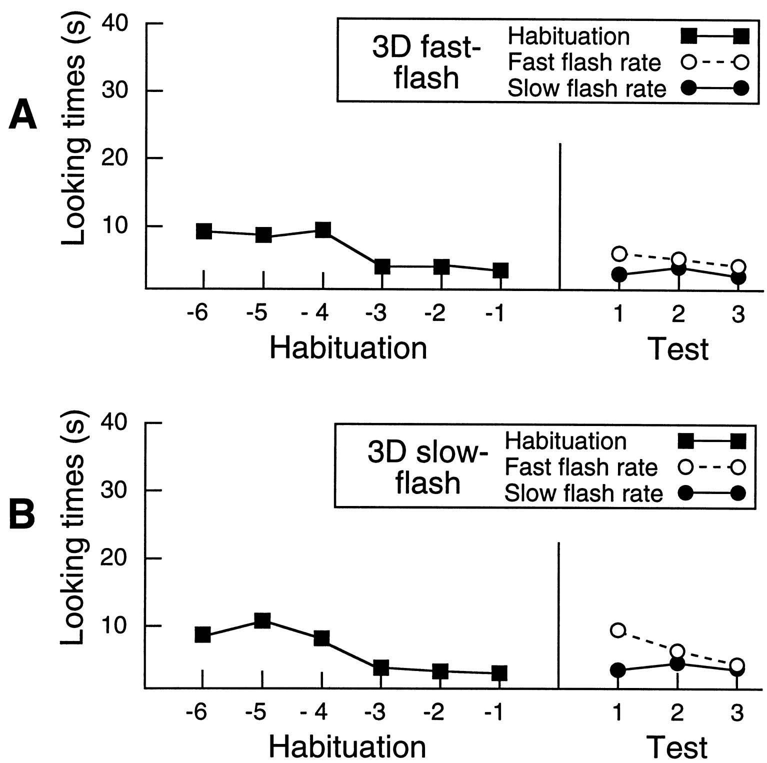

Fig. 8. Looking times during habituation and test from Experiment 7. Posthabituation data show looking at the two flash rates employed during test (i.e. fast vs. slow). (A) 3D fast-flash condition. (B) 3D slow-flash condition. In both conditions, the infants showed a preference for the fast flash rate, indicating that the flash rates employed in the present studies were discriminable.

indicate that the infants detected and discriminated the two flash rates: They showed a reliable preference for the test display that flashed at the faster rate. The infants' intrinsic preference provides evidence that the changes in flash rate used in our experiments were discriminable by 4 months of age. Infants' failure to perceive object unity specified by synchronous flash rates therefore cannot be explained by a failure to detect these rates.

9. General discussion

The present studies provide evidence that adults and infants perceive object unity by detecting the common motion of an object's visible surfaces, but not by detecting other synchronous changes in those surfaces. These findings provide no support for the thesis that object perception depends on a Gestalt law of Prägnanz. They suggest, instead, that object perception depends on sensitivity to the most reliable information for object boundaries, in accordance with ecologically-oriented theories.

Because some of the primary conclusions of this research are negative, they must be viewed with caution: Could the findings reflect limitations of our displays or methods rather than limitations in infants' and adults' perception of objects? Although this possibility can never be eliminated, three features of the present findings render it unlikely. First, our experiments are highly similar, both in method and in displays, to previous studies in which 4-month-olds successfully perceived object unity from patterns of synchronous, common motion (e.g. Kellman and Spelke, 1983; Kellman et al., 1986, 1987; Johnson and Náñez, 1995; Johnson and Aslin, 1996, 1998a). In our studies, moreover, infants successfully perceived object unity specified by motion (Experiment 3) while failing to perceive object unity from synchronous color or brightness changes (Experiments 2 and 4–7). The contrasting findings of these sets of studies suggest that common motion provides more effective information for object unity than do color or brightness changes in a stationary object. Second, the present experiments tested infants with a considerable number of occlusion displays undergoing a variety of synchronous changes. If young infants have any ability to perceive object unity from patterns of synchronous change in a stationary object, the present findings indicate that this skill is fragile at best.[5] Third, Experiment 7 provides evidence that infants detected the synchronous color changes

[5]Recently, Needham (1998) reported that 4.5-month-olds used the surface features of stationary objects to perceive object segregation, providing evidence that young infants have at least limited abilities to perceive unity (or lack thereof) in stationary displays. However, comparisons between Needham's study and other research on infants' perception of center-occluded objects must be undertaken with caution, due to differences in displays and methods. For example, Needham's displays consisted of two adjacent objects that, based on surface appearance (i.e. color and shape), would likely appear segregated to adults, but whose potential connectivity was made ambiguous by hiding the objects' adjacency with an occluder. Moreover, infants' responses to the objects' connectivity was assessed by manually moving one or both objects after a short familiarization period. If Needham's method is more sensitive than ours, then her results imply that sensitivity to stationary color and brightness information is weak, but not absent in infancy. Nevertheless, our principal conclusion stands: motion is the most robust information for object unity, above and beyond any effects of stationary changes in surface color and brightness.

and showed high attention to all the synchronously changing displays. Infants' failure to perceive object unity from these synchronous changes therefore does not likely result from limits to their sensitivity or attentiveness to these changes.

The present findings shed further light on the development of sensitivity to edge alignment as information for object unity. Previous research revealed that infants fail to use edge alignment to specify the unity of a stationary object (e.g. Kellman and Spelke, 1983), but successfully use edge alignment to specify the unity of a moving object (Johnson and Aslin, 1996). One potential explanation for these findings was that a principle of good continuation influences the perception of infants and adults in the same way, but that this influence is masked for infants with stationary displays, because infants are less attentive to those displays. The present findings provide evidence against this interpretation. When the infants in Experiments 2 and 4–7 viewed a stationary, center-occluded rod with aligned edges and synchronously changing surfaces, they showed levels of attention to the occlusion display that were at least as high as infants have shown for moving displays, but they failed to perceive the occluded object's unity. This finding, together with the findings of Experiment 1 showing a strong effect of edge alignment for adults, suggests that infants do not respond to edge alignment as do adults.

Why do infants show effects of edge alignment with moving but not stationary displays? One possibility is that the alignment of spatially separated edges increases the detectability of the common motion of those edges. Both neurophysiological and psychophysical studies of edge detection suggest that relationships among aligned edges are easier to detect than relationships among misaligned edges (e.g. Day et al., 1993; Field et al., 1993). Because sensitivity to the correlated motion of different edges may be higher when edges are aligned than when they are misaligned (compare Saidpour et al., 1994; Shiffrar and Lorenceau, 1996), it is possible that the common motion of the visible surfaces in rod displays was only detectable by infants when the edges were aligned. If that is the case, then infants could not be said to perceive object unity in accord with a principle of good continuation, contrary to Gestalt theory. Rather, object perception would depend only on detection of correlated motion, which in turn would depend in part on other visual relationships.

In summary, the present research adds to the evidence that object perception originates in abilities to perceive object unity and boundaries by analyzing patterns of surface motion. Young infants' ability to use motion to perceive the unity of a center-occluded object has been found to be robust across several laboratories using a number of variations in displays (Kellman and Spelke, 1983; Kellman et al., 1987; Slater et al., 1990; Johnson and Aslin, 1995, 1996, 1998a; Johnson and Náñez, 1995). This ability was apparent with the present displays as well (Experiment 3). Because infants failed to perceive object unity by analyzing other patterns of synchronous change, their sensitivity to motion does not appear to depend on a more general tendency to organize displays into units of maximum simplicity and homogeneity, as Gestalt theory predicts. Instead, our findings support ecological theories emphasizing the role of motion in the development of object perception (e.g. Bertenthal, 1993; Spelke and Van de Walle, 1993; Kellman, 1996). Young infants have been found to segregate surfaces using motion-carried information (Granrud et al., 1984; Kaufman-Hayoz et al., 1986; Johnson and Aslin, 1998a). Infants also perceive visual structure from motion, recovering the form of a figure from kinetic illusory contours (Johnson and Aslin, 1998a; Johnson and Mason, 1998), the jointed structure of a person or animal from biomechanical motions (Bertenthal et al., 1984), and the shape of a solid, three-dimensional object from moving two-dimensional projections (Kellman and Short, 1987; Arterberry and Yonas, 1988; Schmuckler and Proffitt, 1994). Because the infants in all these studies were several months old, the studies do not reveal whether sensitivity to motion depends on probabilistic learning of various sources of visual information, as proposed by Brunswik (1956) and von Helmholtz (1925), or on innate perceptual systems that evolved to capture ecologically significant regularities (Kellman, 1993). This question invites further study of the early development of object perception, and of the developing motion-sensitive mechanisms on which it depends.

Acknowledgements

Supported by NIH grant R01 HD 15795 and NIMH Senior Scientist Award 01490 to P.W.J., ESRC grants R000221813 and R000237093 to S.P.J., and NIH grant R37 HD 23103 to E.S.S. Portions of these studies were presented at the April 1997 meetings of the Society for Research in Child Development, Washington DC. We thank Angie Elkus, Sarah Gomm, Tracy Schomberg, Ann Marie Jusczyk, Chris Long and Uschi Mason for their assistance in conducting the experiments, Dave Hermeier for the design and construction of the apparatus and electrical circuitry used in Experiments 4–7, and Dick Aslin and Tom Bever for comments and suggestions. We are especially grateful to the infants and parents who participated in the studies.

References

Arterberry, M.E., Yonas, A., 1988. Infants' sensitivity to kinetic information for three-dimensional object shape. Perception and Psychophysics 44, 1–6.

Balaban, M.T., Dannemiller, J.L., 1992. Age differences in responses to temporally modulated patterns at 6 and 12 weeks. Infant Behavior and Development 15, 359–375.

Bertenthal, B.I., 1993. Infants' perception of biomechanical motion: intrinsic image and knowledge-based constraints. In: Granrud, C.E. (Ed.), Visual Perception and Cognition in Infancy. Erlbaum, Hillsdale, NJ, pp. 175–214.

Bertenthal, B.I., Proffitt, D.R., Cutting, J.E., 1984. Infant sensitivity to figural coherence in biomechanical motions. Journal of Experimental Child Psychology 37, 213–230.

Bogartz, R., Shinskey, J., 1998. On perception of a partially occluded object in 6-month-olds. Cognitive Development 13, 141–163.

Bornstein, M.H., 1985. Habituation of attention as a measure of visual information processing in human infants: summary, systematization, and synthesis. In: Gottlieb, G., Krasnegor, N.A. (Eds.), Measurement of Audition and Vision in the First Year of Postnatal Life: A Methodological Overview. Ablex, Norwood, MA, pp. 253–300.

Brunswik, E., 1956. Perception and the Representative Design of Psychological Experiments. University of California Press, Berkeley, CA.

Brunswik, E., Kamiya, J., 1953. Ecological cue-validity of 'proximity' and of other Gestalt factors. The American Journal of Psychology 66, 20–33.

Craton, L.G., 1996. The development of perceptual completion abilities: infants' perception of stationary, partially occluded objects. Child Development 67, 890–904.

Day, R.H., Stecher, E.J., Parker, A.L., 1993. The effect of edge orientation and movement direction of the apparent misalignment of collinear bars. Perception and Psychophysics 53, 642–647.

Field, D.J., Hayes, A., Hess, R.F., 1993. Contour integration by the human visual system: Evidence for a local 'association field'. Vision Research 33, 173–193.

Gibson, J.J., 1979. The Ecological Approach to Visual Perception. Houghton Mifflin Company, Boston, MA.

Granrud, C.E., Yonas, A., Smith, I.M., Arterberry, M.E., Glicksman, M.L., Sorknes, A.C., 1984. Infants' sensitivity to accretion and deletion of texture as information for depth at an edge. Child Development 55, 1630–1636.

Hood, B.M., 1995. Shifts of visual attention in the human infant: a neuroscience approach. In: Rovee-Collier, C., Lipsitt, L.P. (Eds.), Advances in Infancy Research, Vol. 9. Ablex, Norwood, MA, pp. 163–216.

Horowitz, F.D., Paden, L., Bhana, K., Self, P., 1972. An infant-control procedure for studying visual fixations. Developmental Psychology 7, 90.

James, W., 1890. The Principles of Psychology. Holt, New York.

Johnson, S.P., 1997. Young infants' perception of object unity: implications for development of attentional and cognitive skills. Current Directions in Psychological Science 6, 5–11.

Johnson, S.P., Aslin, R.N., 1995. Perception of object unity in 2-month-old infants. Developmental Psychology 31, 739–745.

Johnson, S.P., Aslin, R.N., 1996. Perception of object unity in young infants: the roles of motion, depth, and orientation. Cognitive Development 11, 161–180.

Johnson, S.P., Aslin, R.N., 1998. Young infants' perception of illusory contours in dynamic displays. Perception 27, 341–353.

Johnson, S.P., Aslin, R.N., 1998b. Young infants' perception of transparency, in preparation.

Johnson, S.P., Mason, U., 1998. Perception of kinetic illusory contours by 2-month-old infants, submitted.

Johnson, S.P., Náñez, J.E., 1995. Young infants' perception of object unity in two-dimensional displays. Infant Behavior and Development 18, 133–143.

Jonides, J., Yantis, S., 1988. Uniqueness of abrupt visual onset in capturing attention. Perception and Psychophysics 43, 346–355.

Kaufman-Hayoz, R., Kaufman, F., Stucki, M., 1986. Kinetic contours in infants' visual perception. Child Development 57, 292–299.

Kellman, P.J., 1993. Kinematic foundations of infant visual perception. In: Granrud, C.E. (Ed.), Visual Perception and Cognition in Infancy, Erlbaum, Hillsdale NJ, pp. 121–173.

Kellman, P.J., 1996. The origins of object perception. In: Carterette, E., Friedman, M. (Series Eds.) and Gelman, R., Au, T. (Vol. Eds.), Handbook of Perception and Cognition: Perceptual and Cognitive Development, 2nd edn. Academic Press, San Diego, CA, pp. 3–48.

Kellman, P.J., Shipley, T.F., 1991. A theory of visual interpolation in object perception. Cognitive Psychology 23, 141–221.

Kellman, P.J., Short, K.R., 1987. Development of three-dimensional form perception. Journal of Experimental Psychology: Human Perception and Performance 13, 545–557.

Kellman, P.J., Spelke, E.S., 1983. Perception of partly occluded objects in infancy. Cognitive Psychology 15, 483–524.

Kellman, P.J., Spelke, E.S., Short, K.R., 1986. Infant perception of object unity from translatory motion in depth and vertical translation. Child Development 57, 72–86.

Kellman, P.J., Gleitman, H., Spelke, E.S., 1987. Object and observer motion in the perception of objects by infants. Journal of Experimental Psychology: Human Perception and Performance 13, 586–593.

Koffka, K., 1935. Principles of Gestalt Psychology. Harcourt, Brace and World, New York.

Lea, S.E.G., Slater, A.M., Ryan, C.M.E., 1996. Perception of object unity in chicks: a comparison with the human infant. Infant Behavior and Development 19, 501–504.

Lewkowicz, D.J., 1992. Responsiveness to auditory and visual components of a sounding/moving compound in human infants. Perception and Psychophysics 52, 519–528.

Maurer, D., Lewis, T.L., 1998. Overt orienting toward peripheral stimuli: normal development and underlying mechanisms. In: Richards, J.E. (Ed.), Cognitive Neuroscience of Attention: A Developmental Perspective. Erlbaum, Mahwah, NJ, pp. 51–102.

Nakayama, K., He, Z.J., Shimojo, S., 1996. Visual surface representation: a critical link between lower-level and higher-level vision. In: Osherson, D.N. (Series Ed.) and Kosslyn, S.M., Osherson, D.N. (Vol. Eds.), Visual Cognition, Vol. 2: An Invitation to Cognitive Science, 2nd edn. MIT Press, Cambridge, MA, pp. 1–70.

Needham, A., 1998. Infants' use of featural information in the segregation of stationary objects. Infant Behavior and Development 21, 47–75.

Needham, A., Baillargeon, R., 1997. Object segregation in 8-month-old infants. Cognition 62, 121–149.

Papathomas, T.V., Chubb, C., Gorea, A., Kowler, E., 1995. Early Vision and Beyond. MIT Press, Cambridge, MA.

Peterson, M.A., Gibson, B.S., 1994. Must figure-ground organization precede object recognition? An assumption in peril. Psychological Science 5, 253–259.

Ramachandran, V.S., Gregory, R.L., 1978. Does color provide an input to human motion perception?. Nature 275, 55–56.

Runeson, S., 1974. Constant velocity: not perceived as such. Psychological Research 37, 3–23.

Saidpour, A., Braunstein, M.L., Hoffman, D.D., 1994. Interpolation across surface discontinuities in structure from motion. Perception and Psychophysics 55, 611–622.

Sato, A., Kanazawa, S., Fujita, K., 1997. Perception of object unity in a chimpanzee (pan troglodytes). Japanese Psychological Research 39, 191–199.

Schmuckler, M.A., Proffitt, D.R., 1994. Infants' perception of kinetic depth and stereokinetic displays. Journal of Experimental Psychology: Human Perception and Performance 20, 122–130.

Shiffrar, M., Lorenceau, J., 1996. Increased motion linking across edges with decreased luminance contrast, edge width and duration. Vision Research 36, 2061–2067.

Slater, A., Morison, V., Somers, M., Mattock, A., Brown, E., Taylor, D., 1990. Newborn and older infants' perception of partly occluded objects. Infant Behavior and Development 13, 33–49.

Spelke, E.S., 1979. Perceiving bimodally specified events in infancy. Developmental Psychology 15, 626–636.

Spelke, E.S., 1985. Preferential-looking methods as tools for the study of cognition in infancy. In: Gottlieb, G., Krasnegor, N.A. (Eds.), Measurement of Audition and Vision in the First Year of Postnatal Life: A Methodological Overview. Ablex, Norwood, MA, pp. 323–363.

Spelke, E.S., Van de Walle, G., 1993. Perceiving and reasoning about objects: insights from infants. In: Eilan, N., McCarthy, R.A. Brewer, B. (Eds.), Spatial Representation: Problems in Philosophy and Psychology. Blackwell, Oxford, pp. 132–161.

Teller, D.Y., Bornstein, M.H., 1987. Infant color vision and color perception. In: Salapatek, P., Cohen, L. (Eds.), Handbook of Infant Perception, Vol. 1: From Sensation to Perception, Academic Press, Orlando, FL.

von Helmholtz, H., 1925. Physiological Optics. Rochester, NY: Optical Society of America (original work published 1867).

Wallach, H., O'Connell, D.N., Neisser, U., 1953. The memory effect of visual perception of three-dimensional form. Journal of Experimental Psychology 45, 360–368.

Wertheimer, M., 1958. Principles of perceptual organization. In: Beardslee, D.C., Wertheimer, M. (Eds.), Readings in Perception, Van Nostrand, Princeton, NJ, pp. 115–135 (originally published in 1923).

Yantis, S., Jonides, J., 1984. Abrupt onsets and selective attention: evidence from visual search. Journal of Experimental Psychology: Human Perception and Performance 10, 601–621.