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Where Infants Look Determines How They See: Eye Movements and Object Perception Performance in 3-Month-Olds

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A fundamental question of perceptual development concerns how infants come to perceive partly hidden objects as unified across a spatial gap imposed by an occluder. Much is known about the time course of development of perceptual completion during the first several months after birth, as well as some of the visual information that supports unity perception in infants. The goal of this investigation was to examine the inputs to this process. We recorded eye movements in 3-month-old infants as they participated in a standard object unity task and found systematic differences in scanning patterns between those infants whose posthabituation preferences were indicative of unity perception versus those infants who did not perceive unity. Perceivers, relative to nonperceivers, scanned more reliably in the vicinity of the visible rod parts and scanned more frequently across the range of rod motion. These results suggest that emerging object concepts are tied closely to available visual information in the environment, and the process of information pickup.

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A central question of cognitive science and developmental psychology concerns how infants come to perceive and represent objects as continuous and coherent across space and time. The inputs to this process are incomplete, because the light that is projected to the eye from most objects is reflected from only a fraction of their surfaces, due to the ubiquity of occlusion in the visual environment. Yet the adult experience of object perception is not a world of fractionated surfaces, but instead a world of complete objects whose boundaries extend beyond what may be directly visible. Perceptual completion of object surfaces, therefore, is a necessary condition supporting veridical object perception, and there is compelling evidence, outlined subsequently, for fundamental developments in the ability to accomplish this task, beginning with the onset of visual experience.

Research on the development of perceptual completion has made much use of the object unity paradigm, developed initially by Kellman and Spelke (1983). This paradigm exploits the tendency of young infants to exhibit novelty preferences following a period of habituation to a single stimulus and is suitable for a range of age groups in explorations of development of object perception. Many of these experiments have involved presentation of a “rod-and-box” display during a habituation phase. This is followed by a pair of test displays that are each consistent with the visible portions of the rod in the habituation stimulus, yet are distinct in that one test display consists of a single surface (the “complete” rod) and the other consists of two disjoint surfaces (the “broken” rod; Figure 1). Longer looking toward one display is interpreted as a novelty preference, given adequate controls (Bornstein, 1985), and provides evidence of perception of unity versus disjoint surfaces during habituation. That is, a posthabituation preference for the complete object implies perception of disjoint surfaces during habituation, whereas a preference for the broken object implies perception of unity. A lack of consistent preference suggests ambiguity concerning unity under occlu-

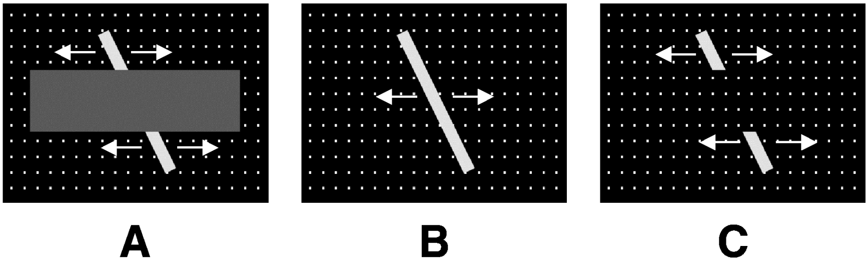

FIGURE 1 Displays used to investigate infants’ perception of object unity. (A) A partly occluded rod, its visible segments undergoing a common lateral motion. (B) Complete rod. (C) Broken rod. A reliable preference for the broken rod relative to the complete rod after habituation provides evidence of unity perception in the occlusion display. The opposite preference indicates perception of disjoint objects in the occlusion display. Lack of preference suggests ambiguity with respect to unity in the sample under investigation. All three outcomes have been reported in the literature, depending on the age of the infants and the display parameters.

sion. (All three of these patterns of data have been obtained in various studies.) A rich descriptive knowledge base bearing on infants' perceptual completion has resulted from the use of this technique. Experiments have tended to address one of two issues: first, the visual information used by infants to determine whether visible object surfaces are likely to be joined behind an occluder, and second, the changes with age that are observed in infants' ability to achieve completion. As we explain subsequently, these issues are closely related.

Research on infants' use of visual information to determine unity has its origins in the initial investigations reported by Kellman and Spelke (1983), who described a series of experiments exploring the role of motion in 4-month-olds' unity perception. These and succeeding studies revealed not only the importance of the motion of the visible surfaces to infants' perceptual completion, but also the surfaces' orientation, shape, pattern, and proximity (see S. P. Johnson, 2001; Needham, Baillargeon, & Kaufman, 1997, for review). Research on the development of perceptual completion has revealed a fundamental shift with age in infants' capacity to perceive unity. Neonates have been found consistently to prefer a complete object following habituation, implying perception of separate objects above and below the occluder (Slater, Johnson, Brown, & Badenoch, 1996; Slater et al., 1990). Unity perception appears to emerge soon after birth, however, first evident in fragile form in 2-month-olds, and becoming more robust by 4 to 6 months (S. P. Johnson & Aslin, 1995, 1996; S. P. Johnson & Náñez, 1995). One effect of development is illustrated by age-related changes in infants' responses to rod-and-box displays in which the proximity of the visible rod parts is manipulated by changing the height of the occluding box. For example, 2-month-olds do not perceive unity in displays with a relatively wide box (such as depicted in Figure 1) but will do so when occluder height is reduced or when gaps are placed strategically in the box such that more of the translating rod is visible (S. P. Johnson & Aslin, 1995). Four-month-olds, in contrast, perceive unity readily in wide-occluder displays (S. P. Johnson & Aslin, 1996). Perceptual completion in infancy, therefore, is a function of both age and display characteristics.

The foregoing series of studies points to the first several months after birth as the time of emergence of perceptual completion, but little is known about mechanisms of development. That is the goal of this investigation. We explored the relation between scanning patterns and incipient object perception by examining individual differences in performance of infants who are at an age of transition toward veridical perception of unity. We achieved this by targeting a specific age group (3-month-olds) and by using a specific type of rod-and-box display (a wide-occluder rod-and-box stimulus). Our reasoning was as follows. Two-month-olds appear to be unable to perceive unity in a rod-and-box display of the type shown in Figure 1 (i.e., a wide-occluder display), although 4-month-olds can (S. P. Johnson & Aslin, 1995; S. P. Johnson & Náñez, 1995). A group of 3-month-olds viewing such a stimulus might be expected to provide a mixed result, with a subset of infants providing evidence of perceptual completion and others failing to do so. One way in which those infants who provide positive evidence (termed *perceivers*) might be distinguished from those who do not (termed *nonperceivers*) is in the way in which the two groups scan the display. We tested a group of 3-month-olds in a standard habituation paradigm (habituation to the rod-and-box stimulus, followed by presentation of broken and complete rod stimuli) as we recorded eye movements with a corneal-reflection eye tracker.

Whether an infant is a perceiver or a nonperceiver tells us about the output of the mechanisms responsible for perceptual completion, but little is known about the inputs to the process. We chose to record fixations and saccade patterns as a first step in understanding this question. That is, previous research has documented the specific features of stimulus displays (e.g., motion, orientation) that support perception of unity and when infants are able to use this information effectively. Precisely how infants scan visual features in real time during an object perception task, however, has not yet been described in the literature. Eye-tracking methodology allows us to document individual differences in the spatial and temporal structure of scans and what these inputs may contribute to what is perceived. The scanning patterns are best interpreted with some caution, noting that visual attention is not limited to foveation and that the size of the visual field effective in attracting eye movements expands considerably across infancy (Maurer & Lewis, 1998). Nevertheless, the outcomes of our analyses, described subsequently, lend credence to the posited relation between infants' patterns of fixation and object perception performance.

We explored four hypotheses. First, we predicted a difference between perceivers and nonperceivers in overall scanning strategies: Perceivers were expected to scan more globally, given past reports of limitations in scanning that improve with age (Bronson, 1990, 1994). Second, we predicted that perceivers would produce more scans (i.e., fixations and saccades) per unit of time. For example, 2-month-olds, relative to older infants, have been shown to fixate less on informative regions of moving object displays and to scan less frequently across the display (S. P. Johnson & Johnson, 2000). We expected these trends to be manifest in our sample as a function of infants' general information-processing skills. Third, we predicted that perceivers would engage in relatively more frequent targeted fixations and saccades that terminated within the vicinity of the rod parts. Fourth, we predicted that perceivers would scan more frequently across the rod's range of motion. Both these latter effects may reflect infants' efforts to obtain critical information about the visible rod parts' relative position, orientation, and motion.

METHOD

Participants

The final sample consisted of 16 three-month-olds (7 boys, 9 girls), with a mean age of 92.9 days ($SD = 5.9$). An additional 5 infants were tested but not included in the sample due to fussiness ($n = 2$), failure to habituate ($n = 1$), persistent inattention to the displays ($n = 1$), or excessive movement that prohibited data collection with the eye tracker ($n = 1$).

Procedure

Two experimenters, the habituation experimenter and the eye-tracker experimenter, worked in concert to collect looking data and record eye movements (see Figure 2). The habituation experimenter was responsible for collecting looking time data. This experimenter (the first author) viewed the infant's face on a television (the image is seen in the lower left quadrant of Figure 3), fed by a signal from a video camera. This camera was located on the table below the stimulus. The habituation experimenter was blind to test stimulus order, did not know when the displays changed from habituation to test, and had no access to the gaze coordinates calculated by the eye tracker. The eye-tracker experimenter (either the second or third author) was responsible for recording eye movements and controlled a computer dedicated to this purpose. This experimenter had full information about the stimulus seen by the infant at any given time but had no influence over the stimulus or over the habituation experimenter's judgments of looking times. The eye-tracker experimenter's goal was to maintain the best possible eye track, which

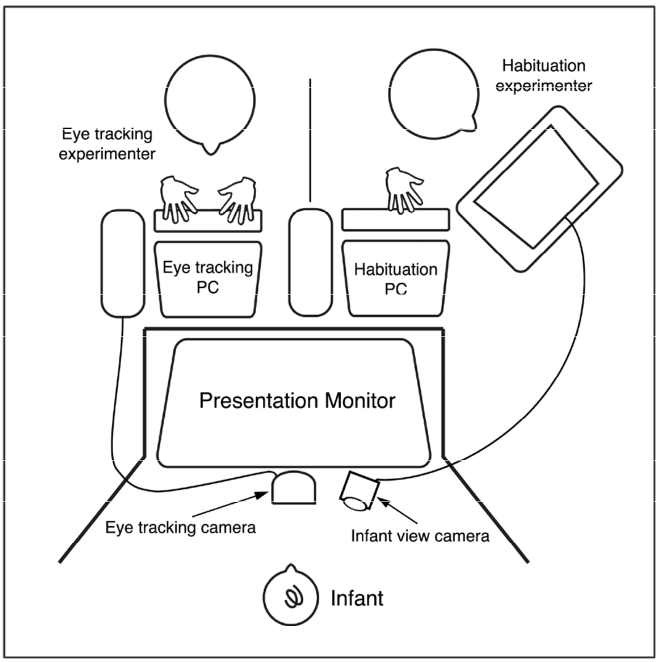

FIGURE 2 Schematic overhead view of the experimental setup.

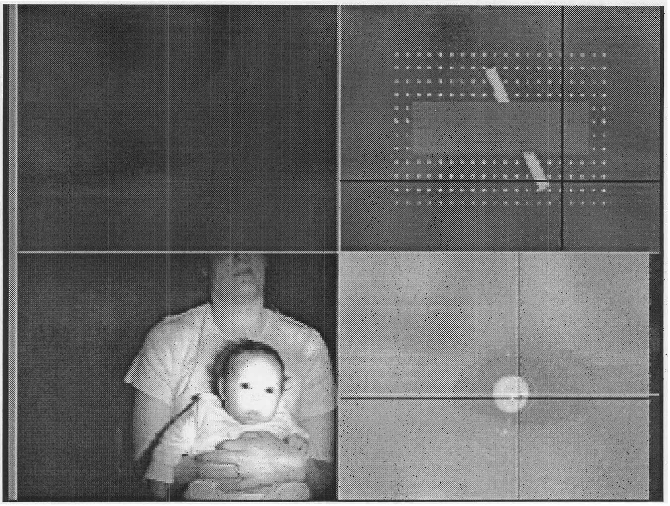

FIGURE 3 A single frame from the video record of one of the infant participants, showing the infant's face from the video camera (lower left, the same image viewed by the habituation experimenter on a separate monitor), the eye image from the pupil camera (lower right), and the display as seen by the infant online, with the point of gaze superimposed on the stimulus as she watches.

was potentially compromised at all times due to motion of the infant out of range of the pupil camera (described subsequently). This was accomplished by watching the infant's movements (provided by the same video camera that fed the monitor viewed by the habituation experimenter, lower left of Figure 3) and the robustness of the crosshairs indicating the center of the pupil and the center of the cornea (provided by the eye tracker's pupil camera, lower right of Figure 3). The normal automatic mode of operation of the pupil camera kept the pupil within view via a pan/tilt mechanism built into the camera's base, sufficient to compensate for small head movements. When the infant moved beyond this field of view, the eye-tracker experimenter changed to a manual mode of operation and reacquired a view of the pupil via remote control.

We wished to conduct this study in as similar a fashion as previous object unity experiments and therefore instructed the parents to let the infants move as much as they wanted. This meant that we have eye movement data from a mean of only 20.4% (*SD* = 14.9) of the total habituation looking time. This is a lower proportion than we would like. Nevertheless, there is no reason to suspect that this 20.4% is a biased sample of fixations. Instead, we have every reason to believe that the eye movement data we collected are fully representative of the scanning patterns of individual infants, especially given the orderly and interpretable differences we observed between perceivers and nonperceivers in their patterns of eye movement (described in the Results section). As suggested by two of the reviewers, it might be that the testing periods for which eye movement data are available were those during which infants were most quiescent and attentive and thus best representative of visual attention during our object perception task. However, we have no empirical verification of this possibility.

Infants were seated 120 cm from the stimulus monitor in a parent's lap. Parents were provided information prior to testing about the eye tracker and data collection methods but not about the specific hypotheses under investigation. The video camera and the pupil camera were placed side by side on the same table as the monitor.

Prior to testing, one of each infant's eyes (usually the left) was calibrated with the quick calibration routine provided by the manufacturer of the eye tracker. All data were collected with the same eye for each infant. Infants were first shown a series of interesting stimuli (a clip from *Sesame Street* and movies of small toys accompanied by different sounds) that were controlled by the habituation experimenter to hold the infant's attention. As the infant watched the monitor, the eye-tracker experimenter made adjustments to the gain and sensitivity of the eye-tracker settings (i.e., pupil and cornea). After the experimenters agreed that subsequent tracks were likely to be robust, the infant was shown an "attention-getter" (a target-patterned beeping ball) at the top left and bottom right corners of an imaginary rectangle that corresponded to the corners of the stimulus background (the texture elements) viewed during test. When the experimenters judged that the infant was looking at each of these two points, this information was entered into the eye tracker, which then interpolated the positions of the remaining points between the two corners. Calibration was checked by moving the attention-getter to random positions on the screen. If the infant's point of gaze (POG) was not directed within 0.5° of the center of the attention-getter at all positions (minimum of six), the calibration routine was repeated until this criterion was reached. We estimate therefore that spatial accuracy was 0° to 1° error, given estimates of the inherent accuracy of the eye tracker provided by the manufacturer (i.e., an additional 0.5° of error possible).

Each trial commenced with presentation of the attention-getter. The habituation experimenter ended the attention-getter and began the stimulus for each trial when he judged that the infant looked at the display. A trial ended when the infant looked away for 2 sec, or when 60 sec had elapsed; the stimulus was then replaced by the attention-getter to begin the next trial. The habituation stimulus was presented until looking times declined across four continuous trials that summed to less than half the total during the first four trials. The minimum number of habituation trials, therefore, was 5, and the maximum was 12. Infants viewed the test displays three times each in alternation. Order was counterbalanced.

Apparatus and Stimuli

A Macintosh computer presented displays on a 76-cm computer monitor, recorded looking time judgments, and calculated the habituation criterion for each infant. The Macintosh also recorded eye movement data as x–y coordinates of the infant's

POG (i.e., a text file) recorded at 30 Hz (the temporal resolution of the stimulus displays) as well as the timing of each stimulus onset and offset. A standard PC computer controlled the eye tracker, an Applied Science Laboratories model 504, and exported the POG coordinates to the Macintosh for recording. The habituation display consisted of a 36.5 × 10.4 cm blue box (17.3° × 5.0° visual angle) and a 2.3 × 26.2 cm green rod (1.1° × 12.5°) that translated laterally through 17.7 cm (8.4°). Each cycle of motion lasted 5 sec (i.e., 2.5 sec either left or right). The rod thus moved at a rate of 7.1 cm/sec (3.4°/sec). The rod moved back and forth continuously as long as the stimulus was shown. The two test displays were identical to the habituation display, except the complete rod had no box, but instead the visible rod parts were connected, and the broken rod had a gap between the rod parts in which the background texture was visible. Objects were presented against a black background with a 12 × 20 grid of white dots (43.8 × 30.2 cm, 20.7° × 14.3°).

RESULTS

Data consisted both of looking times during habituation and test trials, and of eye movements recorded during habituation. Preliminary analyses revealed no differences in habituation or test performance as a function of sex or order of test display presentation.

Looking Time Data

Looking time data were examined for evidence of unity perception, which would be revealed by a consistent preference for the broken rod during test. A 2 (display: broken vs. complete object) × 3 (test trial block) repeated measures analysis of variance on looking times during test yielded no reliable effects, indicating that, as expected, there was no evidence of unity perception across the group. The mean preference for the broken rod was 52.67% (SD = 13.66), computed as the proportion of looking times directed at the broken rod divided by total looking during test (see Figure 4). Infants whose preference was greater than 50% were defined as perceivers, and the others as nonperceivers. Nine infants (the perceivers, 4 girls and 5 boys; M age = 90.7 days, SD = 4.9) preferred the broken rod (M preference = 61.03%, SD = 10.72), and this preference was statistically significant, $t(8) = 3.11$, $p < .05$. Seven infants (the nonperceivers, 3 girls and 4 boys; M age = 95.7 days, SD = 6.2) preferred the complete rod (M preference = 41.92%, SD = 8.60), and this preference was marginally significant, $t(6) = 2.25$, $p = .065$. The test display preference between the two groups was statistically reliable, $t(14) = 3.84$, $p < .01$. There were no reliable differences between perceivers and nonperceivers as a function of total time to habituate (M = 178.56 sec, SD = 113.50), number of trials to habituate (M = 8.29, SD = 3.25), total looking time during test (M = 59.32 sec, SD = 60.72), or

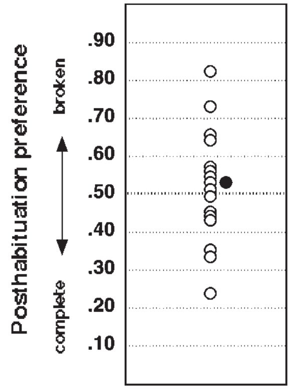

FIGURE 4 Plot of individual infants' posthabituation preferences as a function of proportion of preference for the broken rod test display. Open circles = individual preferences; filled circle = mean of the sample.

tracking time, the amount of eye-tracking data yielded for each infant (M = 41.26 sec, SD = 49.81), all ts < 1.85, *ns*.

Eye Movement Data

Individual fixations were defined as portions of the data during which the x–y coordinates of the POG did not vary more than 0.5° for a minimum of 100 msec. Scanning patterns were interpreted with respect to eight areas of interest (AOIs), which we defined according to the boundaries surrounding the two visible rod parts in the habituation display, the left and right halves of the occluding box, and four quadrants of the display (see Figure 5). The boundaries of the AOIs corre-

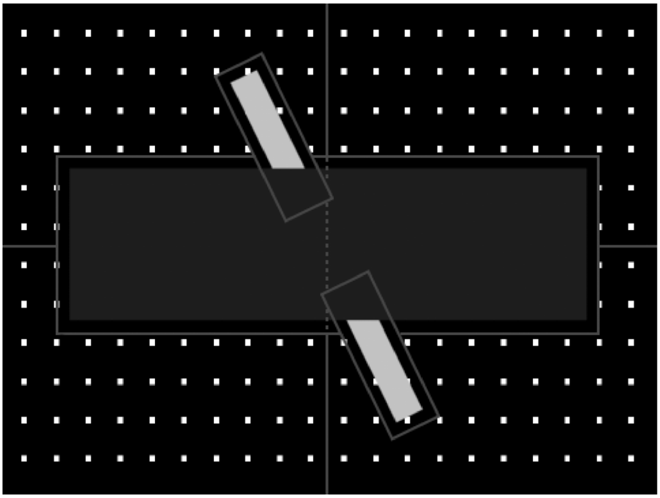

FIGURE 5 Areas of interest used to provide spatial categories for scanning patterns.

sponding to the rod parts and box extended approximately 1° outside the actual stimulus borders to accommodate the spatial limitations of the eye tracker. The two AOIs corresponding to the rod parts "traveled" along with the actual stimulus as data collection progressed. Examples of two infants' scanning patterns, one perceiver and one nonperceiver, are shown in Figure 6.

Hypotheses

To address the four hypotheses presented previously, a series of targeted data analyses was performed. Data consisted of (a) frequencies of fixations per second within one or more AOIs, (b) dwell times within one or more AOIs, and (c) fre-

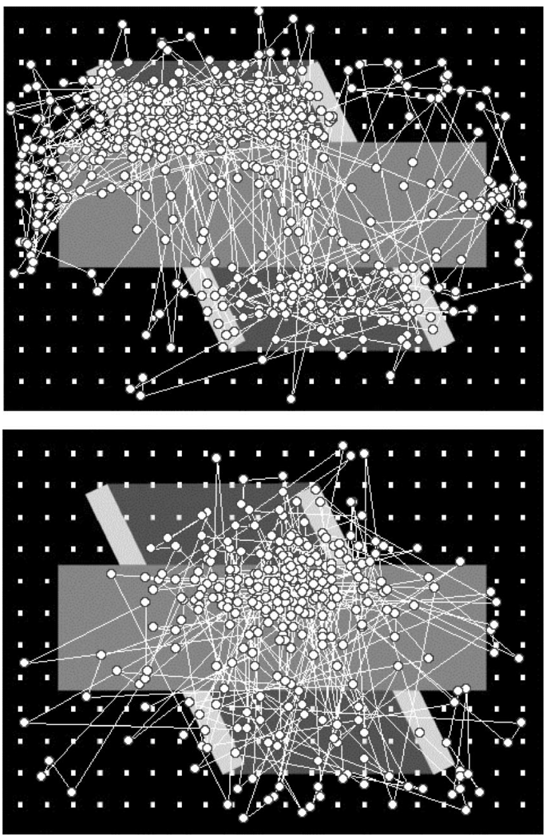

FIGURE 6 Examples of two infants' scanning patterns during habituation. Each is shown with the full lateral extent of rod motion (between the left- and rightmost positions). Top: A perceiver. Bottom: A nonperceiver. Note that both infants scanned actively across the display, but the perceiver spent more time inspecting the rod parts and their motion.

quencies of saccades within and between AOIs. Unless otherwise indicated, all three measures were converted to proportions as a function of tracking time or total number of saccades for each infant prior to analysis. Recall that these data were recorded during habituation only, as a gauge of information processing during the unity perception task.

Hypothesis 1: Perceivers will scan more globally than will nonperceivers. *Global scans* were defined as the proportion of saccades between AOIs, as distinguished from *local scans,* the proportion of saccades within AOIs. Contrary to our hypothesis, we found no reliable differences between groups in global scans, $t(14) < 0.9$, *ns.* Global scans comprised a mean of 57.91% ($SD = 8.82$) of all scans. Across the sample, there were more global than local scans, $t(15) = 3.59$, $p < .01$.

We next asked whether there might be a top bias, a tendency to look more at the top two quadrants and the top visible rod part than at the bottom two quadrants plus the bottom visible rod part. (S. P. Johnson & Johnson, 2000, reported that 2-month-olds showed a reliable top bias, although 3.5-month-olds did not.) The infants we observed exhibited a marginally significant top bias in terms of both dwell times, $t(15) = 2.03$, $p = .061$ (40.85% of looking toward the top, $SD = 24.19$; 21.14% of looking toward the bottom, $SD = 17.89$), and in terms of fixations, $t(15) = 1.97$, $p = .067$ (40.69% of fixations/sec in the top AOIs, $SD = 23.58$; 21.88% of fixations/sec in the bottom AOIs, $SD = 17.40$). However, this tendency did not vary as a function of perceivers versus nonperceivers, $F(1, 14) = 0.30$, *ns,* for dwell times; $F(1, 14) = 0.19$, *ns,* for fixations/sec.

Hypothesis 2: Perceivers will produce more fixations per second than will nonperceivers. Again counter to our hypotheses of more active scanning overall by perceivers relative to nonperceivers, there were no significant differences in fixations/sec, $t(14) = 1.79$, *ns.* The mean number of fixations/sec for the entire sample was 5.54 ($SD = 1.35$). This value is higher than adult scanning frequencies (typically 2–4 fixations/sec; e.g., Schiller, 1998) and higher than reports of infant scanning of static stimuli (e.g., Bronson, 1990, 1994).

Hypothesis 3: Perceivers will look more at the rod than will nonperceivers. Our third hypothesis was supported: As seen in Figure 7, perceivers produced reliably higher proportions of fixations/sec in the vicinity of the rod parts relative to nonperceivers, $t(14) = 3.77$, $p < .01$ (M % fixations/sec by perceivers = 16.13, $SD = 3.98$; M % fixations/sec by nonperceivers = 9.58, $SD = 2.55$). In contrast, there were no reliable differences between the two groups in fixations within other regions. This pattern was echoed in the dwell time data. Perceivers spent a higher proportion of the time looking at the rod relative to the nonperceivers, $t(14) = 3.74$, $p < .01$ (M % dwell time by perceivers = 16.72, $SD = 4.85$; M % dwell times

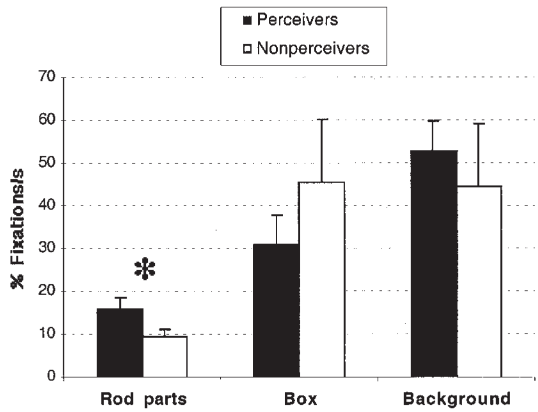

FIGURE 7 Perceivers produced more fixations/sec in the vicinity of the rod parts, relative to nonperceivers, but not in other areas of the display.

by nonperceivers = 8.85, *SD* = 3.07), but there were no significant differences in dwell times in the box or background AOIs.

Hypothesis 3 was also supported by data from patterns of saccades. We computed a measure of rod scanning by combining all saccades that began and ended either within the top or bottom visible rod segment, or between the two. As seen in Figure 8, these rod scans were produced more frequently by perceivers than by nonperceivers, $t(14) = 2.17$, $p < .05$, as a function of the proportion of total numbers of scans (*M* % rod scans by perceivers = 4.97, *SD* = 2.10; *M* % rod scans by nonperceivers = 2.63, *SD* = 2.19).

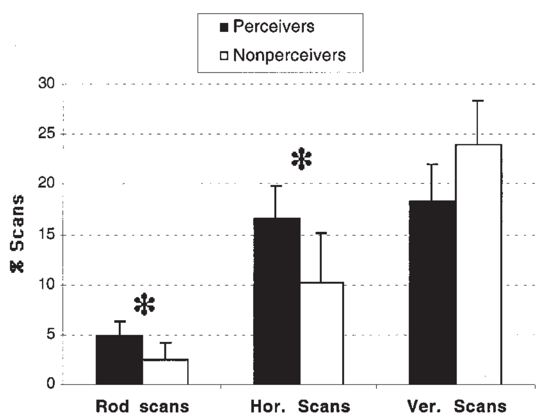

FIGURE 8 Perceivers scanned more actively within and across the visible rod parts, and horizontally across the areas of rod motion, relative to nonperceivers. Other kinds of scans (e.g., vertical scans), however, were not more common among perceivers.

Hypothesis 4: Perceivers will scan more frequently across the vicinity of rod motion. Our fourth hypothesis was supported as well. We computed a measure of horizontal scanning by combining all saccades that began in either one of the upper quadrants or the top rod part and ended in one of the other of the two top AOIs, or that began in either one of the lower quadrants or the bottom rod part and ended in one of the other of the two bottom AOIs. The majority of these horizontal scans, therefore, would be likely to take the POG across the path of the rod's motion. As seen in Figure 8, perceivers produced more horizontal scans than did nonperceivers, $t(14) = 2.21$, $p < .05$ (M % horizontal scans by perceivers = 16.57, $SD = 4.91$; M % horizontal scans by nonperceivers = 10.28, $SD = 6.49$). In contrast, an examination of vertical scans (saccades between the two left quadrants and left half of the box or between the two right quadrants and the right half of the box) revealed a marginally reliable difference in favor of the nonperceivers, $t(14) = 1.99$, $p = .066$ (see Figure 8).

DISCUSSION

This study is the first to our knowledge that combines habituation and eye-tracking methods. Our goal was to determine precisely where and when infants look as they are engaged in an object perception task. Three-month-olds participated in a traditional object unity paradigm, and their posthabituation looking times were taken either as evidence for perceptual completion or as failure to achieve completion. Eye movement patterns, obtained independently of looking times, revealed important differences between those infants who provided evidence of unity perception and those who did not. Infants whose looking times implied unity percepts scanned systematically in such a fashion as to optimize uptake of important information for unity: They fixated the rod more frequently (and longer) and scanned across the rod's path as it translated back and forth, two scanning patterns that would tend to maximize pickup of information about the rod parts' orientation and motion. We obtained no evidence, however, for more general scanning differences: All infants scanned actively across the stimulus, and there is every indication that even nonperceivers were engaged in the task and were interested in the stimuli.

There are at least three reasons why scanning patterns might be related to object perception tasks. First, infants who scan more effectively might be better able to obtain information crucial to support veridical object percepts. On this account, scanning is self-directed, and superior patterns may be rooted in an inherent, general-purpose ability to obtain information in an efficient manner. This notion is similar to distinctions between "short-" versus "long-lookers," infants who have been found to differ with respect to processing of two-dimensional stimulus forms as a function of attentional engagement (e.g., Frick, Colombo, & Allen, 2000). On this account, then, fundamental information-processing skills lead object perception. A second alternative would view the relation in the opposite way: Infants who are capable of perceptual completion are more likely to strategize information pickup in such a way as to meet the perceptual challenge posed by occlusion. On this second account, object perception drives information-processing strategies. A third possibility is based on individual differences in attention. Some visual stimulus properties, such as motion, are especially salient, even from birth (Slater, 1995). Infants who are highly attentive are drawn to this information and are more exposed, relative to less attentive infants, to vital information supporting veridical object percepts. Here, scanning is less self-initiated and more reflexive than posited by the first alternative, but the outcome is similar.

These three reasons for why scanning might be related to habituation data in our task might more profitably be broken down into two types: strategy-driven and stimulus-driven (or intrinsic and extrinsic) reasons. The first reason falls into the strategy-driven category: There are individual differences in infants' oculomotor control routines that efficiently scan the display and as a result capture critical visual information. The second reason falls into the stimulus-driven category: A display that supports completion (presuming such a perceptual ability is already present) triggers scanning patterns consistent with that perceptual ability. The third reason (attention to low-level stimulus attributes) also falls into the stimulus-driven category. It may be that during development, infants progress from Category 3 to Category 2 to Category 1, an intriguing hypothesis, the investigation of which would yield important information concerning fundamental mechanisms of change in infants' perceptual and cognitive skills.

What other kinds of developmental change might lead infants to adopt the kinds of advantageous scanning patterns we observed in the perceivers? We consider three possibilities. First, rapid physical growth during infancy forces the developing visual system into a chronic state of recalibration between retinal input and saccade commands (Aslin, 1993). The infant also must learn to integrate information from head and body movements into saccade plans, and there is evidence of important changes across the first 6 months in the spatial representations that guide eye movements. Initially, infants produce a preponderance of "retinocentric" saccades, or programming of gaze shifts relative to retinal coordinates only, toward "egocentric" saccades, eye movements that take into account retinal, head, and body position from visual, vestibular, and proprioceptive information (M. H. Johnson, Gilmore, & Csibra, 1998). One functional consequence of this early period of continual recalibration and partial integration may be an increase in exploratory or even indiscriminate eye movements relative to other periods in development, a possibility that is borne out by the high scan rates seen in our data, compared to adults. The timing of this exploratory scanning is consistent with the findings of Hunnius and Geuze (2004/this issue), who reported a stabilization of oculomotor behavior in infants who were several weeks older than our sample. It is not clear, however, what the effects of incomplete calibration and integration of spatial frames of reference may be on development of object perception.

A second kind of developmental change is the maturation of cortical networks responsible for oculomotor function, arising, for example, from neural growth, increased myelination, synapse propagation and pruning, progress in neurotransmitter production and uptake, and improvements in coordination and synchronization of neural assemblies. Schiller (1998) identified several circuits subserving eye movement control that appear to develop somewhat independently. Of particular concern to this article is a pathway leading from primary visual cortex through the frontal lobe (frontal eye fields and dorsomedial frontal cortex) and on to the brain stem, where eye movement commands are generated. These frontal regions also receive inputs from parietal and temporal areas that are implicated in object perception and planning of action sequences. Relative to other eye movement systems, this "anterior" circuit appears to be late in developing. For example, reflexive saccades and smooth pursuit are functional in ontogeny prior to anticipatory eye movements and may rely on simpler, early-developing subcortical and cortical networks (M. H. Johnson, 1990). Individual differences in maturation of the anterior pathway, as well as cortical sites coding for object identification, may be responsible in part for the data patterns we obtained in this study, but this possibility awaits empirical verification.

A final consideration is the potential contribution from cognitive development. Evidence has emerged recently for rapid learning of object representations in 4-month-olds when indexed with an oculomotor anticipation paradigm (S. P. Johnson, Amso, & Slemmer, 2003). Baseline comparisons between 4- and 6-month-olds viewing a briefly occluded object on a linear trajectory revealed significantly higher rates of anticipation by the older infants, interpreted to mean stronger object representations under occlusion (cf. Gredebäck & von Hofsten, 2004/this issue). When 4-month-olds were provided with brief experience viewing an unoccluded trajectory, they exhibited anticipatory behavior that was markedly similar to 6-month-olds when tested subsequently with an occlusion display. In other words, more robust object concepts, facilitated by brief experience, were reflected in a developmentally more advanced pattern of eye movements. Clearly, the results reported here are consistent with this finding.

Regardless of which account holds up best under future examination, these results provide convincing evidence that infants who were inclined to perceive unity were also likely to look in the right place. These findings suggest that object perception is not independent of available visual information. That is, nascent object concepts are neither abstract nor innate, but instead are tied closely to the infant's own experience and behavior as well as his or her interactions with the environment.

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