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Competition in Early Exogenous Orienting between 7 and 21 Weeks

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Exogenous (stimulus-driven) orienting between 7 and 21 weeks of age was examined in 2 experiments using a display with multiple potential targets of attention. On each trial a small moving probe was used to draw attention to one side of the display or the other. This moving probe appeared simultaneously with 27 static bars. In the first experiment, sensitivity to the moving target was affected significantly by the spatial distribution of these red and green static bars for 14-week-olds but not for 8-week-olds. Sensitivity to the moving target was lower for 14-week-olds when most of the red bars appeared contralaterally to the moving target. This effect replicated a similar effect observed in J. L. Dannemiller (1998). The lack of a contralateral competition effect in Experiment 1 for the 8-week-olds may have occurred because I used a stronger motion stimulus for the younger infants in an attempt to hold the overall performance constant at the 2 ages. A second experiment using a weaker motion stimulus showed that this contralateral competition effect was observable over the entire age range from 7 to 21 weeks of age. Thus as early as 7 weeks of age, sensitivity for a small moving stimulus can be significantly influenced by the simultaneous presence of competing targets of attention in the visual field. Large increases in overall sensitivity were also found across the age range from 7 to 21 weeks. Results are discussed in terms of the development of putative competition mechanisms involved in exogenous orienting. © 2000 Academic Press

Key Words: orienting; infancy; competition; color; motion; attention.

The infant's visual world is populated with multiple objects and surfaces. Efficient information processing under such circumstances requires visual sampling from different parts of the image. Cycles of fixation and saccade require some mechanism that sequences these fixations and that resolves the competition between different regions in the image to be the next object of regard. As contrast sensitivity and acuity improve over the first 6 months (Fiorentini, Pirchio, &

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Spinelli, 1983; Gwiazda, Bauer, Thorn, & Held, 1997), the need for such a mechanism becomes more crucial because multiple regions in the image presumably become more distinct and smaller image features become more visible. The present work is concerned with changes in the strength of such competitive attentional processes during early infancy.

Competitionlike effects are certainly well known in the literature on the development of selective visual attention (Bushnell, 1979; Hood & Atkinson, 1993). Work on the early development of selective visual attention shows that as infants age, they switch their attention and fixation more quickly from one location in space to another (Bronson, 1994; Johnson & Tucker, 1996). Many of these studies indicate a transition to more adultlike selective attention between 2 and 4 months of age (Atkinson, Hood, Wattam-Bell, & Braddick, 1992). For example, Johnson and Tucker (1996) used a precue that preceded the appearance of an attentional target by various intervals. The results showed that the cue had only weak effects on the orienting of 2-month-olds. In contrast, 4-month-old infants, like adults, showed facilitation to a cued location when a target appeared 200 ms after cue onset and inhibition of responses to the same location when the target appeared 700 ms after the cue onset. Johnson and Tucker (1996) interpreted these results (and others with 6-month-olds) as evidence that infants can shift their attention more quickly as they get older, and that the phenomenon known as “inhibition of return” (IOR) may develop over this age period. IOR refers to the tendency to inhibit attentional shifts to locations that have been recently visited and shows the kind of dependence on cue–target temporal relations in adults found by Johnson and Tucker (1996) with 4-month-olds. These studies indicate that the mechanisms responsible for selecting attentional targets and for switching attention from one spatial location to another show significant development between 2 and 4 months postnatally.

Dannemiller (1998) showed that evidence of competition exists in the initial visual orienting of 3.5-month-olds. In this work a small moving target drew attention to one side of the display. This moving target was embedded in a display with 27 other static bars spatially distributed across the display. When there was an imbalance in the spatial distribution of the red and green bars on the display, evidence of competition emerged. In particular, sensitivity to the moving target decreased significantly when most of the red static bars in the field appeared on the side of the display contralaterally to the moving target. Such an effect is consistent with prior work showing a preference for red over green at approximately 3 months of age (Adams, 1987; Bornstein, 1975). Dannemiller (1998) used a simple signal detection model to capture the major features of this competition. The goal in the present work was to extend this paradigm and model to a wider age range (7 to 21 weeks) to examine the changes in selective attention that have been observed over this age range using other procedures (e.g., Atkinson et al., 1992; Johnson & Tucker, 1996).

These competition effects at 3.5 months of age (Dannemiller, 1998) are similar to the effects predicted for adults by salience computation models (Koch & Ullman, 1985). In such models, the image is first filtered in parallel across the visual field along several dimensions such as color, orientation, movement, and size. Ultimately, these computations result in a master "salience" map—a spatial map of regions of high local conspicuity. In Koch and Ullman's (1985) model there is an explicit "winner-take-all" competition to resolve the problem of which location in the salience map is selected to receive the next fixation. Dannemiller's (1998) data can be understood as showing that color and movement both affect these early salience computations at 3.5 months of age. The present work looks for evidence of these competitive effects across a larger age range from 7 to 21 postnatal weeks.

One prediction about the results of the current experiment can be made based on reasonable assumptions about the locus of mechanisms responsible for color processing and stimulus-driven orienting in the visual pathways. Much work with adults and with nonhuman primates implicates cortical area V4 in the processing of color (Carden, Hilken, Butler, & Kulikowski, 1992; Heywood & Cowey, 1987; Heywood, Gadotti, & Cowey, 1992; Motter, 1994; Rizzo, Nawrot, Blake, & Damasio, 1992; Walsh, Kulikowshki, Butler, & Carden, 1992). Neurophysiological studies and models (Desimone, Wessinger, Thomas, & Schneider, 1990; Grossberg, Roberts, Aguilar, & Bullock, 1997) also indicate that cortical input is integrated with subcortical processing in stimulus-driven attentional selection. One interpretation of the competition effects observed in 14-week-olds by Dannemiller (1998) and indeed of much of the literature on the development of early visual attention is that these effects reflect this type of cortical influence on subcortical orienting mechanisms. Several authors have suggested that this type of cortical influence emerges only gradually over the first several months (Bronson, 1974; Johnson, 1990). Immature cortical color input to subcortical orienting mechanisms should make the orienting behavior of the younger infants in the present experiments less selective for color.

The theoretical model that has been used previously with this paradigm (Dannemiller, 1998) makes it clear that the likelihood of observing competition effects, especially with young infants, depends on several factors. First, there must be some neural substrate that allows objects at different spatial locations to compete with each other in determining which one will be the next object of regard. Immaturity of this substrate at very young ages could weaken such competitive interactions, which are often modeled as inhibitory interactions between spatial locations. Second, high levels of internal noise in the internal sensory responses to such simple objects as small colored bars would make it more difficult to detect the presence of such competitive interactions experimentally. Finally, the model shows that observed magnitude of the competitive interactions in this paradigm depends subtly on the relationship between salience differences between the bar colors and the strength of the motion signal used to probe orienting. This model can be used to make precise quantitative predictions about performance in this paradigm based on assumptions about the strengths of various stimulus effects. Rather than focusing on precise quantitative estimates of sensitivity, the work in this article was focused on the simpler question of whether competition effects can be detected as early as 7–8 weeks, and whether these effects look similar across the age range from 7 to 21 postnatal weeks. The "signature" of competition in this model is a difference in sensitivity to the moving target contingent on the uneven distribution of objects that differ in salience (e.g., red versus green bars).

EXPERIMENT 1

Method

Participants. Infants were recruited from birth announcements in a local newspaper. Seventy-nine full-term infants were tested. Analyses were conducted on the data from 65 of these infants: 32 infants at 8 weeks of age and 33 infants at 14 weeks of age. The average age of the 32 eight-week-olds was 56.6 days (range = 51 to 63 days). The average age of the 33 fourteen-week-olds was 102.2 days (range = 91 to 110 days). Data from 11 eight-week-old infants were excluded for the following reasons: perinatal medical problems/ICU ($n = 3$); familial history of color blindness ($n = 1$); excessive crying, fussiness, or inattentiveness ($n = 3$); fewer than 28 correct out of 48 trials ($n = 4$). Most of these 11 infants provided complete data sets (48 trials). Data from 3 fourteen-week-old infants were excluded for the following reasons: perinatal medical problems/ICU ($n = 1$) or excessive crying, fussiness, or inattentiveness ($n = 2$). All of the 14-week-olds whose data were excluded completed all 48 trials.

Apparatus and stimuli. The displays were presented on a large monitor running at 60 Hz in a noninterlaced frame mode. The stimulus field was 40° (H) × 31° (V). The background color of the stimulus field was white ($x = .271$, $y = .285$), and its luminance was 79.4 cd/m^2. The moving and static bars were 5° vertically by 0.75° horizontally. These bars were either red ($x = .618$, $y = .351$) or green ($x = .29$, $y = .603$) and the luminances of both the red and green bars were 16.2 cd/m^2. Thus, in addition to the color contrast with the white background, these bars were darker than the white background, providing a luminance contrast of 66% as well.

The moving target bar oscillated horizontally at 1.2 Hz for 14-week-olds and at 4.8 Hz for 8-week-olds, with a peak-to-mean amplitude of 1.0° on each trial. I altered the temporal frequency (and hence the bar's speed) of oscillation to attempt to achieve equal overall performance at the two ages. Pilot testing showed that the forced-choice preferential looking (FPL) observer rarely could score above chance with 8-week-olds when the oscillation rate was set at 1.2 or 2.4 Hz. The major effects of interest in this work involved differential performance across conditions at the two ages rather than differences in overall sensitivity. This necessitated analysis of age by condition interactions, so I followed the strategy advocated by Chapman, Chapman, Curran, and Miller

(1994) for avoiding the complication introduced by mean level performance differences in interpreting such interactions.

The display was situated at the infant's eye level in a matte black wall. The infant was seated in an infant seat approximately 50 cm from the display. To the infant's right, next to the display, there was a peephole that an observer used to watch the infant's eye and head movements and to make online judgments. The observer used a button box interfaced to a computer to start the trials and to register right and left judgments. The observer pressed a button to initiate the trial, and she could restart a trial when the infant looked away from the display at the start of the trial. The same practiced observer was used with all of the infants.

The target bar always appeared in one of two location on each trial: in the middle of the display vertically and either 10° to the right or 10° to the left of the center of the display. There were 27 static bars in all of the experiments reported below. The static bars could appear anywhere on the display, with the following constraints. Thirteen of these bars appeared on the same half of the display as the moving target. The remaining 14 bars appeared on the half of the display opposite to the target. Thus, a total of 28 bars appeared on the display on every trial evenly divided between the two sides of the display. The bars were distributed between 14 imaginary columns that divided the horizontal extent of the display into 14 equal segments. Two bars appeared in each column. The vertical positions of the bars in the columns were random, with the constraint that two bars could not overlap and the whole of a bar had to be visible. This produced a display with 28 bars more or less randomly distributed across its extent. The goal was to simulate a situation in which the infant had multiple potential targets of attention within this portion of his/her visual field.

Design and procedure. The experimenter used a blue flashing bar to center the infant's gaze prior to the start of each trial. The observer also used sound centered near midline to attract the infant's gaze to the display. At the start of each trial all 28 of the bars appeared on the screen simultaneously with the onset of movement of the target bar. These bars appeared from a blank field set at the background luminance as soon as the blue centering stimulus was removed.

The main variables were manipulated within subjects. Forty-eight trials were presented to each infant. There were six different trial types comprising a 2 × 2 factorial design plus two additional trial types. The two additional trial types were homochromatic trials in which either all of the bars on the display were red or all of the bars on the display were green. The 2 × 2 factorial design comprised two colors for the moving target, red and green, crossed with two spatial distribution levels, ipsilateral and contralateral. The terms ipsilateral and contralateral refer to the location of *most of the red bars* (11/14) on the display relative to the side of the display with the moving target bar. In all four of these heterochromatic trial types half of the bars on the display were red and half of the bars were green. In the contralateral condition, 11 of the 14 bars on the side of

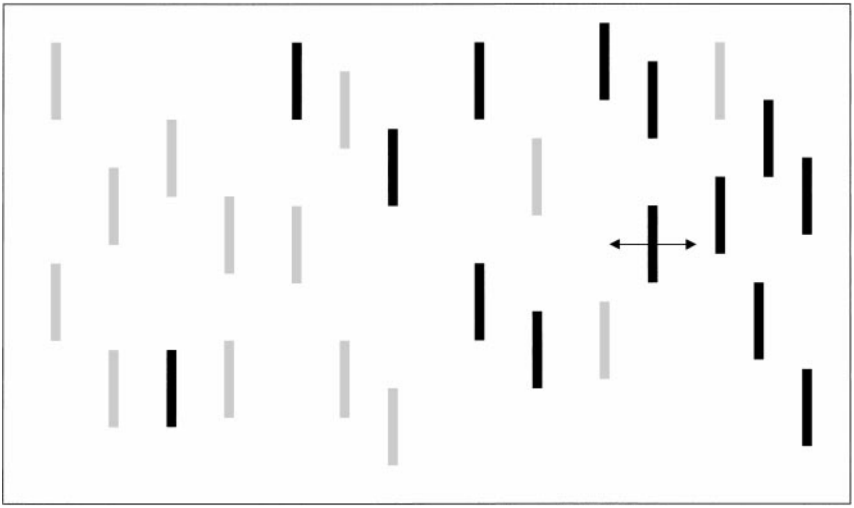

FIG. 1. Example of a heterochromatic display. In this example, the moving target bar is indicated by the arrows. Red bars are drawn as black bars, and green bars are drawn as gray bars. This is an example of an ipsilateral trial with a red target with a ratio of 11:3 red:green on the side ipsilateral to the target. The ratio is the inverse on the side contralateral to the target. The amplitude and sizes are not drawn to scale (please see text for details).

the display opposite to the moving target were red and the remaining 3 bars were green. On the other side of the display in this contralateral condition this proportion of red and green bars was complemented. Thus, on contralateral trials, 11 of the 14 red bars were on the side of the display opposite to the side with the moving target. In the ipsilateral condition, these proportions of red and green bars were reversed from their proportions on contralateral trials. Thus, on ipsilateral trials, 11 of the 14 red bars on the display were on the same side as the moving target while the other side of the display contained most of the green bars. These trial types were randomly ordered within a block of 6 trials, and eight such blocks were presented to each infant, for a total of 48 trials. I chose to examine competition using red and green as the colors because prior work (Adams, 1987; Bornstein, 1975) has shown preferences for red over green at approximately 3 months. The 11:3 red:green imbalance was sufficient to produce competition effects at 14 weeks in Dannemiller (1998). A schematic of the display is shown in Fig. 1.

Data were collected using the FPL technique (Teller, 1979). The adult who was observing the infant made a forced choice on each trial about the location of the moving target. This adult observer was “blind” to the trial type and to the location of the moving target bar on each trial. The computer provided the observer with feedback about the correctness of this judgment after every trial in the form of a brief, audible beep. The FPL observer was instructed to make these judgments as quickly as possible while maintaining reasonably good accuracy because I was interested in orienting or the dominant direction of regard in the seconds immediately following the appearance of all of the bars in the visual field. It is more common with the FPL technique to allow the FPL observer to wait indefinitely on each trial until enough evidence has accumulated to make a forced-choice judgment. This version of the FPL technique differed because the observer made a speeded judgment. The latencies to make these judgments were on the order of 2 to 3 s (see below), so I feel confident that this measure yields information about competitive effects during the initial second or two after the appearance of many potential targets in the visual field. Notice also that *reliability* is not an issue in this paradigm because there is an external stimulus (the location of the moving bar) that provides *validity* for the judgments. Feedback about the correctness of each judgment was provided to the FPL observer to encourage and maintain performance above chance levels. Performance above chance levels tells us at least that infants could detect the moving target. The question of interest then becomes whether other aspects of the visual field systematically perturb this sensitivity to movement.

Data analyses. The primary dependent variable was the percentage of correct judgments in each of the six conditions. The statistical tests were conducted on d' (sensitivity) transformations of these percent correct measures. This transformation is monotonic with the percentage of correct judgments and is preferable- with respect to the homogeneity of variance assumption of ANOVA when percentages are based on small numbers of trials in each condition (Thorpe, Trehub, Morrongiello, & Bull, 1988).[1]

Results

As noted above, all analyses were conducted on d' as the dependent variable. For reference, a d' value of 1.0 in this paradigm is approximately equivalent to 80% correct. Chance behavior (50% correct) corresponds to a d' of 0.0. Perfect detection (8/8 correct) is estimated to be a d' of 2.25 with this transformation. Where it is easier to understand, I discuss particular effects in terms of the mean percentages of correct judgments.

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[1] The d' transformation was implemented separately for each trial type as follows. The number correct out of 8 was increased by .5, and this number was divided by 9. The z score corresponding to this percentage was then determined from a standard normal distribution (e.g., 50% correct corresponds to $z = 0$). This z score was then multiplied by the square root of 2 to transform it into a d' measure appropriate for a two-alternative forced choice as was used here. The reason for adding an initial .5 and dividing by 9 was to handle occasional perfect scores: 8 of 8 correct. A z score is undefined for 100%, so this transformation maintains the rank orderings of all scores and represents perfect scores as $d' = 2.25$. Such a treatment of perfect scores is common in the signal detection literature. Chance (4 of 8 correct) on the original scale remains chance (4.5 of 9 correct) on the transformed scale and always corresponds to $d' = 0.0$.

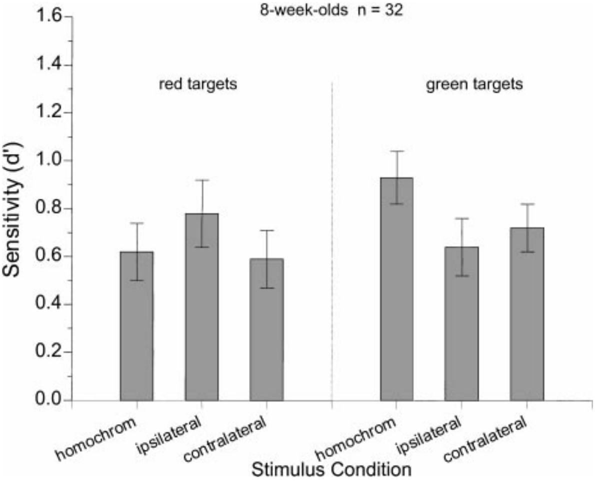

FIG. 2. Mean sensitivity in each condition for 8-week-olds. All of the conditions to the left of the vertical dashed line involved a moving red target, and all of those to the right of this line involved a moving green target. Error bars are ±1 *SEM.*

Homochromatic trials. Sensitivities on the two homochromatic trial types were analyzed first with age as a between-subject factor and color as a within-subject factor.[2] The effect of target color was not significant, $F(1, 63) = 2.933$, $p = .092$. The effect of age was not significant, $F(1, 63) = 0.254$, $p = .616$, and neither was the interaction of these two variables, $F(1, 63) = 0.809$, $p = .372$. Recall that I purposely increased the temporal frequency of the oscillation from 1.2 Hz for the 14-week-olds to 4.8 Hz for the 8-week-olds to attempt to hold overall sensitivity at the same level at the two ages. The above analysis shows that for trials on which all of the objects in the field were the same color, sensitivity to the motion at the two ages did not differ significantly. Sensitivities on the two homochromatic trial types are shown in Fig. 2 for 8-week-olds and in Fig. 3 for 14-week-olds. The overall sensitivities were well above chance ($d' = 0.0$) at both ages ($d'\ M = 0.77$, $SEM = 0.08$ at 8 weeks and $d'\ M = 0.83$, $SEM = 0.09$ at 14 weeks), showing that infants generally oriented to the side of the display with the moving bar.

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[2] Homochromatic trials are useful in the signal detection model for estimating overall sensitivity to movement, although they also have some impact on estimating red versus green salience differences. Heterochromatic trials are more useful than homochromatic trials for detecting competition. I have included data from homochromatic trials from both Experiments 1 and 2 to examine overall sensitivity differences across age, although it is the heterochromatic data that are more relevant to the experimental question of whether or not competition effects exist across the age range used in these two experiments.

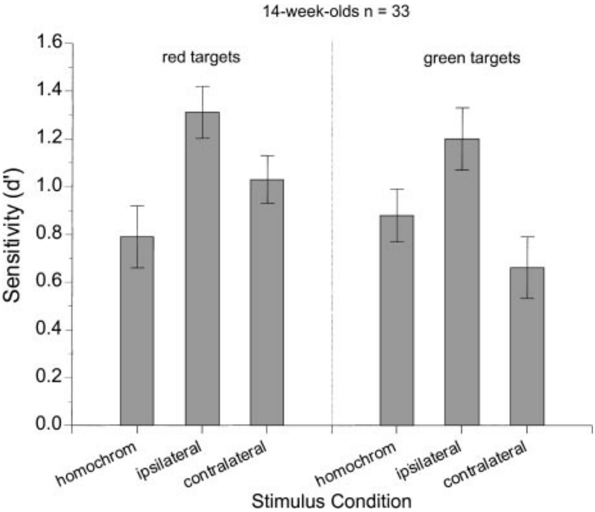

FIG. 3. Mean sensitivity in each condition for 14-week-olds. The conventions are the same as in Fig. 2. Competition driven by color salience differences is indicated by consistently lower sensitivity on contralateral than on ipsilateral trials as shown by these 14-week-olds (cf. Fig. 2 for 8-week-olds).

Heterochromatic trials. The sensitivity data from the heterochromatic trials were analyzed next with a mixed ANOVA. Age was a between-subject factor, the side of most of the red bars relative to the moving target was a within-subject factor (ipsilateral versus contralateral), and the color of the moving target was the second within-subject factor (red versus green). There was a significant main effect of side, $F(1, 63) = 7.37$, $p = .009$. There was also a significant main effect of age, $F(1, 63) = 16.74$, $p < .001$. These two main effects were qualified by an Age × Side interaction, $F(1, 63) = 4.52$, $p = .038$. These effects are shown in Figs. 2 and 3. As expected, 14-week-olds showed lower sensitivity when most (11/14) of the red bars appeared contralaterally to the moving target. For the red moving target this difference between ipsilateral and contralateral conditions averaged 5.7% (percent correct), and for the green target the difference was 12.5%. This effect replicates that shown in Dannemiller (1998) for 14-week-olds. The 8-week-olds, in contrast, showed unsystematic effects of the distribution of the red bars. The differences for red (4.3%) and green (−3.1%) targets were in opposite directions and small. The average decrement between ipsilateral and contralateral conditions for 14-week-olds was 9.1%, while for 8-week-olds the average decrement was 0.6%. The main effect of age indicates that despite our efforts to equate overall detection by increasing the temporal frequency of the oscillation for the 8-week-olds, the 14-week-olds still were more sensitive overall on heterochromatic trials (d' $M = 1.05$) than were the 8-week-olds (d' $M = 0.68$).

Discussion

The major results of this experiment can be summarized succinctly. Fourteen-week-olds are sensitive to the spatial distribution of differently colored objects across their visual fields. When most of the small, red objects in the visual field are placed contralaterally to the side of the visual field with a small moving target, these 14-week-olds initially pay less overt attention to the side with moving object than they do when most of the red bars are on the same side as the moving target. Eight-week-olds, in contrast, did not show systematic evidence of this type of competition within their visual fields. Their attention was drawn to the side of the visual field with the moving target, albeit less reliably than at 14 weeks, regardless of how the static, colored objects were distributed in the visual field.

Why might the 8-week-olds fail under these circumstances to show evidence of competition in their initial orienting? Before it is concluded from these null results that such competition effects do not operate at 8 weeks of age, several alternative explanations should be considered. First, perhaps 8-week-olds could not discriminate the colors of the red and green static bars. This seems unlikely in view of evidence for such discriminations at this age (Hamer, Alexander, & Teller, 1982; Suttle, Anderson, & Harding, 1997). One reason to be cautious, however, in ruling out this explanation for the lack of color effects at 8 weeks is that the bars were small, and they were presented with luminance contrast as dark bars against a brighter background. It is possible that in the presence of high luminance contrast, 8-week-olds might be less able to discriminate the colors of the small, static bars. When adults view a colored object in their peripheral visual fields (i.e., a region with poor spatial resolution), the hue of that object diminishes and appears gray or even black as the luminance of the object drops below that of its surround (Fuld, Werner, & Wooten, 1983; Packer, Hartmann, & Teller, 1984). The differences between the red and green bars may have been less distinct for the 8-week-olds because they were darker than the surrounding white field.

A second, and somewhat related, explanation for the lack of competition effects at 8 weeks is the poor spatial resolution of infants at this age. Much coarser spatial resolution might make color differences between the red and green bars weaker because the chromatic signals from the bars would tend to get neurally averaged or “blurred” with their white backgrounds. There is clear evidence that chromatic discrimination over these ages is strongly affected by the size of the pattern to be detected (Packer et al., 1984). In this case, the luminance contrasts of these bars (which were putatively equal for the red and green bars) might swamp the color contrasts of these bars against their white backgrounds. Even if the competition mechanism observed at 14 weeks were operating at 8 weeks of age, poorer spatial resolution could contribute to making the color competition weaker.

There is another possibility that must be considered for explaining the differ-

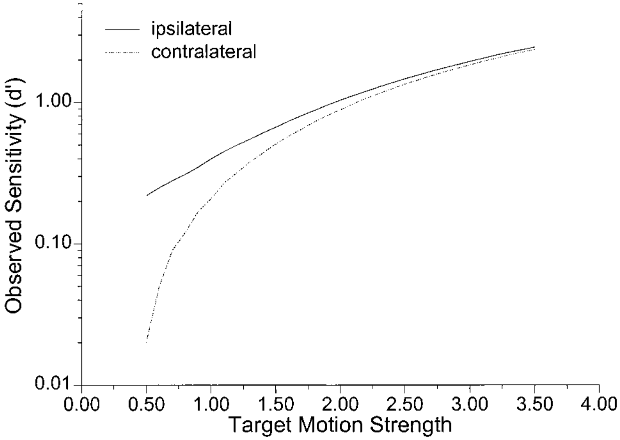

FIG. 4. Predictions from the signal detection model described in Dannemiller (1998). The salience difference between red and green was set at -0.1 d' units (i.e., a green bar produces a mean internal response that is 0.1 z units lower than the mean internal response produced by a red bar). The strength of the motion stimulus increases from left to right on the x axis. The two curves show the predicted ratio (log difference) in sensitivity when most (11/14) of the red bars are placed contralaterally to the moving bar versus ipsilaterally. As the motion stimulus becomes stronger, the model predicts that a fixed red/green salience difference will lead to a smaller observed difference on ipsilateral versus contralateral trials.

ence in the way the 8- versus the 14-week-olds responded to the ipsilateral/contralateral manipulation. It is possible that I failed to observe contralateral competition at 8 weeks not because it does not exist, but rather because in the presence of a relatively strong motion signal it is difficult to detect the effects of this salience difference in the data. The signal detection model makes such a prediction. Figure 4 shows the predicted sensitivity difference between ipsilateral and contralateral conditions as a function of the strength of the moving target. The logarithmic difference between the two curves shows the ratio of sensitivities expected under ipsilateral and contralateral conditions for a slight salience difference between red and green static bars (d' difference $= 0.10$). Notice that as the mean internal response to the motion stimulus increases on the x axis, the likelihood of observing an ipsilateral versus contralateral difference in the data decreases. One hypothesis to explain the results of Experiment 1 is that at 8 weeks of age, contralateral competition exists, but the salience difference between red and green requires a weaker motion stimulus to reveal it than the one that I used in Experiment 1. It is also possible that the internal sensory responses to these stimuli are perturbed by greater levels of internal noise at 8 weeks of age than at 14 weeks of age. Increased internal noise would also make it more difficult to detect a competition effect in the presence of a relatively strong motion stimulus. Greater amounts of internal noise would render the saliences of the red and green bars less distinct, making it more difficult to detect the effects of a spatial distribution manipulation. Increasing the variance of the internal responses in the signal detection model decreases the difference between the ipsilateral and contralateral curves shown in Fig. 4. This idea will be considered in the General Discussion.

These considerations led to Experiment 2. In this experiment, I used a constant motion stimulus and extended our age range by sampling ages across the entire range from 7 to 21 weeks. The motion stimulus that I chose was designed in accordance with the above hypothesis to be much weaker for the younger infants. Roessler and Dannemiller (1997) have shown that infants at the younger end of this age range are much less sensitive to small movements at low temporal oscillation frequencies than are infants in the middle and at the upper end of this range. If contralateral competition exists at the younger end of this age range, then it should be easier to observe with a weaker motion stimulus because the likelihood of the maximum response on a trial arising from one of the static bars increases as the strength of the motion stimulus is reduced.

EXPERIMENT 2

This experiment tested the hypothesis that competition effects may be observed at the younger age used in Experiment 1, but that a weaker motion stimulus is necessary to reveal it. I also extended the age range in this experiment by uniformly sampling infants whose ages spanned 7 to 21 weeks.

Method

Participants. Eighty-eight full-term infants provided complete data (45 female, $M = 95.4$ days, $SD = 28.6$ days; range = 49 to 145 days). Our design in this experiment called for using age as a covariate in the analyses, so I attempted to sample age uniformly across the entire range noted above. This design permits conclusions based on the entire age range rather than on specific age groupings as in traditional cross-sectional designs. The age distribution is shown in Fig. 5. A chi-square on the final sample with age binned into seven categories, each approximately 2 weeks long (expected frequency 12.6), showed that the final age distribution did not differ significantly from a uniform distribution, $\chi^2(6, N = 88) = 3.79$, $p = .705$. Data from an additional 16 infants (15%) were excluded from the final data analysis for the following reasons: (a) inattentive/fussy, $n = 12$; (b) birth complications or medical problems, $n = 3$; and (c) born more than 2 weeks preterm, $n = 1$.

Apparatus and stimuli. The apparatus and stimuli were identical to those used in Experiment 1, with one exception. Instead of trying to equate overall performance across different ages, I held the motion stimulus constant. I presented a weaker motion stimulus as required by the hypothesis advanced above. The moving bar oscillated for all infants at 1.2 Hz through a peak-to-mean distance of 0.75°. This amplitude was slightly smaller than the 1° amplitude that I had used in Experiment 1. The temporal frequency of oscillation, 1.2 Hz, was the same one that I had used

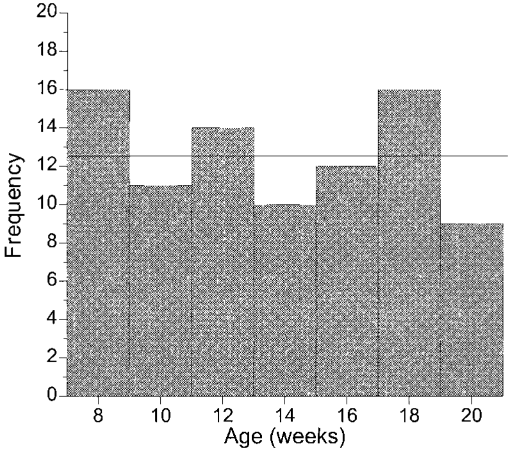

FIG. 5. Age distribution of infants tested in Experiment 2. The age distribution does not differ significantly from a uniform distribution.

for 14-week-olds in Experiment 1, but this was one fourth as fast as the 4.8-Hz rate that I had used with 8-week-olds in Experiment 1.

Design. This was the same as in Experiment 1. All infants received eight blocks of the six trial types. The order of the trial types was randomized within each block.

Data analyses. The sensitivity transformation, d', was used as the dependent variable in all of the analyses. Age in days was used as a covariate in all analyses. For purposes of comparison to Experiment 1 and to present the results, I also blocked age to prepare several figures below.

Results

As in the first experiment, I analyzed the data from the homochromatic trials separately from the data from the heterochromatic trials.

Homochromatic trials. Sensitivity on the two homochromatic trial types was analyzed with color as an independent variable (red versus green) and age as a covariate using analysis of covariance (ANCOVA). The ANCOVA showed a significant effect of color, $F(1,\ 86) = 5.14$, $p = .026$, $MS_{\text{error}} = 0.44$. Sensitivity was slightly higher on red trials ($M = 0.78$, $SEM = 0.081$) than on green trials ($M = 0.55$, $SEM = 0.078$). There was also a significant effect of age, $F(1,\ 86) = 28.85$, $p < .001$, $MS_{\text{error}} = 0.52$. The interaction of age with color was not significant, $F(1,\ 86) = 0.917$, $p = .341$. The age trend is shown in Fig. 6, where the average sensitivity on homochromatic trials is plotted for each participant as a function of age. The best fitting line had a slope of .0103 d'-units/day ($SE = .002$). Perhaps more interpretably, sensitivity increased on

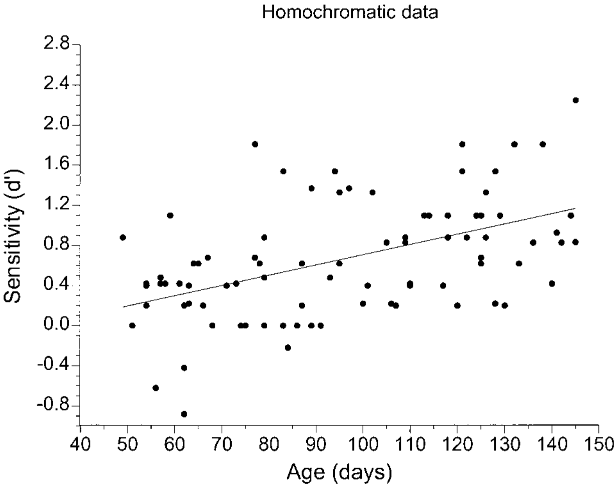

FIG. 6. Scatter plot of average sensitivity on homochromatic trials (y axis) versus age at testing (x axis). The age trend is significant.

homochromatic trials by approximately .29 d'-units over any 4-week, cross-sectional period.

Heterochromatic trials. An ANCOVA was used to analyze the data from the heterochromatic trials. This ANCOVA used side (ipsilateral versus contralateral) and moving target color (red versus green) as within-participant independent variables crossed factorially and age as a covariate. Recall that the ipsilateral versus contralateral distinction refers to the location of most of the red bars relative to the side with the moving bar. The color distinction refers to the color of the moving target bar.

There was a significant main effect of side, $F(1, 86) = 18.91$, $p < .001$, $MS_{\text{error}} = 0.47$. Sensitivity was lower when most of the red bars were contralateral to the moving target ($M = 0.562$) than when they appeared ipsilaterally to the moving target ($M = 0.878$). There was also a significant age trend, $F(1, 86) = 75.23$, $p < .001$, $MS_{\text{error}} = 0.52$, with overall sensitivity increasing with age. The main effect of color was not significant, although the sensitivity difference was in the same direction as it was with homochromatic trials (red $M = 0.77$ and green $M = 0.67$). Color did not interact with the side variable, nor did age interact significantly with either of the within-subject independent variables.

The significant age trend is shown in Fig. 7. As was the case with the homochromatic trials, sensitivity increased with age. The slope of this improvement was .0117 d'-units/day ($SE = .001$), or approximately 0.34 d'-units per 4-week period. This is comparable to the 0.29 increase in sensitivity per 4-week period seen on homochromatic trials, indicating that the processes responsible for

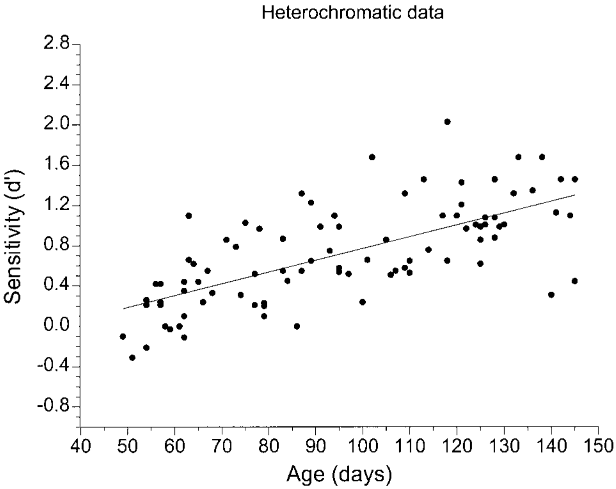

FIG. 7. Scatter plot of average sensitivity on heterochromatic trials (y axis) versus age at testing (x axis). The age trend is significant and similar to the trend observed on homochromatic trials (cf. Fig. 6).

determining overall sensitivity on both homochromatic and heterochromatic trials may be the same. Overall sensitivity is most strongly influenced in the signal detection model by sensitivity to movement, so it may be improvements in sensitivity to movement that are responsible for these increases with age. To display the effect of side (ipsilateral versus contralateral), I blocked the data into three equal-range age groups: 7–11 ($n = 33$), 12–16 ($n = 26$), and 17–21 ($n = 29$) weeks of age. These data are shown in Figs. 8, 9, and 10. Two aspects of these data are evident: (a) Overall sensitivity increases with age on all trial types, and (b) ipsilateral sensitivity is higher than contralateral sensitivity at all ages. The magnitude of this difference does not vary significantly with age despite the large differences in overall sensitivity across age (i.e., the Age × Side interaction was not significant).

For purposes of comparison, I used the regression of average sensitivity on heterochromatic trials in Experiment 2 to estimate sensitivity at 14 weeks of age. Recall that the only difference between Experiments 1 and 2 for the 14-week-olds was that the amplitude of oscillation was reduced by 25% from 1° to 0.75°. This reduction in the strength of the motion stimulus should have resulted in a slight reduction in overall sensitivity. The predicted sensitivity at 14 weeks of age from the regression was $d' = 0.75$. This should be compared to the average observed sensitivity on heterochromatic trials from 14-week-olds in Experiment 1: $d' = 1.05$. This reduction in amplitude (or in average speed) thus resulted in approximately a 0.25-unit decrease in overall sensitivity to the movement as predicted.

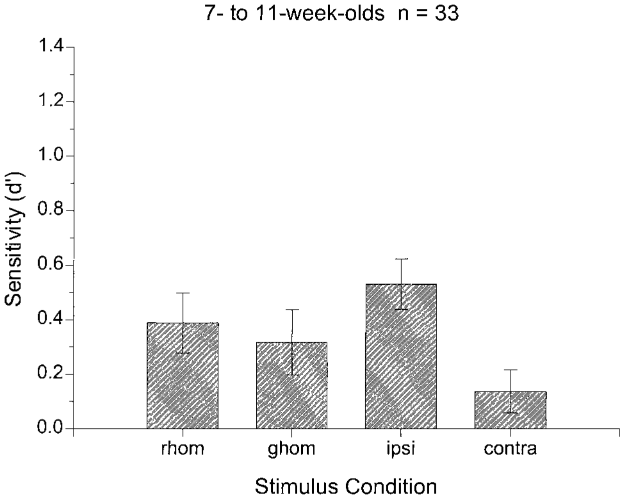

FIG. 8. Mean sensitivity from Experiment 2 for all infants in an age block from 7 to 11 postnatal weeks. Rhom = red moving target, all bars on display red. Ghom = green moving target, all bars on the display green. Ipsi = average sensitivity when most of the 14 red bars on the display appeared ipsilaterally to the moving target. Contra = average sensitivity when most of the red bars on the display appeared contralaterally to the moving target. Error bars are ±1 *SEM.*

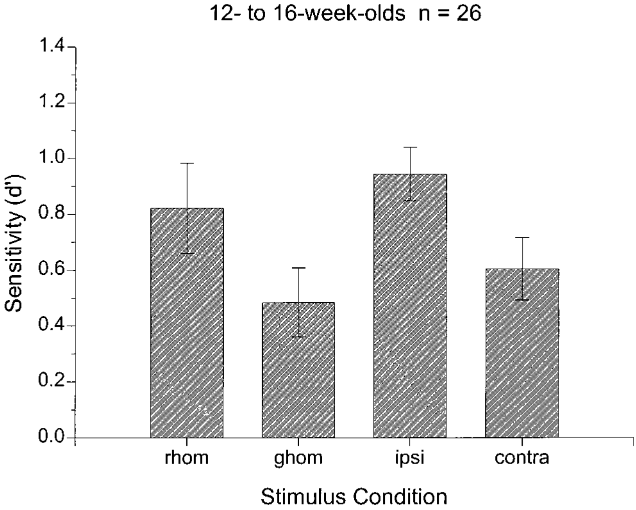

FIG. 9. Mean sensitivity from Experiment 2 for all infants in an age block from 12 to 16 postnatal weeks. Other conventions are the same as in Fig. 8.

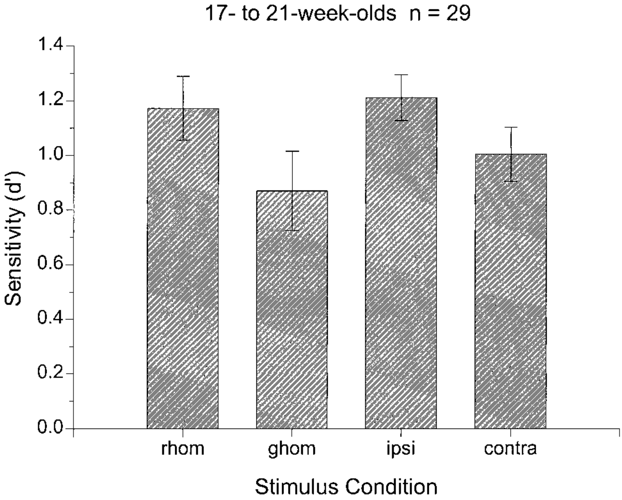

FIG. 10. Mean sensitivity from Experiment 2 for all infants in an age block from 17 to 21 postnatal weeks. Other conventions are the same as in Fig. 8.

Discussion

Unlike in Experiment 1, in which I attempted to equate overall sensitivity and found no ipsilateral versus contralateral difference at the younger age, in Experiment 2 this competition effect was present at all ages. The major methodological difference between these two experiments was that in the current experiment the amplitude and temporal frequency were held constant across age. This led as predicted to much lower overall sensitivities at the younger ages, but it also revealed the spatial distribution effect (ipsilateral versus contralateral) that was not observed with the 8-week-olds in Experiment 1.

The positive evidence for competition found at 8 weeks of age (and at the higher ages) in this experiment must be reconciled with the null results at 8 weeks of age from Experiment 1. This issue will be addressed in the General Discussion.

GENERAL DISCUSSION

Selective attention mechanisms are necessary to resolve the problem of where to look next in a visual field that is populated with multiple objects (as it usually is). The results of these experiments show that when one of multiple, small objects in the visual field is moving, infants at all ages from 7 to 21 weeks of age orient to this object at levels above chance (Experiments 1 and 2). The results also show that for a fixed amount of movement, older infants orient more readily toward this movement than do younger infants (Experiment 2). This result is compatible with previous studies showing large increases in sensitivity to moving stimuli across this age range (e.g., Roessler & Dannemiller, 1997). Finally, although I failed to observe systematic competition between color and motion at 7 to 9 weeks of age in Experiment 1, Experiment 2 revealed that such competition exists and can be readily observed when the strength of the moving stimulus is reduced. Thus, it appears that competitive effects in exogenous orienting can be observed as early as 7 weeks of age. I did not test younger infants, so it is possible that such effects may be observed even earlier.

The results across the two experiments were consistent for the 14-week-olds. In both experiments, I found the contralateral competition effect that has been observed at this age in a previous study (Dannemiller, 1998). This effect was also clearly in evidence for infants older than 14 weeks in Experiment 2. The discrepancy in the results arose at the younger ages across the two experiments. In Experiment 1, I failed to observe a systematic competition effect, while in Experiment 2, this effect was clearly present for infants approximately 8 weeks of age. This difference in results needs to be explained.

There are at least two potential reasons for the difference in the results between the two experiments for the infants at the lower end of the age range that was employed. The first reason was already discussed above. It is related to the difference in the strength of the moving stimulus between the two experiments. The second reason was also briefly mentioned above. It appeals to the possibility that there is more internal noise in the sensory responses to these stimuli at 8 weeks of age than at later ages. Consider how these two factors might have contributed to the differences in the results across the two experiments.

In Experiment 1 I employed a stronger motion stimulus with the 8-week-olds than was used with the 14-week-olds. This was done in an attempt to equate overall sensitivity between the two ages. Eliminating mean level differences between two age groups makes the interpretation of interactions of other variables with age generally easier to interpret (Chapman et al., 1994). The strategy was only partly successful because 8-week-olds were still less sensitive to the movement on the four heterochromatic trial types than were the 14-week-olds despite the use of a much stronger motion stimulus with the 8-week-olds.

So the first factor that might have contributed to the finding of no systematic competition effect with the younger infants in Experiment 1 and the detection of this effect in Experiment 2 was the difference in the strength of the motion stimulus. As shown in Fig. 4, the signal detection model used to interpret these results implies that all other things being equal, a stronger motion stimulus will make it less likely that a salience difference between red and green will produce an observable ipsilateral versus contralateral effect in the data. It is possible that the motion stimulus that I used in Experiment 1 was too strong relative to the size of the red/green salience difference at 8 weeks to observe a competition effect.

This factor by itself, however, is probably insufficient to explain completely the difference between the results of the two experiments at the younger age. A second factor that might explain the difference is the possibility of age differences in the variability of internal sensory responses to these stimuli. In other words, a given bar on the screen might lead to more variable internal responses at the younger ages than at the older ages. Computations with the signal detection model (Dannemiller, 1998) show clearly that increased internal response variability makes it more difficult to observe the effects of a salience difference between red and green when their spatial distribution is manipulated. All other things being equal, more internal noise leads to less distinctiveness across trial types, especially when coupled with a stronger motion stimulus as in Experiment 1.

Is there any independent evidence that the level of internal response variability might be changing across this age range? In fact there is. One estimate of such variability can be obtained by varying the strength of a stimulus and determining how much of a change in sensitivity results from a given change in stimulus strength. Typically, greater internal response variability leads to less of a change in sensitivity per unit change in stimulus strength (slope of the psychometric function relating sensitivity to stimulus intensity). The average sensitivity across all trial types dropped from 0.711 at 8 weeks in Experiment 1 to approximately 0.265 in Experiment 2 when the average speed of the stimulus was reduced by a factor of 5.33 (0.726 log units). This yields an estimate of 0.614 [(0.711 − 0.265)/0.726)] for the slope of the group function relating sensitivity to stimulus intensity. At 14 weeks, in contrast, overall sensitivity dropped from 0.978 to 0.727 across experiments as the average speed of the oscillating stimulus was reduced by a factor of 1.33 (0.125 log units). This yields a corresponding estimated group slope of 2.01. The estimate of internal response variability is inversely related to the steepness of this slope. This implies that the internal responses at 8 weeks of age may be as much as three times more variable than they were at 14 weeks of age.

What effect would this higher internal response variability have on orienting in this paradigm? First, it would lead to lower overall sensitivity. This is consistent with the data across the two experiments. In Experiment 1, 8-week-olds were less sensitive than 14-week-olds on heterochromatic trials despite a motion stimulus whose average speed was 5.33 times as great. In Experiment 2, which allowed a more direct sensitivity comparison because the motion stimulus was held constant, there was a clear age trend in overall sensitivity, with sensitivity improving substantially over the period between 8 and 14 weeks of age (and beyond). Second, greater internal response variability would make it more difficult to observe an ipsilateral versus contralateral sensitivity difference, especially with a strong motion stimulus (Experiment 1) because the underlying salience difference between red and green should be less distinct.

The above analysis implies that one factor that might underlie development across this age period is a reduction in internal, sensory response variability. It should be noted, however, that this internal noise or response variability could involve changes at many levels in the system all the way from the initial sensory response to changes in how reliably infants gaze toward a given stimulus. For example, random dropping of action potentials at the neural level would produce variability in the response to a given stimulus (Banks & Bennett, 1988). Variability in where these stimuli were imaged on the retina because of fixational instability could lead to greater response variability at the younger ages. These and other factors could lead to changes across age in the reliability with which the infants' visual system responds to such stimuli.

Does the involvement of color in this competition effect necessarily imply that cortical processes are influencing the orienting that is induced by the appearance of these stimuli? First, it should be noted that I did not specifically manipulate color across these experiments, so it is possible that the factor responsible for the inferred salience difference is not color but rather luminance contrast. Although the red and green bars were equated for luminance, this was done using a photometer, which ultimately relies on adult color functions. Despite this possibility, there is reason to believe that color contrast is the effective factor underlying the salience difference. In related work (Ross & Dannemiller, 1999), manipulations of color contrast produced differences in the size of the competition effect.

Even if such effects were driven by color, does it necessarily follow that by 7 weeks of age, cortical color processing is exerting an impact on initial orienting? The answer to this question must be no. Despite clear evidence that color is processed cortically (Carden et al., 1992; Heywood & Cowey, 1987; Heywood et al., 1992; Motter, 1994; Rizzo et al., 1992; Walsh et al., 1992), and that a subcortical structure like the superior colliculus (which is probably involved in such orienting responses) processes color poorly (Marrocco & Li, 1977), there is evidence that color may still be discriminated in the absence of a functional geniculostriate pathway (Barbur, Sahraie, Simmons, Weiskrantz, & Williams, 1998). It is interesting to note that in this study of a patient with unilateral damage to primary visual cortex, the most consistent, above-chance color discriminations always involved long-wavelength (i.e., red) stimuli. The present results are consistent with the idea that cortical color processing may influence subcortical orienting as early as 7 weeks of age, but they do not compel this conclusion because of the problem noted above in trying to link color discrimination unequivocally with cortical processing.

These results extend some earlier work on the initial encoding of color by young infants. Catherwood and colleagues (Catherwood, 1994; Catherwood, Skoien, Green, & Holt, 1996; Catherwood, Skoien, & Holt, 1996), in a series of elegant experiments, showed that 5-month-olds encode the colors of objects very rapidly after these objects initially appear in the visual field. One interesting result in this series of experiments was that color may be encoded initially very rapidly, but it may take longer exposures to register the spatial locations of differently colored objects accurately. The present results show using a different paradigm and younger infants that color and spatial location are apparently registered accurately enough within the first several seconds after an object's appearance to influence initial orienting to a moving target in a competition paradigm.

The current results and their interpretation in terms of salience competition are similar to those discussed in the literature on adult visual search. For example, consider the salience model proposed by Koch and Ullman (1985). According to this model, early visual processing involves locally filtering the image along a number of dimensions (e.g., color, size, orientation, motion). This filtering is done in parallel across the visual field. The result of the filtering and subsequent stages is a salience map. This salience map represents regions within the image that differ significantly on any of these dimensions from their local surrounds (e.g., a moving object among static objects or a red object surrounded by green objects). Competition within this map selects the next location for attentional engagement. These salience computations almost certainly involve cortical mechanisms (e.g., orientation), although the ultimate resolution of the competition might take place at a subcortical level (e.g., superior colliculus) with input from these higher cortical centers (Grossberg et al., 1997). Across the age range from 7 to 21 postnatal weeks, there is a remarkable invariance in how color, motion, and location interact as the infant's visual system resolves the problem of where to orient when many potential objects of attention are simultaneously available. When one of a small number of objects in the visual field is moving, infants most often orient to that object; when they do not, however, color plays a prominent role in guiding their orienting to another object.

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