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Early perception-action coupling: Eye movements and the development of object perception

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Abstract

We investigated the scanning strategies used by 2- to 3.5-month-old infants when viewing partly occluded object displays. Eye movements were recorded with a corneal reflection system as the infants observed stimuli depicting two rod parts above and below an occluding box. Stimulus parameters were chosen on the basis of past research demonstrating the importance of motion, occluder width, and edge alignment to perception of object unity. Results indicated that the infants tailored scanning to display characteristics, engaging in more extensive scanning when unity perception was challenged by a wide occluder or misaligned edges. In addition, older infants tended to scan the lower parts of the displays more frequently than did younger infants. Exploration of individual differences, however, revealed marked contrasts in specific scanning styles across infants. The findings are consistent with views of perceptual development stressing the importance of information processing skills and self-directed action to the acquisition of object knowledge. © 2000 Elsevier Science Inc. All rights reserved.

Keywords: Eye movements; Perception-action coupling; Object perception; Perceptual development; Cognitive development; Information processing vs. core principles perspectives

Veridical perception of object layout is a necessary requirement for the selection of appropriate action schemes (Gibson, 1966). Before 4 to 6 months, infants are limited to inaccurate reaching and grasping, and extensive manual exploration of objects is largely precluded (Bushnell, 1985; von Hofsten, 1984). The oculomotor system, however, is relatively mature in young infants when compared to other action systems, and infants engage in active visual exploration of the environment from birth (Slater, 1995; von Hofsten &

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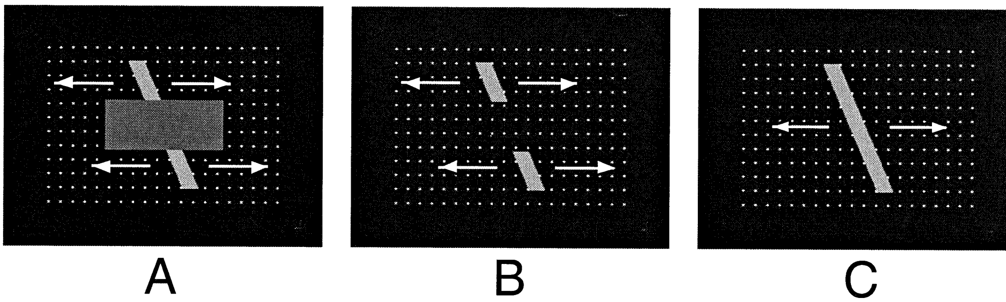

Fig. 1. Displays used in past research on young infants' perception of object unity. (A) Rod-and-box habituation display. (B) Broken rod test display. (C) Complete rod test display. After habituation to A, young infants often look longer at B than at C, suggesting that they perceived the unity of the rod parts behind the box during habituation, and exhibited a novelty preference during test.

Rosander, 1998). These burgeoning perceptual skills are soon used effectively to perceive object layout: There is evidence of rapid development of veridical object perception in the first 4 months after birth, as revealed by experiments investigating perception of object unity (Johnson & Aslin, 1995, 1996; Johnson & Náñez, 1995; Kellman & Spelke, 1983).

In the object unity task, an infant is shown a display consisting of two objects, one partly occluded by another (e.g., the "rod-and-box" stimulus depicted in Fig. 1A). This stimulus is presented repeatedly until habituation, a decline in looking across trials according to a predetermined criterion. After habituation, two new test displays are presented, both consistent with the visible portion of the partly occluded object in the habituation stimulus (e.g., Figs. 1B and 1C). Because infants often exhibit posthabituation novelty preferences (Bornstein, 1985), longer looking at one of the test stimuli provides evidence that it is experienced as relatively novel, and the other stimulus as relatively familiar. For example, longer looking at a "broken" object (e.g., the visible rod parts separated by a gap; Fig. 1B) during test has been interpreted to reflect perception of object unity during habituation (Johnson & Náñez, 1995; Kellman & Spelke, 1983). Longer looking at a "complete" object (Fig. 1C), in contrast, is thought to reflect perception of disjoint objects during habituation (Johnson & Aslin, 1996; Slater et al., 1990; Smith et al., 2001). A lack of a consistent preference, in turn, may indicate no clear percept of either unity or disjoint rod parts (Johnson & Náñez, 1995; Kellman & Spelke, 1983; Smith et al., 2001).

A number of investigations have employed rod-and-box displays to establish when and how young infants achieve veridical perception of occlusion and perceptual completion, and a rich base of empirical findings has resulted. Two principal conclusions have emerged. First, perception of object unity has not been observed in neonates, who appear to perceive a partly occluded rod as consisting of disjoint surfaces (Slater et al., 1990; Slater et al., 1996). Responses to unity emerge rapidly after birth, however, having been observed at 1–2 months under limited conditions (Johnson & Aslin, 1995; Johnson et al., 2000c; Kawataba et al., 1999). Second, by 4 months of age, infants are able to achieve veridical percepts in occlusion displays by utilizing a variety of sources of visual information, including motion, edge orientation, shape, depth, and color (Johnson & Aslin, 1996, 1998, 2000; Johnson et al., 2000a; Johnson et al., 2000b; Kellman & Spelke, 1983; Needham, 1998; Smith et al., 2001; see Johnson, 1997, 2000 for reviews).

Experiments employing the object unity paradigm, then, have revealed a fundamental shift in how infants perceive the world, from birth through the next few months. With the onset of visual experience, neonates may perceive the environment as consisting of a "sensory tableaux," or disconnected fragments that do not cohere into tangible, bounded objects (Piaget, 1954). Veridical perception of occlusion, however, emerges rapidly. The period between 2 to 4 months seems especially important for the development of those attentional and cognitive skills necessary to detect and utilize visual information that supports perception of object unity (Johnson, 1997).

Although much is known currently about the emergence of unity perception at a descriptive level, decisive explanations of underlying mechanisms of development have been more difficult to achieve. How exactly do veridical percepts arise in the infant? Several candidate accounts have been proposed. Spelke, for example (1990, Spelke & Van de Walle, 1993), has suggested that infants experience objects in accord with a set of core principles. Development, on this account, consists of refinements and enrichment of an incipient conceptual system that is predisposed to perceive objects as bounded, solid entities. This system is modular, or self-encapsulated, and independent of perception (Spelke & Hermer, 1996). In contrast to this core knowledge hypothesis, Johnson (2000, in press) proposed that veridical object perception and object knowledge are dependent on subsidiary information processing skills, along with experience viewing objects that become occluded and are again fully visible. The lower-level perceptual abilities are required to detect the visual information necessary for segmentation of the optic array into its constituent surfaces, alongside the conjoining of these visible surface fragments across spatial and temporal gaps into percepts of coherent objects. The visual experience is critical for the building of associations of partial views of surfaces to views of fully visible objects. Object knowledge, then, arises from lower-level perceptual proficiency that develops over the first few months after birth, and exposure to partly occluded and unoccluded objects in the visual environment (see Johnson, 2000, in press; Jusczyk et al., 1999; Mareschal & Johnson, in press for further discussion.)

A key prediction of the information processing perspective is that the development of veridical object perception is accompanied by improvements in the effectiveness with which infants sample the optic array. Clearly, without adequate scrutiny of the visual information that specifies object layout (such as relative depth, orientation, and surface appearance), accurate percepts of the environment are precluded. The goal of the present experiments, therefore, was to explore the relation between perception of partly occluded objects and eye movements. We reasoned that one potential limitation in infants' perception of object unity may be rooted in inefficient scanning strategies, such that very young infants, relative to older infants, would be less likely to scan the entire stimulus, and to limit fixations to uninformative regions of the display. We also explored whether scanning strategies might vary as a function of display characteristics, by including stimuli in which unity either would or would not likely be perceived.

1. Experiment 1

In the first experiment, infants were presented with four displays depicting two rod parts above and below an occluding box. Stimuli were chosen on the basis of past research showing that responses to object unity in rod-and-box displays vary both as a function of occluder width, and of the alignment of the rod edges across the occluder: Two-month-olds have been found to perceive unity when the occluder was narrow, but not wide (Johnson & Aslin, 1995; Johnson & Náñez, 1995), and 4-month-olds have been found to perceive unity when the rod edges were aligned, but unity perception is attenuated when rod parts are misaligned (Johnson & Aslin, 1996; Johnson et al., 2000a, b; Smith et al., 2001). The four stimuli employed in Experiment 1, therefore, were varied along these two dimensions, yielding two levels of occluder width (wide and narrow) and two levels of edge alignment (aligned and misaligned) (see Fig. 2). Infants were presented each of the four displays twice and their eye movements recorded.

1.1. Method

1.1.1 Participants

Fourteen full-term infants (5 females) comprised the final sample, ranging in age from 59 to 127 days. An additional 17 infants were observed but not included in the analyses, due to fussiness (2 infants), equipment failure (3), experimenter error (3), an inability to obtain a reliable point of gaze (POG) for unknown reasons (2), excessive movement on the part of the infant, such that we were unable to record eye movements (3), or poor calibration of the POG (4; see subsequent discussion of calibration).

1.1.2. Apparatus and stimuli

A Macintosh 7600 computer and 76 cm Barco color monitor were used to present the stimuli. The infants were shown one of four rod-and-box displays as eye movements were recorded. Each stimulus was viewed twice (one infant viewed only one of each stimulus due to excessive fussiness), and was presented for an average 21.6 s ($SD = 8.4$). Between rod-and-box displays, an "attention-getter" stimulus was shown, to keep the infant engaged in the task. Stimulus duration was controlled by the experimenter (see Procedures section).

Each rod-and-box display was presented against a black background with a 12×20 grid of white dots serving as texture elements (see Fig. 2). (Background texture has been found to lead to longer looking, and therefore perhaps greater attentional engagement, in habituation experiments; background texture also provides depth information to aid in perceptual segregation of stimulus elements; see Johnson & Aslin, 1996.) The background measured 32.5×23 cm ($15.4° \times 10.9°$ visual angle, at the infant's 120 cm viewing distance). The four rod-and-box displays each contained a blue occluding box and two green rod parts, but differed with respect to occluder width and alignment of the rod parts. In the wide occluder displays, the box measured 25.2×6.0 cm ($11.9° \times 2.8°$). In the narrow occluder displays, the occluder was half this height. In the aligned rod displays, the rod measured 17.3×1.5 cm ($8.2° \times 0.7°$) and was oriented 22° counterclockwise. The rod parts' edges were aligned across the occluder. In the misaligned rod displays, the bottom rod part was displaced 2.7 cm

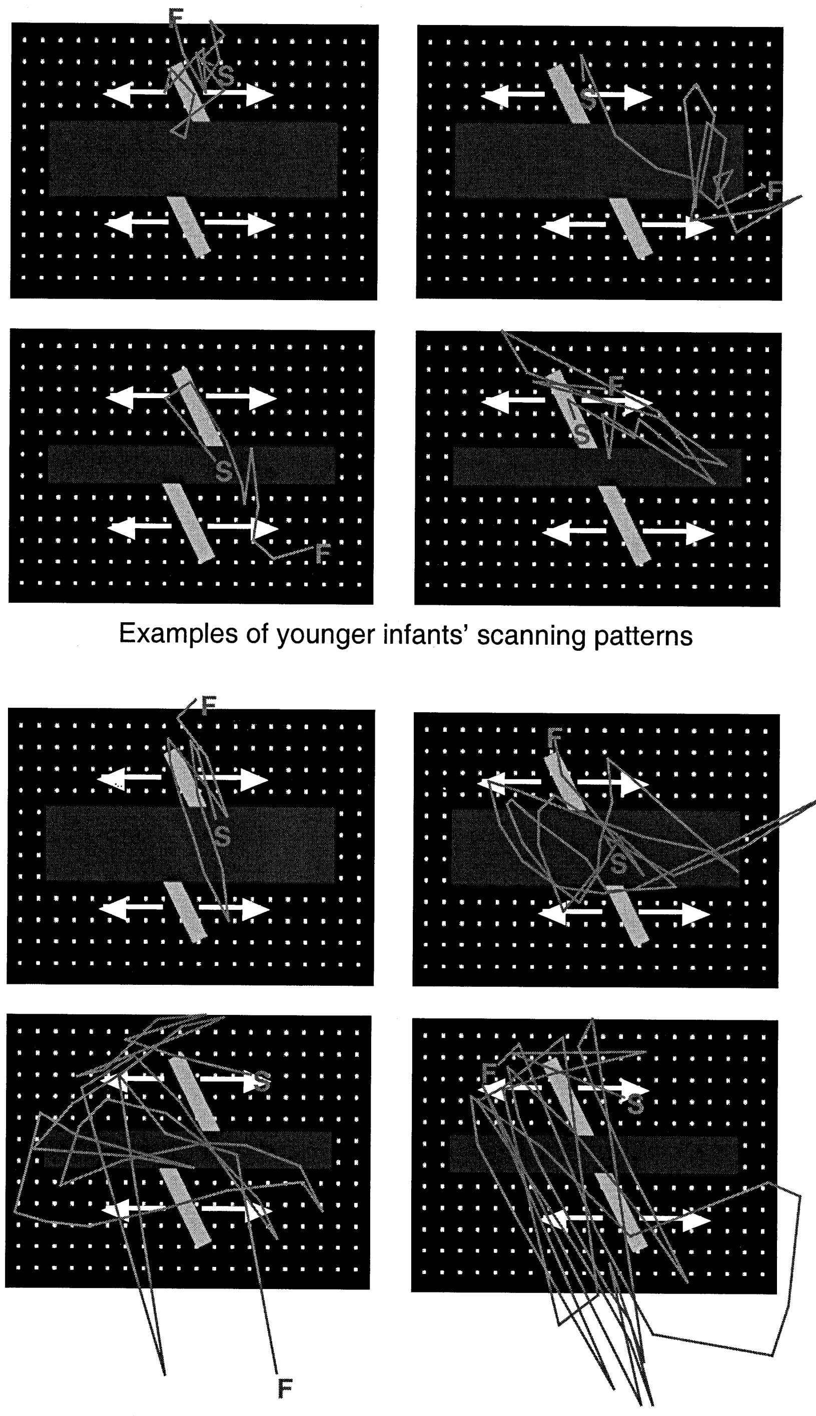

Fig. 2. Displays used in the present experiments, and examples of superimposed scan paths from the two age groups we observed. S = start of scan path; F = finish of scan path.

(1.3°) to the left. The attention-getter display consisted of a target-patterned ball, presented against the same dot background, that expanded and contracted rhythmically (each cycle lasting 2 s) in time with a gentle beep. At its maximum size, the ball measured 10.1 cm (4.8°) in diameter; at its smallest, it measured 2.2 cm (1.0°).

An Applied Science Laboratories Model 504 corneal reflection eye tracking system was used to collect looking time data. A remote pupil camera with a pan/tilt base was placed on the table below the stimulus monitor. The stimulus viewed by the infant was imported directly into the eye tracker from the Macintosh for purposes of off-line data coding (see Results section). Data were saved on the hard drive of the PC as X-Y coordinates of the POG, recorded at 60 Hz on a 260 $\times$ 240 grid of points on the stimulus. The eye tracker also fed a signal into a videotape recorder in the form of crosshairs superimposed on the stimulus.

1.1.3. Procedure

Infants were seated in a parent's lap 120 cm from the stimulus monitor. Two experimenters worked in concert to collect data. The "observer" watched the infant, and held a remote control that directed the pupil camera, through a peephole in one of two partitions extending out from either side of the stimulus monitor. The "video experimenter" sat behind the stimulus monitor and watched an image of the infant's pupil on a 25 cm achromatic monitor, and the POG and stimulus on the VTR monitor. Both the observer and the video experimenter were out of sight of the infant (see Fig. 3).

The room lights were first turned off and the infant shown a Mickey Mouse cartoon to engage his or her interest, as the observer directed the pupil camera toward the infant's eye with the remote control. After the eye was in view, the video experimenter changed from this "manual" mode of camera control to an automatic mode, during which the camera remained directed at the pupil despite small displacements of the infant's head (via an algorithm built into the eye tracker). (Occasionally during the experiment, the infant moved his or her head more quickly than the camera could follow, such that the pupil was lost from view. At this point the video experimenter changed from the automatic mode back to manual, the observer again located the pupil in the camera, and automatic control was resumed.) Following acquisition of the pupil image, and as the infant watched the cartoon, adjustments were made on the eye tracker to maximize robustness of the POG. This varied somewhat from infant to infant with respect to reflectance of infrared and visible illumination (corneal and pupil reflection, respectively). The infant was then shown the four rod-and-box displays, ordered according to a balanced Latin-square design. Between displays, the attention-getter was presented.

Trial length varied according to the video experimenter's judgment of the infant's interest level. The video experimenter attempted to obtain consistent tracking of as many displays as possible (up to a maximum of 8), for as long as possible, which was accomplished by keeping trials short and switching stimuli frequently. The data collection session usually lasted about 4 min.

1.1.4. Calibration

The eye tracker was calibrated on the second author's left eye with a 9-point calibration routine (i.e., the POG for 9 known points was entered). Individual infants were not calibrated, but accuracy of POG was checked by presenting the attention-getter at 5 points across the

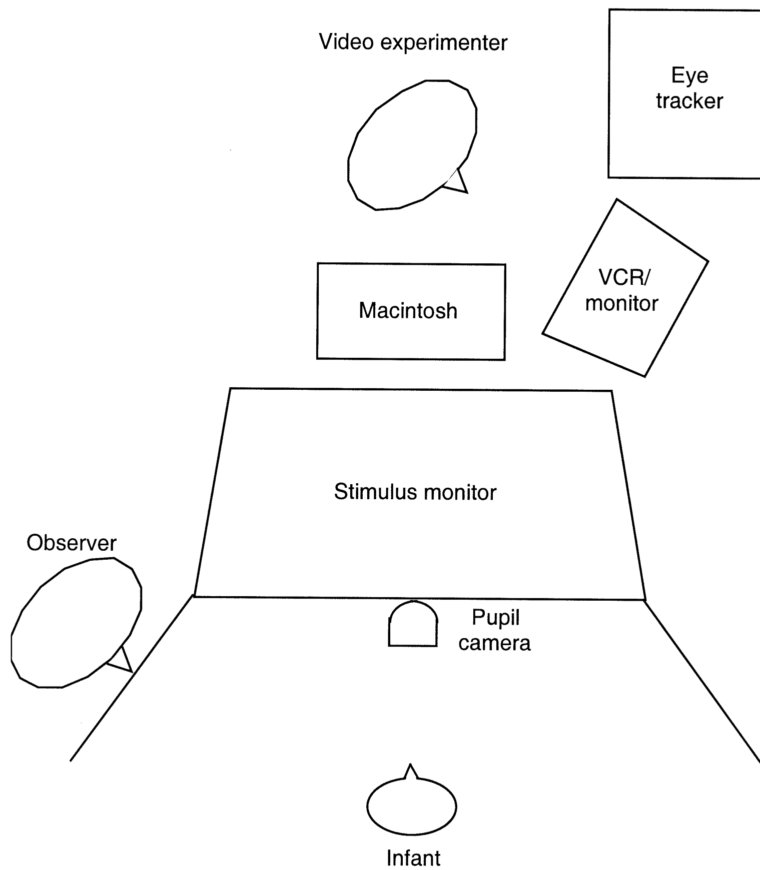

Fig. 3. Schematic overhead view of the experimental setup. The video experimenter controlled stimulus presentation and data collection, and the observer helped ensure that the pupil camera was directed at the infant.

monitor at the end of the data collection session. If an infant's POG did not come within 2° of the center of this stimulus, his or her data were discarded ($n = 4$). Along with the limitations inherent in the eye tracker itself (±0.5°, as determined by the manufacturer), therefore, we estimate that all infants' points of gaze were accurate within 2.5–3°.

1.2. Results

To explore whether there would be age differences in scanning regions of the display that we expected would be informative with respect to perception of object unity, we defined five *areas of interest,* or AOIs: (1) the rectangular area above the box in which the top rod part moved back and forth, which we termed *top rod,* (2) the *box* (occluder), (3) the rectangular area below the box in which the bottom rod part moved, which we termed *bottom rod,* (4) the *top half* of the display, and (5) the *bottom half* of the display. The AOIs were each defined in terms of X-Y coordinates on the stimulus. Two measures were computed: *dwell times,* defined as the time during which the X-Y coordinates of the POG remained within a single

AOI, and *fixations*, defined as individual segments in the data stream during which the X-Y coordinates of the POG remained within 0.5° for at least 100 ms. Dwell time and fixation data were computed by the "Eyenal" software included in the eye tracker system.

Infants were divided into two age groups for purposes of analyses, a younger group (n = 6; M age = 69.8 days, SD = 8.1), and an older group (n = 8; M age = 98.5 days, SD = 14.5). Initial analyses revealed no significant age differences in mean time of display presentation, $t(12) = 1.70$, *ns* (M = 26.2 s, SD = 9.0 for younger infants; M = 18.8 s, SD = 7.2, for older infants), total number of fixations, $t(12) = -1.09$, *ns* (M = 98.3, SD = 40.1 for younger infants; M = 125.9, SD = 50.8, for older infants), or total dwell time, $t(12) = 0.72$, *ns* (M = 64.7 s, SD = 30.5 for younger infants; M = 52.5 s, SD = 32.1, for older infants). As seen in the examples shown in Fig. 2, however, there were distinct differences in the manner in which younger and older infants scanned the displays, a conclusion confirmed by analyses of dwell times and fixations.

1.2.1. Dwell time data

Prior to analysis, dwell times were equated for differences in display duration by converting them to proportions, relative to time of each display presentation. A 2 (age) × 3 (AOI: box, top rod, or bottom rod) × 2 (box width: wide vs. narrow) × 2 (edge alignment: misaligned vs. aligned) mixed ANOVA, with repeated measures on the second, third, and fourth factors, revealed a significant main effect of AOI, $F(2, 24) = 8.10$, $p < .01$, which was qualified by a significant box width × edge alignment interaction, $F(1, 12) = 8.48$, $p < .05$, an AOI × box width interaction, $F(2, 24) = 16.07$, $p < .001$, and an AOI × box width × edge alignment interaction, $F(2, 26) = 13.32$, $p < .001$. As seen in Fig. 4A (left panel), these effects were due to greater dwell times in the box region when the edges were aligned vs. when edges were misaligned, but only when the occluder was wide, as revealed by simple effects tests, $F(1, 12) = 15.43$, $p < .01$; no other comparisons of dwell times in each AOI as a function of box width and edge alignment reached significance, all Fs < 2.9, *ns* (the reasons for this pattern of looking are explored in more detail subsequently, in the section on *Vertical scans*).

There was also a significant age × AOI interaction, $F(2, 24) = 3.81$, $p < .05$. As seen in Fig. 4A (right panel), younger infants' dwell times in the top rod region were greater than in box region, $F(1, 12) = 6.29$, $p < .05$, and dwell times in the box region were greater than in the bottom rod region, $F(1, 12) = 4.88$, $p < .05$. In contrast, all comparisons between dwell times in each AOI fell short of significance for the older infants, all Fs < 1.9, *ns*.

1.2.2. Fixation data

Like dwell time data, fixation data were converted to proportions to equate for differences across trials in display time. Fixations/s were analyzed to investigate age differences in scanning across the three AOIs, as a function of occluder width and edge alignment, with an age × AOI × box width × edge alignment mixed ANOVA. This analysis yielded a significant age difference, $F(1, 12) = 5.70$, $p < .05$: Older infants tended to exhibit more fixations/s (M = 0.40, SD = 0.15) than did younger infants (M = 0.24, SD = 0.08). There was also a significant effect of AOI, $F(2, 24) = 4.41$, $p < .05$, which was qualified by a significant box width × AOI interaction, $F(2, 24) = 10.79$, $p < .001$, and a significant edge

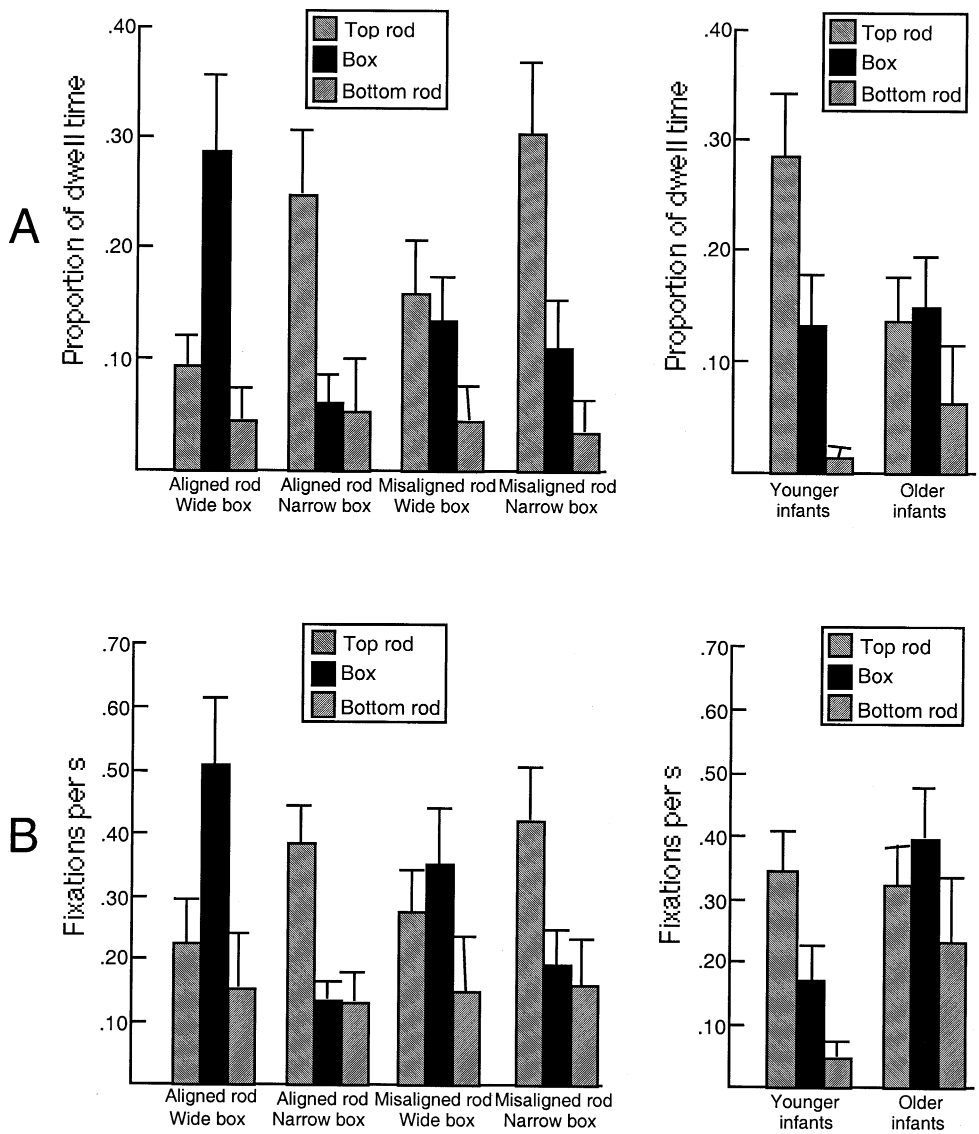

Fig. 4. Data from Experiment 1. Both dwell times (A, left panel) and fixations per s (B, left panel) revealed a scanning strategy geared toward determining the unity of the two rod parts. The larger proportion of dwell times and fixations in the box AOI in the aligned rod, wide box display reflects greater vertical scanning between the top and bottom halves of the display. There was also a high rate of vertical scanning in the misaligned rod, wide box and misaligned rod, narrow box displays, but not the aligned rod, narrow box display. The right panels show age differences in dwell times (A) and fixations (B) in scanning AOIs, and reveal that older infants engaged in more fixations per s, and that dwell times and fixations per s were more evenly distributed across AOIs, relative to younger infants.

alignment × box width × AOI interaction, $F(2, 24) = 5.14$, $p < .05$. These effects paralleled those obtained in the analysis of dwell times (see Fig. 4B, left panel): more fixations/s in the wide vs. narrow box AOI when the edges were aligned, $F(1, 12) = 5.46$, $p < .05$; no other comparisons of fixations/s in each AOI as a function of box width and edge alignment reached significance, all *F*s < 3.5, *ns* (again, the reasons for this pattern are examined in more detail in the *Vertical scans* section).

There was also a marginally significant age $\times$ AOI interaction, $F(2, 24) = 2.90$, $p = .07$. (Because age differences in scanning are a central focus of this article, we followed up on this finding with simple effects tests even though the interaction failed to reach statistical significance.) Both younger and older infants fixated the box more when it was wide than when it was narrow, $F(1, 12) = 18.18$, $p < .01$, and this difference did not vary reliably as a function of age, $F(1, 12) = 2.17$, *ns.* Age differences were revealed, however, in the extent to which the infants fixated the top and bottom rods (Fig. 4B, right panel). For older infants, there was no reliable difference in fixations toward the top and bottom rods, $F(1, 12) = 0.19$, *ns.* Fixations in these two AOIs, however, varied as a function of box width, $F(1, 12) = 6.34$, $p < .05$. In the wide box displays, there were more fixations toward the bottom rod, a nonsignificant difference, $F(1, 12) = 0.75$, *ns,* and in the narrow box displays, there were more fixations toward the top rod, but this difference was only marginally significant, $F(1, 12) = 4.04$, $p = .07$. Younger infants, in contrast, fixated the top rod more than the bottom rod, $F(1, 12) = 6.58$, $p < .05$, and this difference did not vary reliably as a function of box width, $F(1, 12) = 0.07$, *ns.*

1.2.3. Vertical scans

The next analyses explored the extent to which infants scanned between the top and bottom portions of the displays. We reasoned that one way in which age-related improvements in perception of object unity might be revealed is in increased vertical scanning, to facilitate detection of edge alignment and common motion of the two visible rod parts. *Vertical scans* were defined as changes in fixation/s from one half of the display to the other (top to bottom or vice versa, between AOIs incorporating the entire top or bottom half of the display). These measures were also examined as a function of display type. Vertical scans were investigated with an age $\times$ box width $\times$ edge alignment mixed ANOVA that yielded a significant effect of age, $F(1, 12) = 8.78$, $p < .05$, due to more vertical scans by older infants ($M = 0.25$, $SD = 0.12$) relative to younger infants ($M = 0.09$, $SD = 0.07$). There was also a significant box width $\times$ edge alignment interaction, $F(1, 12) = 5.06$, $p < .05$, and no other significant effects. Simple effects tests revealed no significant difference in vertical scans in misaligned rod displays as a function of occluder height, $F(1, 12) = 0.04$, *ns* (wide occluder $M = 0.20$, $SD = 0.18$; narrow occluder $M = 0.20$, $SD = 0.19$). When the rod was aligned, in contrast, there were more vertical scans when the box was wide ($M = 0.22$, $SD = 0.15$) than when it was narrow ($M = 0.13$, $SD = 0.12$), although the difference was only marginally significant, $F(1, 12) = 4.28$, $p = .06$.

1.3. Discussion

The results from dwell time and fixation data suggest important age differences in scanning strategies when infants view rod-and-box displays. Scans within the three AOIs were relatively proportional for older infants, whereas younger infants tended to concentrate scans in the top portions of the stimulus (the top rod and the box). Older infants also scanned between the top and bottom halves of the stimulus more frequently than did younger infants, a strategy that would be expected to facilitate extraction of important visual information that supports perception of object unity.

The finding that younger infants did not often fixate the bottom rod part appears to be inconsistent with reports that 2-month-olds perceive object unity under some circumstances (Johnson & Aslin, 1995; Johnson et al., 2000c). It seems unlikely that this effect would obtain unless infants inspected the entire stimulus. These discrepant results might be due to the limited amount of time during which the display was available for inspection in the present study, necessitated by the need to keep the infants' interest level high throughout the procedure. Does this mean that in the present study, younger infants will look more at the bottom rod part if provided additional exposure to the stimulus? This question was explored by computing correlations between display time and number of fixations (not fixations/s) in each of the AOIs (box, top rod, bottom rod). For the younger infants, the only correlation that approached significance was that between display time and fixations in the vicinity of the bottom rod, $r = 0.79$, $p = .06$. For the older infants, none of the correlations reached significance. Given extra time, then, the younger infants engaged in somewhat more extensive scanning, a pattern characteristic of the older infants. Although this finding must be considered tentative, as the correlation was only marginally significant statistically, it is consistent with recent reports that young infants may follow a local-to-global processing strategy, and older infants are more adept at processing global information (e.g., Colombo et al., 1995; Freeseman et al., 1993; Ghim & Eimas, 1988; Johnson et al., 2000a).

Another important consideration is the interaction of box width and edge alignment on measures of dwell times, fixations, and vertical scans: All these measures were greater when the box was wide and the edges were aligned. These results are consistent with the interpretation that edge orientation is central to perception of object unity. Eye movement patterns, then, would be expected to reveal a scanning strategy dedicated to obtaining information concerning whether or not two edges across an occluder are aligned. When the rod edges were aligned, the infants engaged in more vertical scanning in the wide-occluder display, relative to the narrow-occluder display. This suggests that the wider spatial gap challenged perception of the edge alignment, and more scans were needed to detect the edge relations. Many of these scans crossed the midline (between the top and bottom halves of the display) and fell in the box AOI, because it was centrally located and intersected both the top and bottom rod parts. Vertical scans were comparable in frequency to the wide box, aligned edge display when infants were presented with the two misaligned rod displays, suggesting active comparison of the edge relations in an attempt to determine alignment. In contrast, when the infants viewed the display with aligned edges across the narrow occluder, determination of alignment was more readily accomplished, necessitating fewer scans. These conclusions must be considered speculative as we have no independent evidence (e.g., from habituation data) concerning percepts of unity or disjoint objects among our sample of infants (see General Discussion). Nevertheless, the infants' scanning patterns conformed to the hypothesis that the task of perceiving object unity is based on a prior determination of edge relations, a central tenet of the information-processing view.

2. Experiment 2

The second experiment explored scanning patterns in a small sample of infants observed longitudinally, across an age range between 2 and 5 months. The purpose of Experiment 2 was to explore individual differences in scanning patterns, with the goal of revealing both commonalities across infants (to confirm the results of Experiment 1), and continuity over time in individual infants' responses. That is, we asked whether individual infants would show an increase with age in the type of extensive scanning observed in the older infants in Experiment 1, as well as distinct "styles" of scanning patterns that remained stable over the first few months.

2.1. Method

2.1.1. Participants

Five full-term infants (1 female) were observed for five to eight data collection sessions, spaced at least one week apart. An additional five infants were observed but not included in the sample because they completed fewer than four sets of data (either for reasons described in Experiment 1, or because they were not brought to the lab for scheduled appointments). Across the sample observed for the present experiment, five sessions failed to result in usable data, due to an inability to obtain a reliable POG (1) or excessive movement on the part of the infant (4).

2.1.2. Apparatus, stimuli, procedure, and calibration

All other methodological aspects of Experiment 2 were identical to those of Experiment 1.

2.2. Results

Data from each of the five infants in Experiment 2 are considered separately with a series of analyses targeted at specific questions arising from Experiment 1. First, do data from individual infants provide evidence of age-related changes in dwell times and fixations in the bottom rod AOI? Second, do these data reflect age-related improvements in vertical scanning? Third, are these vertical scans more frequent in the aligned rod, wide box condition? Fourth, is there evidence of other, more idiosyncratic scanning strategies on the part of individual infants? Each infants' data were first subjected to box width $\times$ edge alignment $\times$ AOI mixed ANOVAs (collapsed across age) on dwell times, fixations/s, and vertical scans/s, along with a series of correlations among age and the dependent measures.

Figs. 5–9 plot dwell times, fixations/s, and vertical scans/s as a function of AOI (panels a-c, respectively), and dwell time (panel d) and fixation data (panel e) as a function of AOI and age for each of the five participants. Inspection of Figs. 5–9 reveals marked individual differences in scanning strategies across the five infants. However, as discussed subsequently, these infants' data also provide confirmation of the conclusions reached from Experiment 1.

Infant SH was observed six times from 64 to 99 days (Fig. 5). His data exhibit several of the patterns observed in Experiment 1. First, dwell times varied with box width and edge

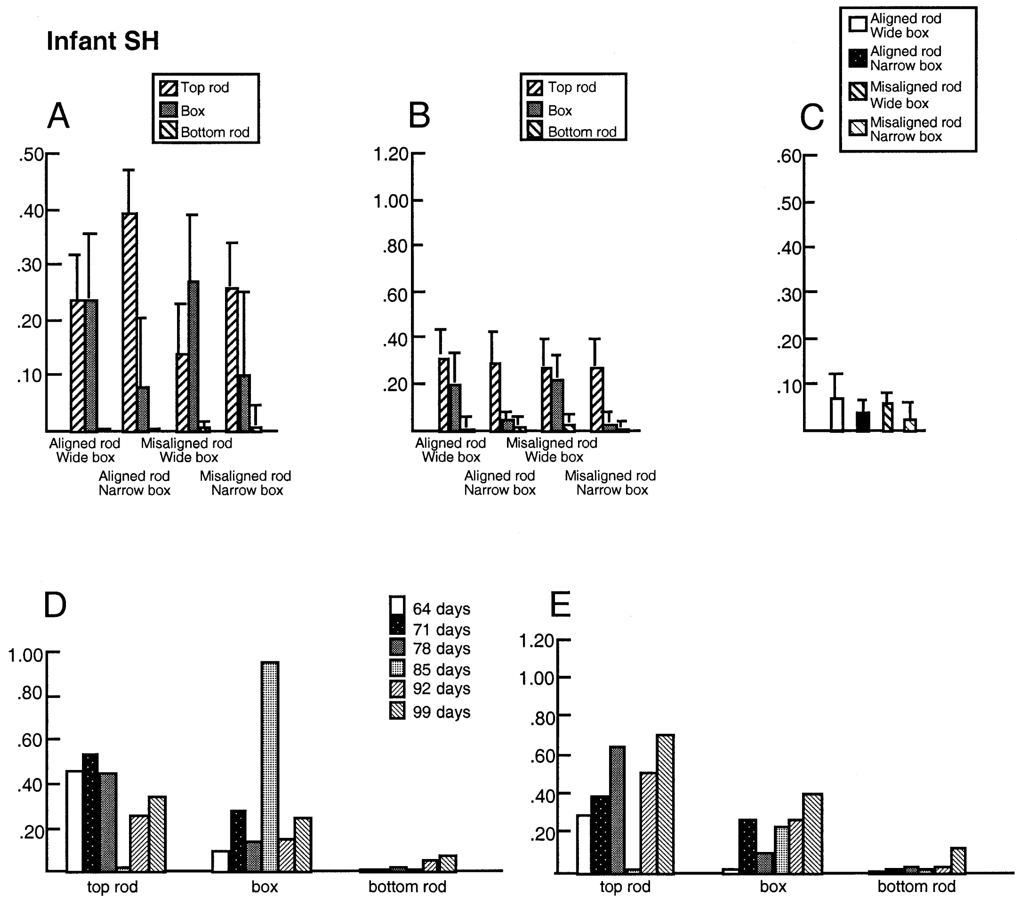

Fig. 5. Data from infant SH, Experiment 2. (A) Dwell times as a function of display. (B) Fixations per s as a function of display. (C) Vertical scans per s as a function of display. (D) Dwell times as a function of age and AOI. (E) Fixations per s as a function of age and AOI.

alignment, as reflected in a significant main effect of AOI, $F(2, 10) = 20.81$, $p < .001$, a significant edge alignment × AOI interaction, $F(2, 10) = 12.91$, $p < .01$, and a significant box width × edge alignment × AOI interaction, $F(2, 10) = 15.26$, $p < .001$ (Fig. 5A). This pattern was repeated in fixation data, evinced by a significant main effect of AOI, $F(2, 10) = 96.35$, $p < .001$, a significant edge alignment × AOI interaction, $F(2, 10) = 36.45$, $p < .001$, and a marginally significant box width × edge alignment × AOI interaction, $F(2, 10) = 3.56$, $p = .07$ (Fig. 5B).

There were more vertical scans in the wide box, aligned edge display than the other displays, although the interaction did not reach significance, $F(1, 5) = 4.87$, $p = .08$ (Fig. 5C). Finally, extensive scanning of the display increased with age, as reflected in a marginally significant correlation between age and fixations/s in the bottom rod AOI, $r = 0.74$, $p < .10$ (Figs. 5D, E). SH, then, scanned more in the top portions of the display, especially in the earlier observations, a pattern characteristic of the data from Experiment 1. Dwell times and

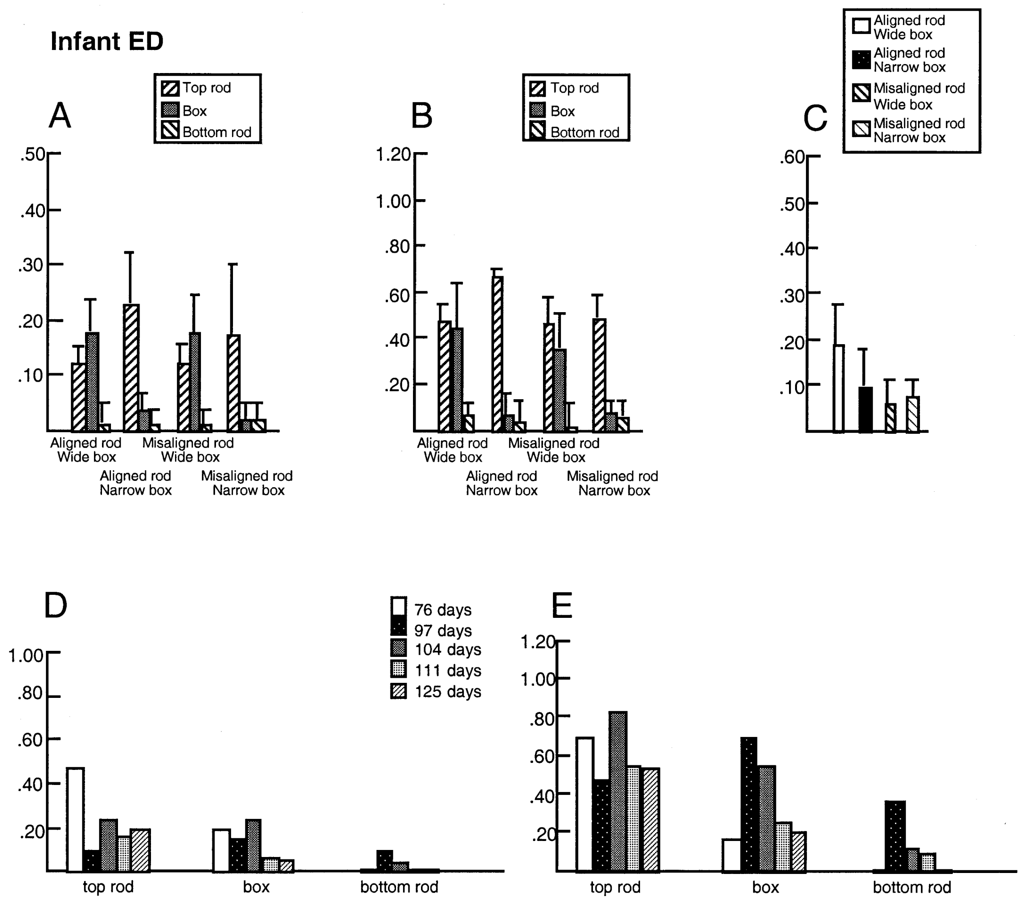

Fig. 6. Data from infant ED, Experiment 2. (A) Dwell times as a function of display. (B) Fixations per s as a function of display. (C) Vertical scans per s as a function of display. (D) Dwell times as a function of age and AOI. (E) Fixations per s as a function of age and AOI.

fixations were concentrated primarily on the top rod AOI when the box was narrow, and split more evenly between the top rod and box when the box was wide. (An exception to this pattern was a high proportion of dwell times in the box AOI at 85 days. There were few fixations at the same time, suggesting that SH was not as actively engaged in the task that day as in the other sessions.) There was also a nonsignificant trend toward more vertical scans in the wide box, aligned edges display.

Infant ED was observed five times from 76 to 125 days (Fig. 6). Like SH, her data reveal tendencies to scan in the top portions of the display, and varied with both box width and edge alignment. Interestingly, however, effects of box width were evident only in the dwell time analysis, and effects of edge alignment were evident only in the fixation analysis. The analysis of dwell time yielded a significant main effect of AOI, $F(2, 8) = 5.66$, $p < .05$, and a significant box width $\times$ AOI interaction, $F(2, 8) = 5.88$, $p < .05$ (Fig. 6A). The analysis of fixation data yielded significant main effects of edge alignment, $F(1, 4) = 11.10$, $p < .05$,

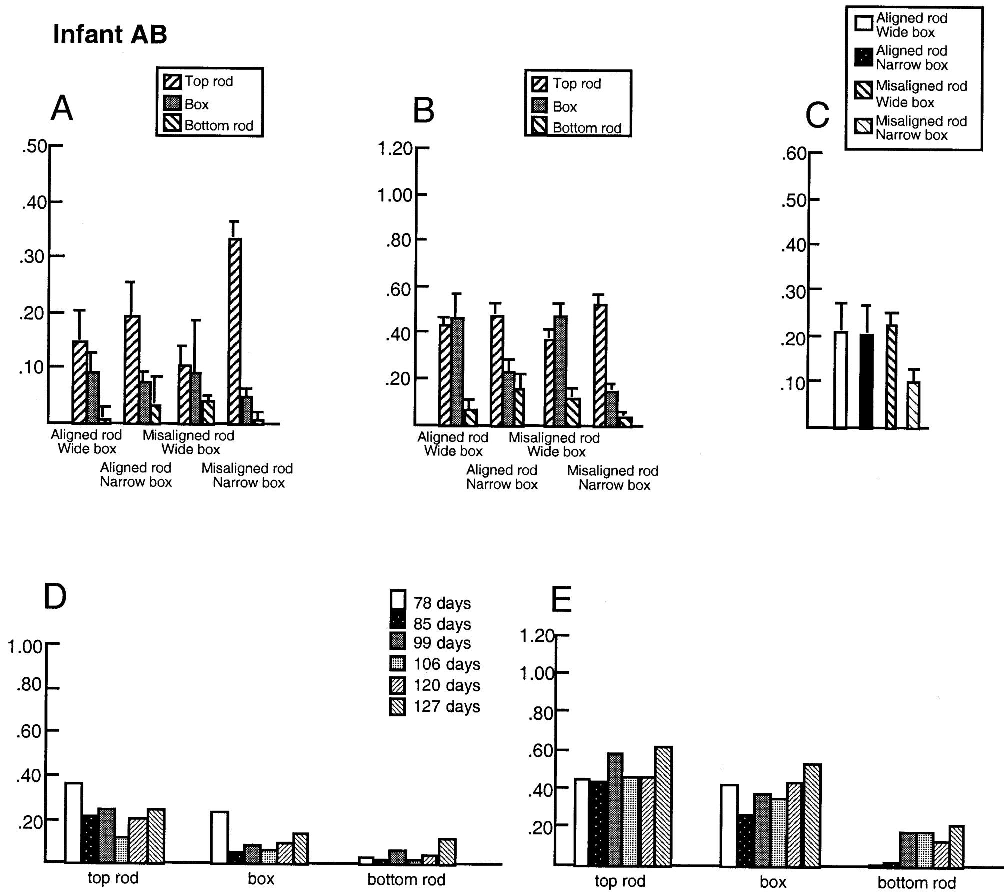

Fig. 7. Data from infant AB, Experiment 2. (A) Dwell times as a function of display. (B) Fixations per s as a function of display. (C) Vertical scans per s as a function of display. (D) Dwell times as a function of age and AOI. (E) Fixations per s as a function of age and AOI.

and AOI, $F(2, 8) = 12.38$, $p < .01$, and a significant box width × AOI interaction, $F(2, 8) = 13.61$, $p < .01$ (Fig. 6B). Vertical scans were more frequent in aligned-edge displays, $F(1, 4) = 13.36$, $p < .05$, but there were no significant differences as a function of box width, nor a box width × edge alignment interaction (Fig. 6C). Finally, there were no significant increases with age in any scanning measures (Fig. 6D, E). ED, then, demonstrated a scanning pattern similar to that of SH: Dwell times and fixations were centered largely on the top rod AOI when the box was narrow, and distributed more consistently between the top rod and box when the box was wide. Unlike SH and the sample in Experiment 1, however, there was no evidence of age differences in scanning patterns in ED's data.

Infant AB was observed six times from 78 to 127 days (Fig. 7). Like SH, ED, and the infants in Experiment 1, AB's dwell times and fixations/s varied as a function of both edge alignment and box width, and like ED, these variables altered dwell time and fixation responses in different ways. The analysis of dwell time revealed significant interactions between edge alignment and AOI, $F(2, 10) = 4.45$, $p < .05$, and between edge alignment and box width, $F(2, 10) = 16.67$, $p < .001$ (Fig. 7A). The analysis of fixation data revealed significant main effects of box width, $F(1, 5) = 7.29$, $p < .05$ and AOI, $F(2, 10) = 10.68$, $p < .01$, along with a significant box width × AOI interaction, $F(2, 10) = 5.00$, $p < .05$ (Fig. 7B). There was also a marginally significant difference in vertical scans as a function of box width, with fewer vertical scans in narrow box displays, $F(1, 5) = 6.18$, $p = .06$ (Fig. 7C). Finally, there were increases with age in looking to the bottom rod region, as reflected in correlations between age and dwell time in the bottom rod AOI, $r = 0.75$, $p < .10$, fixations/s to the bottom rod AOI, $r = 0.88$, $p < .05$, and vertical scans, $r = 0.73$, $p < .10$ (Figs. 7D, E). These patterns are comparable, by and large, to those of SH and ED: more looking in the top portion of the displays, and a greater proportion of fixations in the top rod AOI relative to the box AOI in the narrow-box displays. Like SH, there was more extensive scanning with age across the display. In contrast to the other infants, however, vertical scans showed a trend toward less active scanning in the narrow box, misaligned rod display.

Infant KR was observed eight times from 78 to 163 days (Fig. 8). Like the other infants, KR's dwell times and fixations/s varied with edge alignment and box width, but in a unique way. The analysis of dwell times yielded significant interactions between edge alignment and box width, $F(1, 7) = 8.41$, $p < .05$, and between box width and AOI, $F(2, 14) = 3.78$, $p < .05$ (Fig. 8A). The analysis of fixation data yielded significant interactions between edge alignment and AOI, $F(2, 14) = 3.93$, $p < .05$, and between edge alignment, box width, and AOI, $F(2, 14) = 12.79$, $p < .001$ (Fig. 8B). There was also a significant main effect of edge alignment in the analysis of vertical scans, $F(1, 7) = 9.31$, $p < .05$ (Fig. 8C). Finally, correlations between age and the dependent variables revealed no significant outcomes (Figs. 8D, E). Several features of results provide evidence of a distinctive scanning strategy. Vertical scans were more numerous in the misaligned rod displays relative to the aligned rod displays. As seen in Figs. 8A, B, dwell times and fixations/s were high in the misaligned rod, wide box display, a pattern that indicates that KR's scans may have been directed toward determining the edge relations of the misaligned rod parts. Interestingly, there is no consistent evidence of age changes in any measures of scanning, suggesting that KR's scanning strategy was available to him early on. Especially surprising is the relative frequency of fixations in the bottom rod AOI during all sessions except the first (Fig. 8B, E).

Infant JW was observed five times from 98 to 147 days (Fig. 9). Like all the infants we observed, JW's scanning patterns varied as a function of edge alignment and box width. Like KR, however, JW exhibited a unique scanning style. The dwell time analysis revealed significant main effects of edge alignment, $F(1, 4) = 15.63$, $p < .05$, and of box width, $F(1, 4) = 15.85$, $p < .05$, as well as a significant box width × AOI interaction, $F(2, 8) = 6.03$, $p < .05$ (Fig. 9A). The fixation analysis revealed a significant main effect of AOI, $F(2, 8) = 4.54$, $p < .05$, and a significant box width × AOI interaction, $F(2, 8) = 13.40$, $p < .01$ (Fig. 9B). The analysis of vertical scans revealed no significant effects (Fig. 9C). Analyses exploring age differences revealed significant correlations between age and dwell time in the top rod AOI, $r = 0.97$, $p < .01$, and between age and fixations/s in the top rod AOI, $r = 0.97$, $p < .01$ (Figs. 9D, E). The extensive number of vertical scans (Fig. 9C), along with the numerous fixations across displays (Figs. 9B, E), relative to the other infants, provide evidence of especially active scanning in all displays. There is some evidence of more extensive

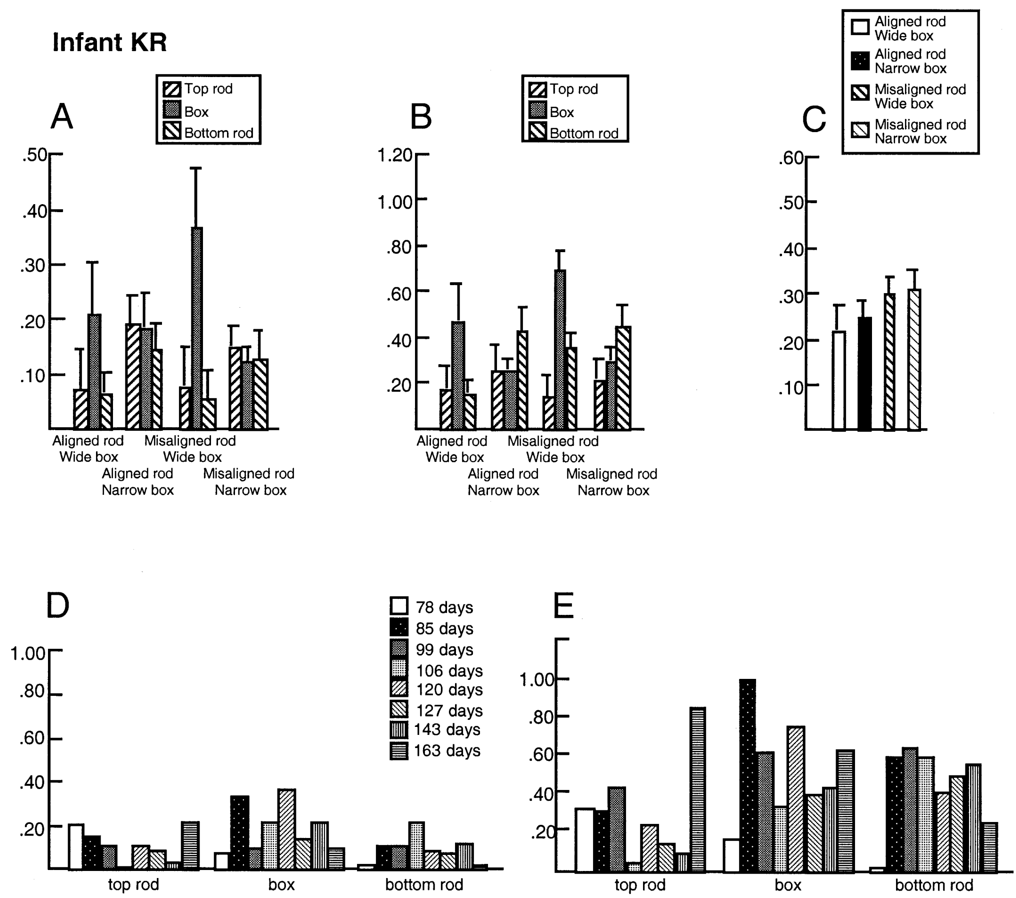

Fig. 8. Data from infant KR, Experiment 2. (A) Dwell times as a function of display. (B) Fixations per s as a function of display. (C) Vertical scans per s as a function of display. (D) Dwell times as a function of age and AOI. (E) Fixations per s as a function of age and AOI.

scanning with age, but overall, JW's characteristic frequent scans were seen during all sessions. Like KR, but unlike the other infants in Experiment 2, JW made frequent fixations in the bottom rod AOI.

2.3. Discussion

The findings of Experiment 2 provide evidence of both similarities and differences in scanning strategies across individual infants. Notably, scanning patterns for the five infants appear to have been adapted for purposes of effective acquisition of relevant visual information concerning edge connectedness in each display, similar to the results obtained in Experiment 1. All the infants, for example, modified the proportion of dwell times and fixations across the AOIs as a function of display type. Support for hypothesized age-related improvements in scanning in the bottom rod AOI was obtained in only two infants, and in only one infant for improvements in vertical scanning. This is likely a result of the limited

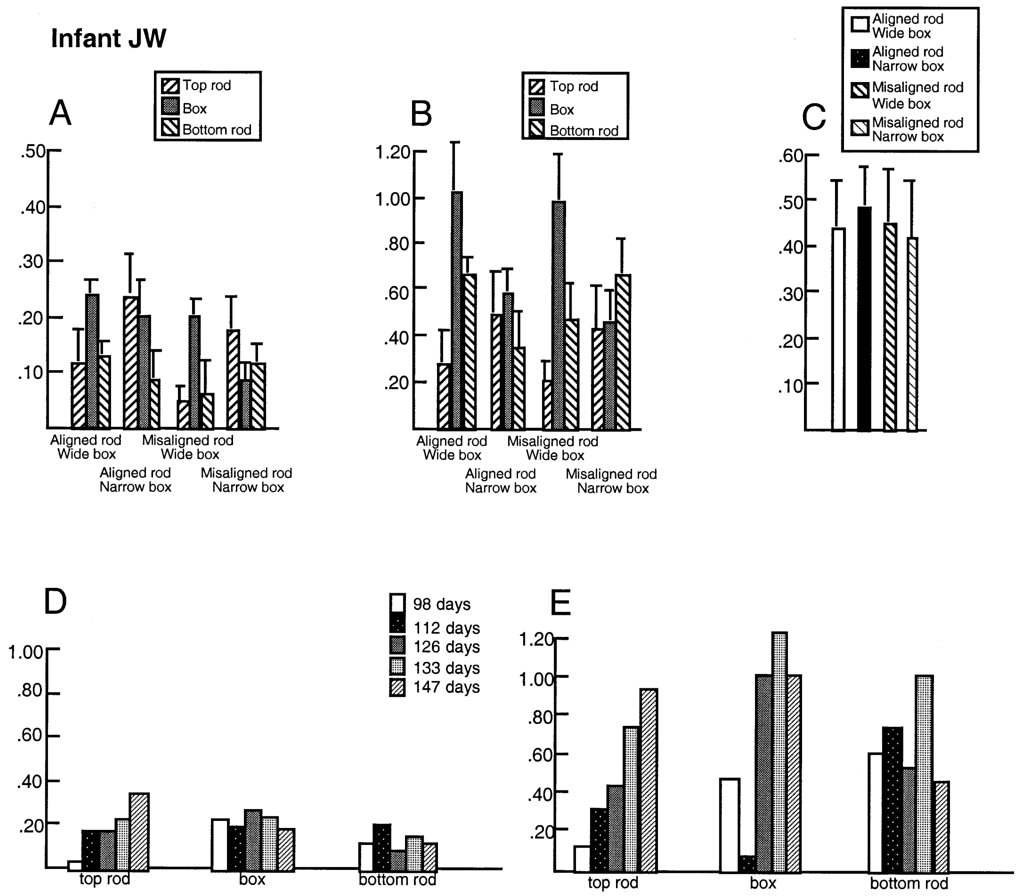

Fig. 9. Data from infant JW, Experiment 2. (A) Dwell times as a function of display. (B) Fixations per s as a function of display. (C) Vertical scans per s as a function of display. (D) Dwell times as a function of age and AOI. (E) Fixations per s as a function of age and AOI.

age range across which the infants were observed. Nevertheless, the two infants who exhibited greater scanning in the bottom rod AOI (SH and AB), and the one infant who engaged in more vertical scans with age (AB), were in the same age range as the younger infants in Experiment 1, who also showed these effects. It is also possible that the repeated exposure to the same stimuli across sessions contributed to differences in performance across Experiments 1 and 2.

The most important outcome of Experiment 2, however, was that distinctive processing styles were revealed. Consistent with studies of motor development (e.g., Thelen et al., 1993), the results of the present studies suggest that there are multiple routes to achieving a goal during the development of a new skill: When the objective is to obtain visual information via scanning patterns, our data suggest that individual infants have strikingly different means to this end.

3. General discussion

Eye movements were recorded as young infants viewed partly occluded object displays, to address questions of underlying mechanisms of the development of object perception. In Experiment 1, evidence was obtained in a cross-sectional sample for differences in infants' scanning as a function of age and stimulus characteristics. Older infants tended to engage in more extensive scanning, as revealed by both more frequent scanning in the lower part of the display, and more frequent vertical scans. Both these scanning patterns would be expected to have the effect of imparting more information concerning the alignment and common motion of the partly occluded rod edges. The infants also exhibited more extensive scans when determination of edge alignment might be challenged, either by misalignment or by a relatively wide occluder. Evidence was also obtained, in Experiment 2, for individual differences in scanning strategies with a longitudinal sample. Three infants' scanning patterns conformed with some of the principal findings of Experiment 1, but two did not, and each infant's scanning was unique in its own way.

These data bear important implications for theories of perceptual development. As noted in the Introduction, two current views provide contrasting predictions with respect to perceptual organization in infants and the role of visual information in development of perception of object unity. According to an account stressing "core knowledge," young infants' object percepts are guided by a limited set of reasoning principles (Spelke & Van de Walle, 1993). One of these is the *contact* principle: two surfaces undergoing a common motion belong to the same object. Static information, in contrast, has no inputs to initial percepts of unity. On this view, then, motion information alone dictates perception of object unity, and information such as edge and surface orientation is excluded from the process until later in the first year after birth (cf. Kellman & Banks, 1998). According to an opposing account stressing information processing skills, the development of object perception derives from improvements in the detection and utilization of available visual information, accompanied by cortical maturation and visual experience, rather than core principles (Johnson, 2000, in press). This view is consistent with evidence that static information such as edge alignment and global form has a strong influence on 4-month-olds' perception of object unity. Edge alignment, in particular, appears to be an important cue for unity, for both infants (Johnson & Aslin, 1996; Johnson et al., 2000a, b) and adults (Jusczyk et al., 1999). When two rod edges are misaligned, for example, unity perception is attenuated, even when the two surfaces undergo common motion. Edge alignment without motion, nevertheless, is insufficient to specify unity to young infants under many circumstances (Jusczyk et al., 1999; Kellman & Spelke, 1983; but see Needham, 1998). Johnson (1997, 2000; Johnson & Aslin, 1996) proposed a *threshold model* to account for these and other results, stipulating that perception of object unity depends on both the visual information available to the observer (to specify the depth relations among display elements and edge interpolation behind the occluder), as well as the readiness of the observer to attend to that information. That is, a certain threshold of information must be exceeded for veridical percepts to obtain, and this threshold is higher among infants than adults.

The bulk of extant research would appear to be more consistent with the information processing view, rather than the core principles view: Static information, such as edge orientation, has clear inputs into young infants' object percepts. A newer version of the core principles view, however, acknowledges the role of edge alignment and other static information in unity perception, but challenges the thesis that this role is direct (Jusczyk et al., 1999; Smith et al., 2000). Instead, edge alignment may have an *indirect* influence on perception of object unity, by modulating infants' sensitivity to motion information. That is, it might be more difficult to detect the common motion of two edges that are not aligned across and occluder. Without access to motion information, then, perception of object unity is precluded. This conjecture gains plausibility from findings that 4-month-olds do not appear to perceive unity in static displays with aligned rod parts (Jusczyk et al., 1999; Kellman & Spelke, 1983).

The results of the present experiments provide evidence against this more recent version of the core principles account. In Experiment 1, there were no reliable differences overall in scanning as a function of edge alignment, either in terms of dwell times or fixations. Rather, these measures varied as a function of the *interaction* between box width and edge alignment, a result that is readily interpreted in light of data from vertical scans: Vertical scans were frequent across all four stimulus types except the aligned rod, narrow box display, a scanning strategy that would maximize the likelihood of obtaining effective information about the rod parts' connectedness when such a determination might be hindered by misaligned edges or a wide occluder. There were age differences in the extent to which infants scanned both halves of the display, but edge alignment had no bearing on this effect. The infants, therefore, exhibited extensive scanning in both aligned and misaligned edge displays, and it seems likely that motion sensitivity was equivalent across the two stimulus types.

A clear implication of the present results is the utility of eye movement recordings in studies of the development of object perception. Our results provide for speculation concerning basic information processing skills and information pickup, but do not provide more direct evidence concerning what the infants actually experienced during the task. In the present case, this would be whether the infants perceived unified or disjoint objects in the stimuli, or some other percept. One strategy to achieve this next step would be to record eye movements as the infants are tested in an habituation paradigm.

Perhaps the most important implication of our findings is the possibility that the eye movement patterns we observed reveal an *active* process of strategy selection, and that this process undergoes development between 2 and 4 months in support of fundamental object perception skills. Previous reports of the development of visual scanning found marked improvements in the extent to which young infants' eye movements were adapted to stimulus characteristics. For example, Hainline and Lemerise (1982) found that 1- to 3-month-olds' scan patterns were tailored to stimulus size and shape, and Bronson (1990, 1994, 1997) reported gains across 2 to 14 weeks in the extent to which infants scanned between two stimuli, scanned extensively across a large stimulus, and engaged in "brief fixations" (i.e., average fixation duration was reduced), permitting a more thorough inspection of the stimulus per unit of time. These past studies used achromatic, geometric forms as stimuli, in contrast to the more complex moving, colorful depictions of objects in depth employed in the present research. Our data replicated each of these developmental trends, but in an older sample, suggesting that the development of basic mechanisms controlling purposive visual scanning may extend at least into the second half year after birth. This protracted developmental profile may reflect the demands of applying burgeoning information processing skills to object perception tasks, in contrast to scanning within or between simple stimuli.

Our results are consistent with systems views of perceptual and cognitive development in infancy, stressing the interactivity and interdependence of action and cognition. ". . .action of the infant within the environment must be considered the common primitive of cognitive development, and may well be the common control parameter of many early skills. If self-produced movement is critical, then dynamic category formation–the infant's basic organization of the world–must be paced and constrained by the ability to produce and control that movement" (Thelen & Smith, 1994, pp. 194–195). This quote referred in part to the elegant series of studies by Bertenthal, Campos and colleagues (Bertenthal & Campos, 1990; Bertenthal et al., 1994; Campos et al., 1992) in which infants with locomotor experience were found to exhibit wariness of heights when placed on a visual cliff, and superior spatial skills in a search task, relative to age-matched controls. Locomotor experience appears to trigger the emergence of a cascade of ancillary abilities that impact social, emotional, perceptual, cognitive, and further motor development, due to new opportunities offered by locomotion for exploration of the environment. A similar effect may underlie the relation between infants' sitting and reaching effectiveness: As infants gain postural control, and can sit unaided, the upper limbs are freed from the need to maintain balance and can be used more effectively for object manipulation and exploration (Rochat & Goubet, 1995; Rochat et al., 1999; see Bushnell & Boudreau, 1993 for further evidence of the impact of motor development on perceptual and cognitive development). The results of the present research suggest a corresponding process at work in early perceptual development. Self-directed eye movements appear to be critical to acquisition of object knowledge in the young infant, which in turn directs the infant toward more effective means of obtaining information in the form of selection of scanning strategies. The striking individual differences noted in Experiment 2 imply that there is no single developmental path followed by infants toward this goal. Rather, the infant him- or herself must *select* where to look, a process that is initiated at birth by a functional preference for edges and motion, two essential cues to veridical object perception (Slater, 1995; Johnson, 2000).

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