Developmental Mechanisms of Perceptual Completion

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***Abstract* - Adults have little difficulty perceiving objects as complete despite occlusion, yet newborn infants perceive partly occluded objects solely in terms of visible surfaces. The developmental mechanisms leading to perceptual completion have never been adequately explained. Here, we examined the potential contributions of motion sensitivity and visual attention to development of perceptual completion in infancy. Young infants were presented with two tasks in which a center-occluded rod moved back and forth against a textured background to assess oculomotor scanning patterns and perceptual completion. Infants also participated in tasks to assess motion direction discrimination and smooth pursuit. Individual differences in perceptual completion performance were unrelated to either motion direction discrimination or smooth pursuit performance, but were strongly correlated with scanning patterns. Implications for theories of developmental mechanisms are discussed.**

Index Terms – human development, perceptual completion, object perception, visual attention, motion perception, eye movements

I. Introduction

Do infants experience a world of coherent objects? Veridical perception of objects presupposes perception of occlusion [1]. Occlusion is ubiquitous in the visual environment, because from any single vantage point, nearer objects and surfaces often overlap those that are farther away. Human adults, nevertheless, experience a world composed of coherent objects with regular shapes, rather than a world of surface fragments, and by 4 months after birth, infants provide evidence of occlusion perception in displays that depict partly occluded [2] and fully occluded [3] objects. Newborn infants, in contrast, appear to perceive partial occlusion displays solely in terms of their visible surfaces, failing to make the perceptual "inference" necessary to achieve perceptual completion of object surfaces [4-5]. Evidence comes from tasks in which infants are shown a center-occluded rod, its visible portions undergoing common motion against a textured background, which is viewed repeatedly until infant looking times decline according to a predetermined habituation criterion (Fig. 1, left). Following habituation, infants view a pair of test displays in alternation, each matching the habituation display in a different way. Posthabituation looking time patterns are thought to reflect a novelty preference, and can be used to assess whether infants achieved perceptual completion in the habituation display. Older infants (i.e., 4-month-olds) consistently prefer the "broken" rod test display (Fig. 1, center), implying that the "complete" rod is familiar relative to the habituation display—hence consistent with perception of unity. But neonates consistently prefer the complete rod test display (Fig. 1, right), implying that the broken rod is familiar relative to the habituation display—hence consistent with perception of disjoint surfaces, rather than perceptual completion. Preferences at 2 months tend to fall between these patterns, depending on display characteristics [6]. Together, these findings point to 0-4 months as an important time of transition toward veridical occlusion perception.

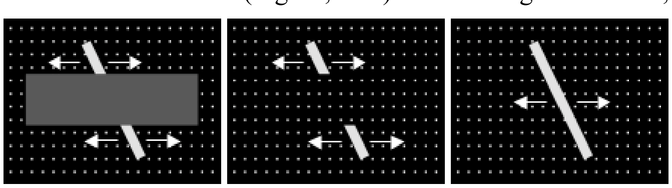

Fig. 1 Displays used to assess perceptual completion in infants. Left: habituation display. Center: "broken" rod test display. Right: "complete" rod test display.

The mechanisms of development that lead to perceptual completion in infants are poorly understood. Recently, [6] addressed this question by testing two extant hypotheses of development of perceptual completion. According to a "core principles" account, infants are predisposed to perceive objects as structured, solid entities, persisting across occlusion [7]. According to a contrasting "constructivist" account, infants are predisposed to process information hierarchically across developmental time; initially, infants are limited in the capacity to organize simpler components into more complex wholes [8]. These two accounts provide opposing views of development of perceptual completion. On the core principles account, young infants respond to objects as coherent solid bodies and occlusion perception is available early. On the constructivist account, the young infant's visual system processes visible parts prior to coherent wholes, and occlusion perception emerges with time.

The evidence recounted previously on perceptual completion in neonates [4-5] would appear to be inconsistent with the core principles account, but this account has an explanation. Discrimination between different directions of motion is limited in very young infants [9-10], and perceptual completion in static displays has not been observed until 6-8 months [11]. Moreover, motion direction discrimination and perceptual completion are first observed at 2 months, leading to speculation that limits in perceptual completion are rooted in a failure to detect common motion: If common motion is unavailable, then perceptual completion is precluded in young infants [12]. On this account, therefore, the visual system is predisposed to view objects as solid and enduring and uses motion as a primary cue to identify unity of objects. Motion processing mechanisms must develop before this cue is available.

This hypothesis leads to a prediction: Infants should achieve perceptual completion in any occlusion display in which rod parts undergo common motion, and in which that motion is detectable. The constructivist account provides an opposing prediction: There will be conditions in which infants detect the motions of visible surfaces that lead to the edge of an occluder, and yet not perceive occlusion, because perceptual completion is a higher-order perceptual function than simple registration of visible object parts.

These contrasting predictions were tested by [6] and the outcome supported the constructivist view. Two-month-olds provided evidence of completion when the visible rod parts moved in tandem behind a narrow occluder, but not in a wide-occluder display (Fig. 1), nor in a display in which the rod parts were misaligned. In a second experiment, however, 2-month-olds failed to discriminate two different kinds of rod motion (same phase vs. opposite phase) when occluder size and visible rod orientation across the two experiments were held constant. These results imply that infants register the motions and orientations of object parts prior in development to perceiving organized wholes (in the present case, occlusion), as stipulated by a constructivist account.

Yet the outcome of [6] does not provide unequivocal evidence that infants discriminated different kinds of motion, because performance may have stemmed solely from a mechanism sensitive to changes in *position* of visible rod parts, rather than a mechanism sensitive to motion. More broadly, *all* extant studies of infants' perceptual completion in dynamic displays are subject to this interpretation: The role of motion sensitivity remains unknown.

Also left open is the central question of precisely what the developmental mechanisms might be that support emergence of perceptual completion. A study described in [13] begins to provide an answer. Three-month-old infants were tested in a perceptual completion task using the habituation paradigm described previously. The infants' eye movements were recorded with a corneal reflection eye tracker during the habituation phase of the experiment. We reported differences in scanning patterns between infants whose posthabituation test display preferences indicated unity perception and those infants who provided evidence of perception of disjoint surfaces: "Perceivers" tended to scan more in the vicinity of the two visible rod segments and to scan back and forth between them. Ref. [14] indicates as well that there is a shift across 2-4 months in the extent to which young infants overcome a "top bias," when visual attention is directed preferentially or exclusively toward the upper portions of a rod-and-box stimulus. Ontogeny of perceptual completion, therefore, seems to be accompanied by an inclination to direct visual attention to relevant aspects of a stimulus, in this case, the upper and lower moving rod parts.

What is the relation between infants' visual attention and motion perception, and what are their contributions to perceptual completion? To address this question, we observed infant performance in four tasks on the same day, asking whether motion perception is related directly to perceptual completion in early development. If so, we predicted a correlation between performance on motion direction discrimination and perceptual completion tasks, alongside patterns of visual attention. If not, we predicted that performance on the motion direction discrimination task would be independent of both perceptual completion and attention toward rod parts. As a manipulation check to ensure that our measure of motion perception was a valid index of true motion direction discrimination, and to provide a second index of oculomotor performance, we observed infants' performance on a smooth pursuit task. It has been speculated that motion direction discrimination and smooth pursuit are subserved by the same cortical mechanisms [12, 15] but this has never been tested directly.

In the present study, therefore, we observed young infants' performance in four tasks:

(1) *Scanning*: We recorded oculomotor behavior as infants viewed a rod-and-box occlusion display.

(2) *Smooth Pursuit*: We recorded oculomotor behavior as infants viewed small moving targets moving against a black background (Fig. 2).

(3) *Perceptual Completion*: We recorded looking times as infants were habituated to a rod-and-box display, followed by broken and complete rod test displays.

(4) *Motion Direction Discrimination*: We recorded oculomotor behavior as infants viewed pairs of random-dot kinematograms, presented side-by-side. In half of each display, the dots moved in the same direction; the other half was divided into three regions in which dots moved in opposing directions (Fig. 3).

II. Methods

A. Participants

We collected a complete data set in each of the four tasks from 14 full-term infants, ranging in age from 58 to 97 days (M = 76.5). An additional 27 infants were observed but not included in the final sample due to poor calibration of point of gaze (7 infants), failure to calibrate or complete one of the four tasks due to fussiness (13 infants) or sleepiness (3 infants), computer error (1 infant), or insufficient attention (<10%) toward the displays in either the Scanning, Smooth Pursuit, or Motion Direction Discrimination task (3 infants).

B. Stimuli

Scanning. The stimulus for the Scanning task consisted of a center-occluded green rod measuring 1.5 x 15.5 cm (1.4 x 14.7° visual angle at the infant's 60-cm viewing distance), undergoing lateral translation at 4.3 cm/s (4.1°/s), reversing direction every 2.5 s. The occluder consisted of a 3.8 x 21.6 cm (3.6 x 20.4°) blue box. Rod parts and box were presented against a 12 x 20 grid of small white dots serving as background texture.

Smooth Pursuit. The stimuli for the Smooth Pursuit task consisted of five small color photos of children's toys, presented individually, translating across a black background in one of five positions on the screen and at one of five speeds (see Fig. 2). Each target was approximately 3° across. The target identity, location of its path, and its speed were randomized within each block of five trials to hold the infant's interest. For the same reason, between the first and second 5-trial blocks, a photo of two young girls in princess costumes

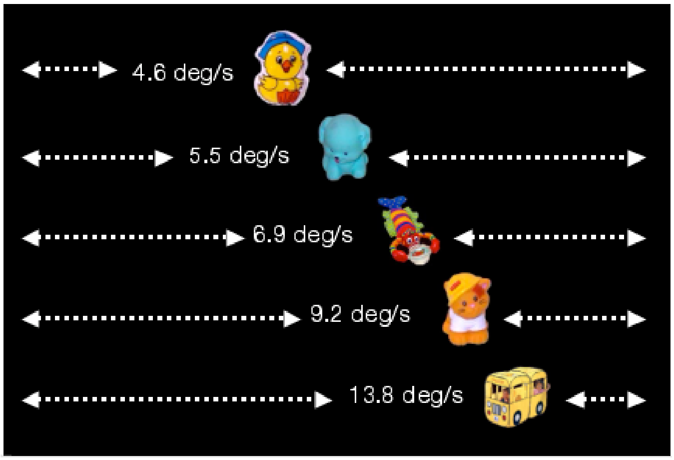

Fig. 2 Schematic depiction of stimuli used in the Smooth Pursuit task

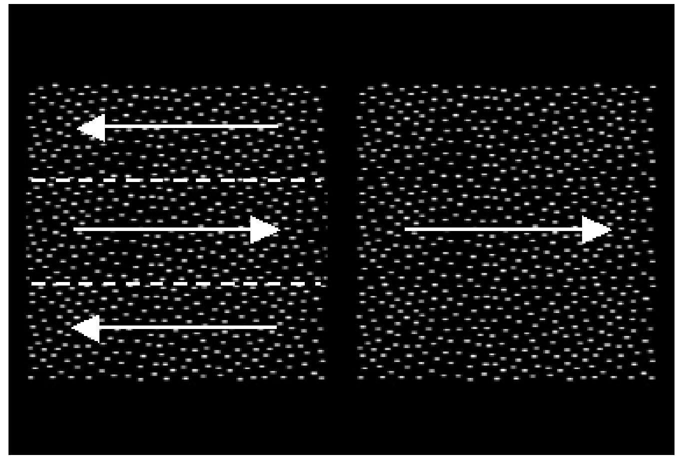

Fig. 3 Schematic depiction of a stimulus used in the Motion Direction Discrimination task. Complex motion is seen at left; simple motion at right. Arrows and dotted lines are shown for illustrative purposes only.

was shown for 5 s, and between the second and third 5-trial blocks, a toy was shown bouncing across the screen on an irregular trajectory in tandem with a periodic "boing" sound for 5 s. Finally, and also to maintain interest, we played snappy music during the entire smooth pursuit task ("Fun Fun Fun" by the Beach Boys), which pilot testing revealed to be highly effective in maintaining alertness.

Perceptual Completion. The habituation stimuli for the Perceptual Completion task consisted of the same center-occluded green rod, blue occluder, and textured background as in the Scanning task, except its size was increased by x% to accommodate a larger viewing distance (100 cm). The broken rod test stimulus consisted of rod parts moving in the same manner as in the habituation stimulus, but there was no occluder and background dots were visible between the rod parts. In the complete rod test stimulus, the center of the rod was filled in (see Fig. 1).

Motion Direction Discrimination. The stimuli for the Motion Direction Discrimination task consisted of 24 pairs of random-dot kinematograms. In one half of each display, the dots all moved in the same direction, which we termed simple motion. The other half was divided into thirds; the center portion of this half contained dots that moved in opposition to the others, such that there were three distinct regions of motion (Fig. 3), which we termed complex motion. Direction of simple motion (up, down, left, or right), left-right placement, and direction of motion in the center of complex motion were randomized across trials. Each region of dot motion (simple and complex) measured 10.2 x 14.0 cm (9.7 x 13.3˚). Dots moved at 3.2 cm/s (3.0˚/s).

Pilot testing revealed that infants were largely uninterested in viewing random-dot kinematograms. Therefore, we embedded the displays within a digitized 4-min segment of "A Charlie Brown Christmas." The sound from the video (e.g., the children's voices) was maintained throughout the task. Prior to presentation of each 4-s kinematogram pair, we presented an interesting audiovisual stimulus for 2 s in the center of the screen to re-center the infant's point of gaze. Each kinematogram pair was followed by 4 s of Charlie Brown video.

C. *Apparatus*

The Scanning, Smooth Pursuit, and Motion Direction Discrimination tasks were conducted with a Tobii model ET-17 corneal-reflection eye tracker. Stimuli were viewed on a 43-cm flat panel (thin-film transistor) monitor. Eye movement data were recorded at 30 Hz. Experiments were designed using software provided by Tobii.

The Perceptual Completion task was conducted with a G4 Macintosh and a 76-cm CRT monitor. An observer viewed the infant on a monitor attached to a closed-circuit camera. The experiment was controlled by Habit software [16].

D. *Procedure*

Each infant was tested individually, seated in a parent's lap for all tasks. The four tasks were presented in the same order for all infants. If needed, infants were given a short break between tasks.

After the parent was briefed and provided informed consent, the infant's point of gaze was calibrated with the eye tracker. The point of gaze was calibrated by comparing it to known coordinates on the screen as the infant viewed a target pattern, pulsing in time with a rhythmic sound. The target was presented at five locations on the monitor, and the infant looked at each in turn.

Following calibration, each infant was observed in the Scanning task. Infants were shown four 15-s presentations of the rod-and-box display described previously as their eye movements were recorded. Between trials an attention-getter was shown for 2 s to center the point of gaze and maintain the infant's interest in the task.

Second, each infant was observed in the Smooth Pursuit task. The infant viewed fifteen trials, each consisting of a moving toy target translating back and forth once across the screen. Measures taken to maintain interest in the task were described previously.

Third, each infant was observed in the Perceptual Completion task. 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 released 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. Prior to the first trial, and between each trial, an attention-getter was shown. The rod-and-box display was presented until the infant reached a predetermined habituation criterion, computed as a decline in looking times across four consecutive trials, beginning with the second trial, adding up to less than half the total looking times across the first four trials. 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.

Finally, each infant was observed in the Motion Direction Discrimination task, consisting of 4-s segments of the Charlie Brown video, a 2-s attention-getter, and 4-s moving dot displays. Segments of the Charlie Brown video were presented in sequence. Order of dot displays was randomized.

III. Results

A. Data Scoring

Scanning. Data from the Scanning task consisted of the proportion of visual attention directed at specific areas of the stimulus. As in [13], we reasoned that the most informative regions with respect to perceptual completion encompassed the visible rod parts and their range of motion. Of central interest was the extent to which individual infants exhibited a top bias, computed as the percentage of looking in the top region (above the occluder) as a function of total looking in both (top + bottom) regions.

Infants contributed a mean of 34.00 s of scanning data (*SD* = 14.33), out of 60 s possible. A mean of 72.08% (*SD* = 17.89) of all scanning was directed toward the regions of the display encompassing rod motion. Overall, a mean of 59.84% (*SD* = 35.95) of rod scanning was directed toward the top rod region (i.e., a weak but nonsignificant top bias across the sample).

Smooth pursuit. The index of Smooth Pursuit performance consisted of the ratio of oculomotor pursuit speed to target speed, also known as gain. (A gain of 1.0 would mean that speed of point of gaze matched perfectly the target speed.) Mean gain was .3671 (SD = .1133) across the sample.

Perceptual Completion. Data from the Perceptual Completion task consisted of the posthabituation preference for the broken rod stimulus, computed as the percentage of looking toward the broken rod as a function of total looking at both test stimuli. The mean preference for the broken rod was 47.92% (SD = 20.57).

Motion Direction Discrimination. The index of Motion Direction Discrimination was the proportion of visual attention directed at complex motion, computed as the percentage of looking in the complex region as a function of total looking in both regions (simple + complex). Overall, a mean of 72.21% (*SD* = 12.52) of attention was directed at the complex region.

B. Relations Between Measures of Task Performance

To test relations between performance in the Scanning, Smooth Pursuit, Perceptual Completion, and Motion Direction Discrimination tasks, we computed a series of correlations across the four measures.

There was a reliable correlation between Motion Direction Discrimination and Smooth Pursuit gain (Fig. 4), providing convergent evidence for the validity of the Motion Direction Discrimination measure as an index of motion sensitivity. There was no reliable correlation between Motion Direction Discrimination and posthabituation preference in the Perceptual Completion task (Fig. 5), implying that perception of unity relies on mechanisms that are independent of those tapped by the motion sensitivity task. Performance on the Perceptual Completion task was, however, strongly negatively correlated with the tendency to exhibit a top bias in the Scanning task (Fig. 6). That is, the tendency to scan evenly across the two regions of rod motion was associated with perceptual completion. The correlation between measures of Motion Direction Discrimination and Scanning (top bias) was not reliable, $r(12) = -.0374$, $p = .90$.

C. Relations between Age and Task Performance

We considered also whether there were correlations with task performance and age (in days). The correlation between age and posthabituation preference was not statistically significant, $r(12) = -.4664$, $p = .09$; nor was the correlation between age and Scanning (top bias), $r(12) = .3810$, $p = .18$. However, there was a reliable correlation between age and Smooth Pursuit performance (gain) and a near-reliable correlation between age and Motion Direction Discrimination (Fig. 7).

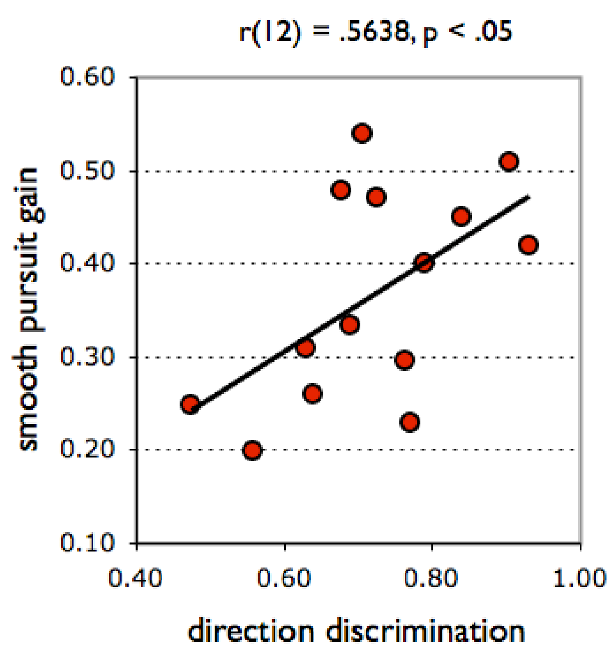

Fig. 4 Correlation between performance on the Motion Direction Discrimination and Smooth Pursuit tasks.

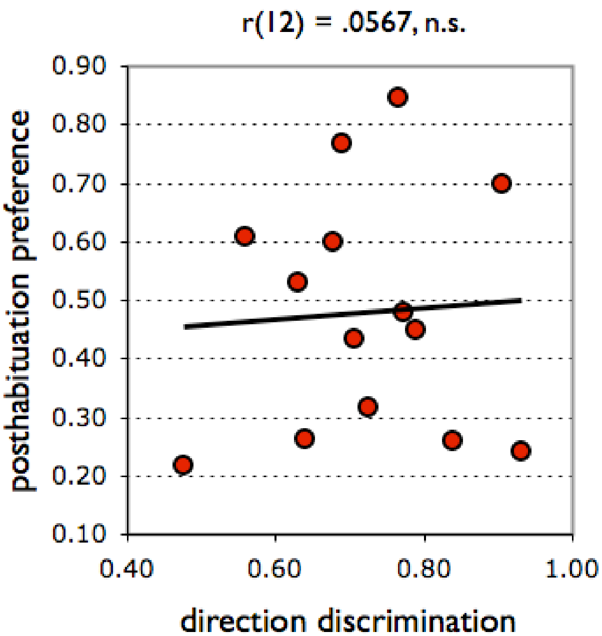

Fig. 5 Correlation between performance on the Motion Direction Discrimination and Perceptual Completion tasks.

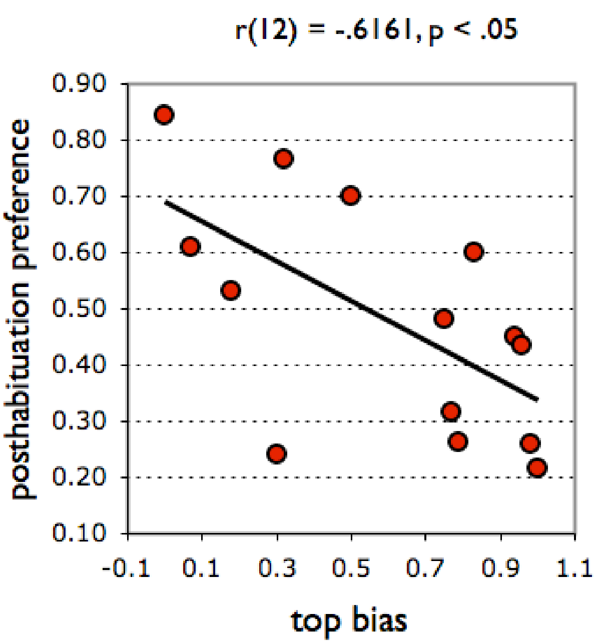

Fig. 6 Correlation between performance on the Scanning (i.e., top bias) and Perceptual Completion tasks.

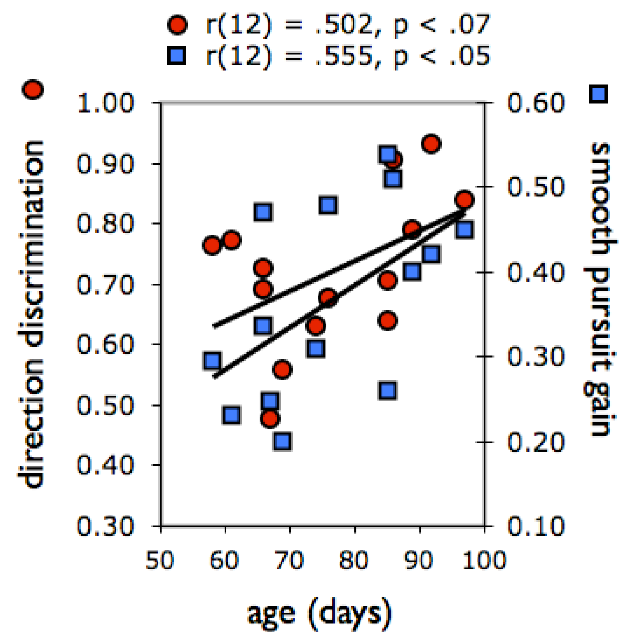

Fig. 7 Correlation between age (in days) and performance on the Motion Direction Discrimination and Smooth Pursuit tasks.

IV. Discussion

We examined relations between motion sensitivity and perceptual completion in young infants who are at an age of transition toward perception of occlusion [6]. We found that our measure of motion sensitivity (detection of discrepant motion direction in random-dot kinematograms) was strongly correlated with a measure of oculomotor performance (smooth pursuit) that has been thought to rely on cortical motion-sensitive mechanisms [12, 15]. In contrast, motion sensitivity performance was uncorrelated with a second measure of oculomotor performance, the tendency to scan consistently between regions of rod motion as opposed to a top bias. Nor was motion sensitivity related to perceptual completion.

These results suggest that our tasks tapped into separate visual functions, both undergoing development at 2-3 months. One function computes direction of motion and motion direction, rather than simple change in position, and supports control of eye movements to track motion of small targets in the environment. The second function identifies objects, and supports perception of the unity of the visible portions of a partly occluded surface.

Our results imply that development of smooth pursuit in infancy relies not on lower-level mechanisms that direct gaze, such as the oculomotor musculature or subcortical structures (e.g., brain stem and superior colliculus), but rather on higher-level cortical mechanisms, such as areas MT and MST in the monkey visual system (and, presumably, their human analogues) that are implicated in motion processing [15, 17]. Smooth pursuit performance in our task was correlated with age, and the correlation of age with our measure of motion sensitivity was nearly statistically reliable, providing evidence that performance is at least somewhat age-dependent. This finding is consistent with a view positing a strong role for cortical maturation in development of motion perception, in particular pathways to and from areas of the visual system that specialize in processing motion [12, 15, 17].

Perceptual completion performance in our task was independent of motion sensitivity. It was also independent of age, despite a wealth of evidence that 2-3 months is a time of relatively rapid development in occlusion perception [2, 3, 6]. The best predictor of perceptual completion, instead, was the extent to which infants directed visual attention consistently toward informative regions in the occlusion display, overcoming an early tendency toward a top bias [14]. This finding is consistent with other recent experiments reporting important associations between scanning patterns and perceptual completion. In particular, examination of individual differences in scanning and perceptual completion performance has revealed that in a slightly older population (3-month-olds), infants who provided evidence of unity perception attended more to the visible surfaces of the partly occluded object relative to other infants [13, 18]. Together, these results suggest that development of perceptual copmpletion relies less on cortical maturation (if age can be taken as a proxy for maturation) and on motion sensitivity than on the infant's own oculomotor behavior. Infants appear to "assemble" surfaces in the visual environment that are spatially segregated via active examination of visible parts: their color, luminance [19], orientation [20], and changes over time in position [21], the latter of which might or might not derive from motion sensitivity. This view of developmental mechanisms of perceptual completion is compatible with other approaches that emphasize a strong role for the infant's behavior in his or her development [22-23].

What, then, is the role of motion in perceptual completion? We suggest that perceptual completion proceeds in several steps. First, the observer must segment or parse the scene into its constituents, a process based on differences in surface texture, contour, color, motion, and other information [24-25]. Next, the observer must determine in which depth plane each surface resides, relative to the point of view, as well as assign each visible contour to its appropriate surface, taking account of occlusion [26]. The importance of motion, on this account, is its contribution to segmentation, rather than to unity.

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