Research Article

Development of Perceptual Completion in Infancy

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ABSTRACT—*Perceptual completion consists of bridging the gaps imposed by occlusion, such as perceiving the unity of center-occluded objects. It is unknown at present what developmental mechanisms underlie the emergence of functional perceptual completion in infancy. One current debate centers on the role of visible surface motion. According to a core-principles account, perceptual completion emerges simultaneously with the onset of motion discrimination, the sole determinant of unity percepts in infants. According to a contrasting constructivist account, motion discrimination is but one of several independent inputs to perceptual completion. In the present study, 2-month-old infants were tested for both unity perception and motion discrimination in partial-occlusion displays. Motion discrimination obtained under all conditions, even under circumstances in which infants were unable to perceive completion. Four-month-olds showed marked improvements in perceptual completion, most likely because of improvements in information integration. Taken together, these findings support a constructivist view of early perceptual and cognitive development.*

Occlusion is ubiquitous in the optical patterns reflected from visible object surfaces. As a consequence, what is projected to the visual system from the environment does not match the true extent of objects. Nevertheless, we experience a stable world of coherent objects, each having substance, volume, and depth and appearing at a particular distance, rather than a world of surface fragments. *Perceptual completion* is the process of bridging the gaps induced by occlusion. To accomplish perceptual completion of a partly occluded object, for example, an observer must register its missing portions using available information from the visible segments, analyzing their shape, position, orientation, motion, relative distance, luminance, color, and texture. Such tasks usually pose little difficulty for adults, who readily report perception of edge continuity under many conditions (e.g., Kellman & Shipley, 1991).

How do infants come to achieve perceptual completion? Recent theories of infant perception provide conflicting views. According to a *core-principles* account emphasizing contributions to development that are independent of experience, humans are endowed innately with a set of specialized cognitive modules; such modules are thought to provide veridical perception of objects and occlusion from early in postnatal life (e.g., Spelke, 1990). According to a contrasting *constructivist* account focusing on developmental change subsequent to the onset of visual experience, humans build veridical object percepts with maturation and experience; the ontogeny of object perception has its roots in simpler, multipurpose processes such as short-term memory, allocation of attention, and rudimentary categorization (e.g., Cohen, Chaput, & Cashon, 2002). These two views offer divergent explanations of the development of perceptual completion, yet each is consistent with extant data. The present experiments were intended to work toward a resolution of the fierce debate that has been generated by these opposing perspectives.

Much of what is known about infants' perceptual completion can be summarized succinctly. A considerable body of research has examined visual information used by young infants to perceive unity of surfaces that are partly hidden by an occluder, as in Figure 1. Motion of visible surfaces across the gap is a powerful cue: If the surfaces are stationary, young infants do not appear to perceive unity (Jusczyk, Johnson, Spelke, & Kennedy, 1999; Kellman & Spelke, 1983). Edge alignment also is an important determinant of unity perception, as is the proximity of visible surfaces: If edges are not aligned or are separated by a large gap, young infants do not perceive them as connected, even if the surfaces undergo common motion (Johnson & Aslin, 1995, 1996; Smith, Johnson, & Spelke, 2003). A second body of evidence concerns age-related changes in responses to occlusion. Neonates have been tested for unity perception and consistently provide evidence that they perceive only what is directly visible: the two surfaces leading behind the occluder

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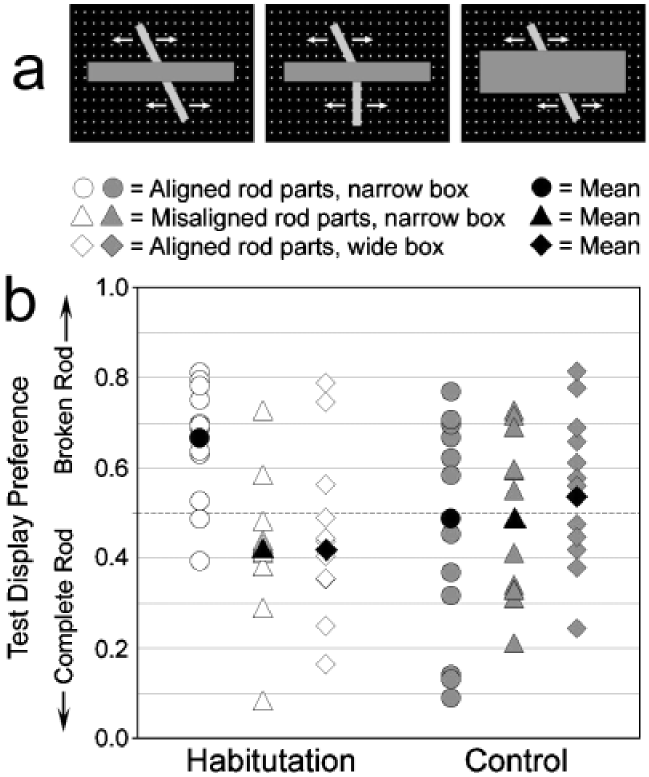

Fig. 1. Displays (a) and results (b) from Experiment 1, which examined perceptual completion in 2-month-old infants. In this experiment, infants were habituated to the *aligned, narrow* display (left), the *misaligned, narrow* display (center), or the *aligned, wide* display (right) and then presented with *broken* and *complete* test versions of the rod parts, the broken displays containing a gap between parts, and the complete displays joining the parts into a single, continuous surface. Infants in the control group were not habituated to the displays before the test trials. The graph of test-display preferences shows individual data points and group means. Chance response (dashed line) = .50 preference.

and the occluder itself (Slater, Johnson, Brown, & Badenoch, 1996; Slater et al., 1990). The earliest age at which infants have been found to perceive occlusion (i.e., object unity) is 2 months (Johnson & Aslin, 1995).

How do the core-principles and constructivist theories explain these patterns of data? Consider first the core-principles account. According to this view, infants are predisposed to perceive objects as persistent, solid, and coherent entities, maintaining representations of these properties across space and time. Initially, however, formation of veridical object representations may be fragile and obtains only under a narrow range of circumstances. For example, young infants perceive the unity of moving but not static surfaces because common motion triggers the *continuity* principle (one of three object-related core principles), which stipulates that two surfaces that move together tend to be connected (Spelke & Van de Walle, 1993). If motion is undetected, the continuity principle remains inactive. According to the core-principles account, alignment and proximity modulate sensitivity to common motion. When edges are misaligned, or too distant, infants may be unable to discern their motion patterns as effectively as when edges are aligned or in close proximity (see Jusczyk et al., 1999; Smith et al., 2003). In the absence of motion detection, therefore, unity perception is precluded.

Consider next the constructivist account. According to this view, infants are predisposed to process incoming information in a hierarchical fashion, attending to the most complex units possible in a given stimulus (Cohen, 1991). Early in development, however, infants are limited in their capacity to organize simpler components into more complex wholes. In the case of perceptual completion, the ability to register the orientations and motions of visible surface fragments is present prior to the ability to integrate units over space and time into perception of connectedness across a gap. According to the constructivist account, alignment and proximity directly increase or decrease the likelihood of continuity perception. Adults' perceptual judgments of the strength of edge connectedness fall off as the angle of intersection deviates from 180° (Kellman & Shipley, 1991) and as distance increases (Ringach & Shapley, 1996), irrespective of common motion (Jusczyk et al., 1999). Perception of object unity in young infants, likewise, is contingent on edge alignment and proximity (Johnson & Aslin, 1995, 1996).

The present study provides a critical test of the core-principles versus constructivist views by examining predictions about young infants' perceptual completion favored by each perspective. A key distinction between the two views centers on the putative roles of edge motions and their orientations and proximity across a spatial gap. The core-principles account stipulates that there are no conditions under which infants would detect common motion of surfaces yet fail to perceive them as unified, because unity perception follows from motion perception. The constructivist account, in contrast, predicts circumstances in which infants discern the orientations and motions of disparate surfaces in a scene yet fail to perceive them as unified, because unity perception is distinct from motion discrimination and develops as infants become more facile at information integration.

These competing hypotheses were examined in three experiments. In Experiment 1, 2-month-old infants were tested for perceptual completion in displays in which edge alignment and proximity across a gap were manipulated. In Experiment 2, the hypothesis that 2-month-olds' motion discrimination is a function of edge orientation and proximity was examined. In Experiment 3, 4-month-olds were observed to investigate development of effects of proximity and alignment on perceptual completion.

EXPERIMENT 1

In this experiment, 2-month-old infants were observed for evidence of perceptual completion under three conditions. In the *aligned, narrow* condition, infants were habituated to a rod-and-box stimulus in which the rod edges were aligned across a narrow occluder (Fig. 1a, left). In the *misaligned, narrow* condition, infants were habituated to a stimulus in which the rod edges were arranged to form a 154° angle across a narrow occluder (Fig. 1a, center). In the *aligned, wide* condition, infants were habituated to a stimulus with aligned edges across a wide occluder (Fig. 1a, right). Following habituation, the infants viewed a *broken* test display consisting of the visible surface fragments separated by an open gap of the same width as the occluder in the corresponding habituation display, alternating with a *complete* test display consisting of rod parts connected to form a single object. The infants were expected to attend preferentially to the broken rod if they perceived the visible rod parts as unified in the habituation display, because the complete rod more closely matches a unity percept and infants generally exhibit novelty preferences following habituation (Bornstein, 1985). The infants were predicted to show this pattern only in response to the aligned, narrow display, because misalignment and greater edge separation may preclude perceptual completion (Johnson & Aslin, 1995, 1996). Perception of disjoint surfaces, in contrast, would be reflected by a posthabituation preference for the complete rod, a response observed in infants who view misaligned rod parts (Johnson & Aslin, 1996; Smith et al., 2003).

Twelve infants were in each condition. Another 12 infants were in each of three control conditions involving no prior exposure to any habituation stimulus, so that any potential inherent preference for one of the two test stimuli could be assessed. Infants were randomly assigned to one of the six conditions.

Method

Participants

Seventy-two full-term infants (35 girls, 37 boys) composed the final sample (mean age = 64.8 days, $SD = 7.0$). Sixteen additional infants were observed but excluded from the analyses because of fussiness (10 infants), sleepiness (5), or persistent inattention toward the displays (1). Infants were recruited by letter and telephone from hospital records of new parents who expressed willingness to be contacted for future studies, as well as from birth announcements in the local newspaper. Parents were provided with a small gift for participation.

Apparatus and Stimuli

A Macintosh computer and 76-cm color monitor were used to generate the stimuli. An observer, blind to the stimulus on the screen at any given time, recorded looking times by pressing a key as the infant looked and releasing it when the infant looked away. The computer presented stimuli, stored the observer's data, calculated the habituation criterion for each infant, and changed displays after the criterion had been met. Sessions were recorded on videotape for later coding by a second observer, blind to the stimuli and experimental hypotheses. Interobserver agreement was high (mean Pearson $r = .99$).

The aligned, narrow habituation display contained a 37.4- × 4.9-cm blue box (21.3° × 2.8° visual angle). This box occluded the center of a green rod, measuring 27.5 × 2.1 cm (15.7° × 1.2°) and oriented 26° from vertical. The rod translated horizontally through 18.3 cm (10.5°) at 7.3 cm/s (4.2°/s), reversing direction every 2.5 s. The misaligned, narrow habituation display was identical except the bottom rod part was vertical. The aligned, wide habituation display was identical to the aligned, narrow display except the box was 11.0 cm wide (6.3°). Each habituation display had a corresponding complete test display and broken test display that matched the orientation of the rod and gap (broken display only) in the habituation display. Thus, each of the three broken-rod test displays contained rod segments that matched the size and motion of the visible rod parts in the habituation displays, and a gap the same width as the box; each of the three complete-rod test displays contained a center segment joining the upper and lower portions of the rod parts. Between trials an "attention getter" (a ball that expanded and contracted in time with a repetitive beep) was shown to return the infant's gaze to the screen.

Procedure

Infants were seated in a parent's lap and tested individually. The habituation display was presented until the infant reached a predetermined habituation criterion, which was that total looking times across 4 consecutive trials, beginning with the 2nd trial, added up to less than half the total looking times across the first 4 trials. The minimum number of trials was 5, and the maximum was set to 12. Infants who did not habituate after 12 trials ($n = 4$) moved on to the test phase.

On each trial, timing commenced after the infant looked at the attention getter, which was replaced by a habituation or test stimulus as the observer pressed a key. A trial ended when the infant looked away and the observer released the key, or when the infant had looked for 120 s. A delay of 2 s placed into the habituation program allowed the trial to continue if the infant returned his or her gaze to the screen after short glances away. When looking times declined to the habituation criterion, the computer switched automatically to test displays. Broken- and complete-rod displays were presented three times each in alternation. Order of initial presentation was counterbalanced.

The procedure for testing infants in the control condition was identical except that they viewed only the six test displays.

Results and Discussion

The data consisted of looking times toward the two test displays. Prior to analysis, data were log-transformed due to excessive skew in many cells, violating assumptions of heterogeneous distributions required by analysis of variance (ANOVA). Preliminary analyses incorporating sex of infant as a factor revealed no pertinent significant effects of this variable (i.e., no sex differences in performance) in this experiment or in either of the other two experiments in this study.

Looking-time preferences are plotted in Figure 1b. A 3 (habituation display: aligned, narrow vs. misaligned, narrow vs. aligned, wide) × 2 (condition: habituation vs. control) × 2 (order: broken vs. complete test display first) × 2 (test display: broken vs. complete) × 3 (trial block: first, second, or third pair of trials) mixed ANOVA yielded a significant main effect of condition, $F(1, 60) = 27.70$, $p < .001$, due to longer looking overall by infants in the control condition. There was also a significant interaction among experiment, condition, and test display, $F(2, 60) = 4.65$, $p < .05$. No other effects were reliable. Post hoc analyses (simple effects tests) revealed no reliable preferences by infants in the control condition, $F(1, 60) = 0.81$, n.s. Infants who viewed the aligned, narrow habituation display looked reliably longer at the broken rod than did infants who were shown the misaligned, narrow or aligned, wide habituation displays, $F(1, 60) = 10.00$, $p < .01$ (Cohen's $d = 0.72$). There was a significant preference for the broken rod relative to the complete rod among infants in the aligned, narrow habituation condition, $F(1, 60) = 5.86$, $p < .05$ ($d = 0.44$). Infants in the combined misaligned, narrow and aligned, wide habituation conditions, in contrast, looked longer at the complete than at the broken rod, $F(1, 60) = 4.22$, $p < .05$ ($d = -0.40$).

These data suggest that perceptual completion was achieved only under limited circumstances: when moving, aligned edges were presented in close proximity across the gap imposed by the occluder. When the edges were misaligned or viewed across a wider gap, 2-month-olds appeared to perceive the visible rod segments as disjoint surfaces, rather than as part of a unified object.

EXPERIMENT 2

The next experiment probed reasons for the apparent failure of perceptual completion in the misaligned, narrow and aligned, wide displays. If the failure were rooted in an insensitivity to motion, infants would be unable to distinguish the common, or *corresponding*, motion available in these displays from a motion pattern in which the rod parts move in opposite directions, a *converse* motion. This would provide evidence in favor of the core-principles view. However, if infants can distinguish corresponding from converse motion despite variations in edge orientation and proximity, this would provide evidence in favor of the constructivist view, implying that deficits in motion discrimination were not responsible for the performance differences across displays in Experiment 1.

These competing hypotheses were examined by presenting 2-month-olds with one of the three habituation displays used in Experiment 1. The infants were tested not for unity perception, however, but rather for motion discrimination. Habituation was followed by a test phase in which each corresponding-motion stimulus alternated with a converse-motion display in which the rod parts moved laterally in opposite directions (see Fig. 2a). A second group of 2-month-olds was habituated to the converse-

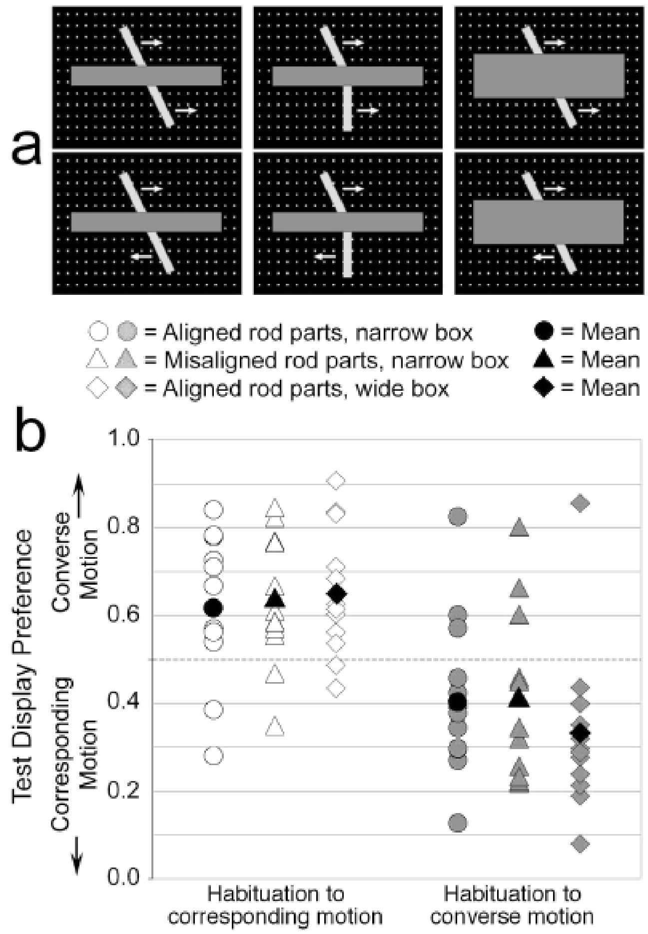

Fig. 2. Displays (a) and results (b) from Experiment 2, which examined motion discrimination in 2-month-old infants. The top row in (a) depicts the *corresponding-motion* stimuli, in which rod parts underwent common motion (these stimuli were identical to the habituation displays from Experiment 1). The bottom row in (a) depicts the *converse-motion* stimuli, in which rod parts underwent opposite directions of motion. Infants in both motion conditions viewed test displays consisting of the identical stimulus seen during habituation and the display with the opposite kind of motion. The graph of test-display preferences shows individual data points and group means. Chance response (dashed line) = .50 preference.

motion displays and then observed for a preference for corresponding motion during the test phase. The core-principles hypothesis predicted a posthabituation novelty preference only among infants who had viewed the aligned, narrow displays. The constructivist hypothesis predicted novelty preferences among infants regardless of the display to which they had habituated.

Method

Participants

Seventy-two full-term infants (40 girls, 32 boys) composed the final sample (mean age = 59.5 days, *SD* = 9.0). An additional 27 infants were observed but excluded from the analyses because of fussiness (16 infants), sleepiness (8), persistent inattention toward the displays (1), or maternal interference (2). Infants were recruited from the same sample as in Experiment 1.

Apparatus, Stimuli, and Procedure

The apparatus and procedure were the same as in Experiment 1, except as noted. Each infant was habituated to one of the three types of display—aligned, narrow; misaligned, narrow; or aligned, wide—with either corresponding or converse motion of the visible rod parts. Following habituation, the infants viewed test displays consisting of the same display seen during habituation alternating with the opposite-motion display having the same arrangement of the rod parts and box. Interobserver agreement was again high (mean Pearson $r = .99$). As in Experiment 1, infants who did not habituate after 12 trials ($n = 7$) were moved on to the test phase.

Results and Discussion

Looking-time preferences are plotted in Figure 2b. A 3 (habituation display: aligned, narrow vs. misaligned, narrow vs. aligned, wide) × 2 (condition: habituation to corresponding vs. converse motion) × 2 (order: corresponding vs. converse motion first after habituation) × 2 (test display: corresponding vs. converse motion) × 3 (trial block) mixed ANOVA yielded a reliable Habituation Display × Condition interaction, $F(2, 60) = 3.92, p < .05$, due to variations in overall looking times across the conditions; these variations were unrelated to test-display preference. There was also a significant Condition × Test Display interaction, $F(1, 60) = 33.42, p < .001$: Infants tended to prefer the novel motion regardless of habituation condition. There were no other reliable main effects or interactions.

Post hoc analyses (Habituation Display × Test Display ANOVAs) were conducted on data from each condition separately. The analysis of the corresponding-motion condition revealed a significant preference for the novel motion, $F(1, 33) = 25.17, p < .01$ ($d = 0.58$), but no significant Habituation Display × Test Display interaction, $F(2, 33) = 0.22$, n.s. Likewise, the analysis of the converse-motion condition also revealed a significant novelty preference, $F(1, 33) = 11.32$, $p < .01$ ($d = 0.54$), but no significant Habituation Display × Test Display interaction, $F(2, 33) = 0.85$, n.s.

The infants in Experiment 2 looked longer at the novel than at the habituated motion of visible rod segments in all conditions, providing evidence that infants' motion discrimination is not a function of edge orientation or proximity. This result implies that the infants in Experiment 1 were able to register the motion of the rod parts across the occluder regardless of the type of display.

EXPERIMENT 3

In this experiment, 4-month-old infants were tested for developments in perceptual completion using the more demanding stimuli employed with 2-month-olds in Experiment 1, the misaligned, narrow and aligned, wide stimuli. As in Experiment 1, infants were examined for unity perception by presenting broken and complete test displays subsequent to habituation.

Method

Participants

Forty-eight full-term infants (30 girls, 18 boys) composed the final sample (mean age = 123.5 days, $SD = 9.7$). An additional 3 infants were observed but excluded from the analyses because of fussiness (2 infants) or sleepiness (1). Infants were recruited from the same sample as in Experiments 1 and 2.

Apparatus, Stimuli, and Procedure

The apparatus and procedure were the same as in Experiment 1. Half the infants were shown either the misaligned, narrow or the aligned, wide habituation display, and half were in a no-habituation control condition. Interobserver agreement was again high (mean Pearson $r = .99$). Two infants did not habituate after 12 trials and were moved on to the test phase, as in Experiment 1.

Results and Discussion

Looking-time preferences are plotted in Figure 3. A 2 (habituation display: misaligned, narrow vs. aligned, wide) × 2 (condition: habituation vs. control) × 2 (order: broken vs. complete test display first) × 2 (test display: broken vs. complete) × 3 (trial block) mixed ANOVA yielded a reliable main effect of condition, $F(1, 40) = 19.56, p < .01$, due to longer looking overall by infants in the control condition, and a reliable main effect of trial block, $F(2, 80) = 15.47, p < .01$, due to an overall decline in looking across trials. There were also two significant interactions involving order: a Condition × Order interaction,

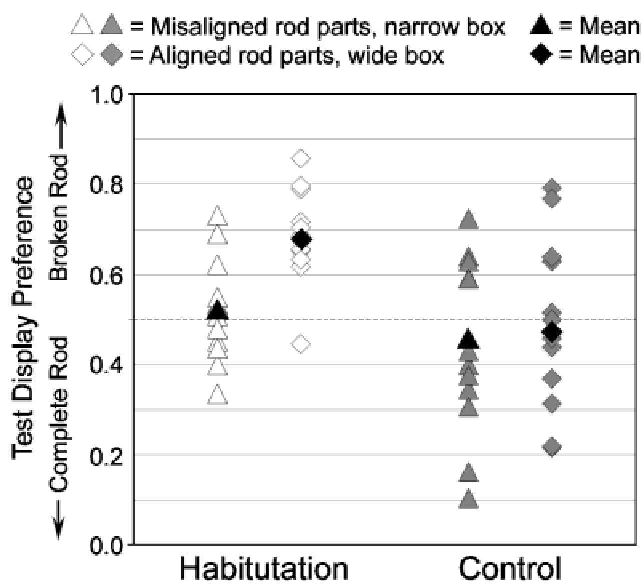

Fig. 3. Test-display preferences (individual data points and group means) in Experiment 3, which examined perceptual completion in 4-month-old infants. The habituation displays (misaligned, narrow and aligned, wide) and test displays (broken rod and complete rod) from Experiment 1 were used. Chance response (dashed line) = .50 preference.

$F(1,\ 40) = 5.18$, $p < .05$, and a Condition × Order × Test Display interaction, $F(1, 40) = 4.90$, $p < .05$. These interactions stemmed from the tendency of infants in the control condition, and those in the misaligned, narrow habituation condition, to look longer overall at the display that was presented first than at the display that was presented second. In contrast, infants in the aligned, wide habituation condition looked longer at the broken rod regardless of order.

Finally, there was a significant Condition × Test Display interaction, $F(1, 40) = 7.68$, $p < .01$. Post hoc analyses (simple effects tests) revealed a reliable preference for the broken rod among infants in the aligned, wide habituation condition, $F(1, 40) = 16.65$, $p < .01$ ($d = 1.14$), but no consistent test-display preference among infants in any of the other three groups, Fs < 0.5, n.s. Taken together, the results of Experiment 3 suggest that the 4-month-olds perceived unity in the aligned, wide display, but not the misaligned, narrow display.

GENERAL DISCUSSION

These three experiments provide evidence concerning development of a fundamental perceptual skill in infancy: the ability to perceive continuity of edges across an occluding surface. Two-month-olds succeeded at perceptual completion when edges were aligned, in close proximity, and moving together (Experiment 1). When edges were misaligned or separated across a wider gap, in contrast, they were perceived as part of disjoint rather than unified surfaces (Experiment 1), although their movement patterns were detected (Experiment 2). This outcome disaffirms an account of infants' perceptual completion based on core principles guiding early object perception from a limited set of inputs, such as motion. Instead, these findings corroborate constructivist claims postulating that initially in postnatal development, infants analyze the positions, orientations, and motions of visible surfaces, and only later integrate these into percepts of objects whose boundaries extend beyond what is directly visible.

These results provide evidence for both continuity and change across development. Evidence for continuity comes from the detrimental effect of edge misalignment on perception of connectedness, demonstrated here to begin from the earliest point in development when perceptual completion can be observed (2 months of age) and shown elsewhere as extending through adulthood (e.g., Hess & Field, 1999; Jusczyk et al., 1999; Kellman & Shipley, 1991). Evidence for change comes from the sharp difference in perceptual completion skills between 2- and 4-month-olds (Experiments 1 and 3), implying rapid development of mechanisms responsible for detecting edge connectedness across a spatial gap, beginning with the onset of visual experience at birth.

What are these mechanisms and how do they change in infancy? Research with adults has focused on visual information that supports connectedness, such as edge alignment (Field, Hayes, & Hess, 1993), proximity (Ringach & Shapley, 1996), curvature (Kovács & Julesz, 1993), junctions (Rubin, 2001), and depth (Hess & Field, 1995). Some grouping mechanisms, such as perceptual completion, may be rooted in long-range interactions between receptive fields in area V1, the first stage of cortical visual processing. Activation of orientation-tuned neurons causes excitation of nearby cells with a preference for similar orientations, triggering a pooling of activity across an organized assembly of neurons, all participating in coding of a single edge (Field et al., 1993).

This notion provides a straightforward explanation for the falloff in perception of connectedness as edge orientation across a gap deviates from 180° alignment or as proximity increases, because the activations of participating neural assemblies become degraded along an orientation, curve, or angle. This thesis can also account for why perceptual completion in infancy becomes robust to distance across a spatial gap: V1 in the neonatal primate contains tuned receptive fields supporting orientation sensitivity (Kiorpes & Movshon, 2004), but maturation of long-range interactions progresses over the first several postnatal months, resulting in delays in edge detection across larger portions of the visual field (Burkhalter, Bernardo, & Charles, 1993; cf. Kovács, Kozma, Fehér, & Benedek, 1999). Full maturation of these mechanisms is dependent on postnatal visual experience (White, Coppola, & Fitzpatrick, 2001). There are also extensive contributions to perceptual grouping from higher levels of the visual processing stream, feeding back to V1 (Hess & Field, 1999), such as ventral areas that participate in coding object form and shape, and that maintain object representations over occlusion. Less is known about maturation of these areas than about development of V1, although evidence for protracted development of function across the first postnatal year in primates is emerging (Rodman, 2003).

It seems likely, then, that visual information integration requires contributions of cortical substrate beyond V1, necessitating the coordination of outputs of visual areas involved in coding motion, form, texture, depth, and other information. No known theories based on cognitive modules or core principles provide an adequate description of how such integration might occur. The neurophysiological data, and a growing body of evidence from behavioral paradigms (including the present study), are more consistent with the hierarchical developmental pattern postulated by constructivist theory, which highlights the emergence during infancy of mechanisms responsible for detection, extraction, and synthesis of available information (Cohen et al., 2002). The maturational account offered here emphasizes cortical processes of integration that may be unlearned, yet still dependent on visual input for normal development (Daw, 2003). Recent evidence from computational modeling (Mareschal & Johnson, 2002) and experiments examining the role of early experience on acquisition of object concepts (Johnson, Amso, & Slemmer, 2003) provide support as well for a strong role for associative learning in building object representations (viewing objects as they become progressively occluded and unoccluded). Clearly, a comprehensive account of development of veridical object perception requires consideration of multiple developmental mechanisms.

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