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# A Competition Model of Exogenous Orienting in 3.5-Month-Old Infants

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Four experiments are reported on exogenous (stimulus-driven) orienting in 3.5-month-old infants. A small moving bar embedded in a field of static bars was used to draw the infant's attention to one side of the display or the other. The bars could be either red or green. In all four of these experiments sensitivity to this small moving bar was affected significantly by how unevenly the red and green bars were distributed across the visual field. Sensitivity to the moving bar was lower when most of the red bars were in the field contralateral to this probe suggesting competition between the motion stimulus and contralaterally placed red but not green bars on a small, but significant proportion of trials. This basic effect replicated in four separate experiments and depended coarsely on how unevenly the red and the green bars were distributed across the field. A competition model of exogenous orienting with a winner-take-all rule captured the most important features of the data. The distribution of color within the visual field can bias attention significantly at 3.5 months making it either more or less likely that an infant will detect a moving stimulus.

Much of what we know about the development of perception and cognition during infancy comes from studies ultimately involving the infant's visual orienting. The preference paradigm developed by Fantz (1958) involves showing infants pairs of visual stimuli and measuring how long they look at each stimulus. The habituation paradigm (e.g., Pancratz & Cohen, 1970) involves showing infants a single stimulus and measuring how long they look at the stimulus. In each case, the infant must orient to (look at) the stimulus and then look elsewhere. The processes that govern the initial phase of this visual orienting are the subject of this study.

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Research on the early development of visual attention shows that over the first six months infants are better able to disengage their attention from a fixation stimulus to switch attention to a new stimulus (*cf.* Aslin & Salapatek, 1975 with Atkinson, Hood, Wattam-Bell & Braddick, 1992) and that they are quicker to shift attention from one location in space to another (Johnson & Tucker, 1996). How consistent and selective is visual attention at these early ages? When a visual transient (e.g., the sudden appearance of an object or the onset of movement) fails to capture attention, do these failures appear to be random or do they show selectivity in the sense that some objects are more likely to induce these failures than others? Theeuwes (1992) showed that even when adults are trying to detect an object with certain known features, the presence of strong, highly salient objects elsewhere in the visual field can interfere with their search. Random failures on the part of the infant to orient to a strong stimulus might be attributed to slow modulations of alertness. Nonrandom or selective failures may be evidence of competition and selectivity in the processes that govern orienting. One way to distinguish these two situations would be to show that the failures to orient were correlated with the distribution of certain stimulus features (e.g., color) within the visual field.

Attention to a visual stimulus in adults can be under endogenous (internal, goal-directed) control or under exogenous (external, stimulus-driven) control (Theeuwes, 1991; Yantis & Jonides, 1984). Exogenous orienting probably involves different neuronal structures than endogenous orienting (Posner & Cohen, 1984; Lynch & McLaren, 1989; Posner & Petersen, 1990; Robinson & Petersen, 1992; Robinson, 1993; Cavegn & Dydewalle, 1996; Walker & Findlay, 1996). Exogenous orienting usually involves a strong stimulus that interrupts attention from its current focus and often triggers an eye movement to a peripheral stimulus. This more or less reflexive saccade to a peripheral stimulus may be accomplished in part by the superior colliculus, a part of the brain's eye movement control circuitry (Bronson, 1974; Kustov & Robinson, 1996; Keating, Gooley, Pratt & Kelsey, 1983; Cavegn & Dydewalle, 1996; Zackon, Casson, Stelmach, Faubert & Racette, 1997). The experiments in this paper tested a model of exogenous orienting so I will not say anything further about endogenous orienting.

Even these reflexive saccades characteristic of exogenous orienting probably involve competition between different potential targets of attention. Ultimately the eyes must move to one location in the visual field or to another (Sheinberg & Zelinsky, 1993), and this movement involves decisions about how long to continue looking at the current object or location and where to look next. It also involves the ability to disengage attention and fixation from its current focus. The superior colliculus contains neuronal circuitry ideal for executing these decisions (Munoz & Wurtz, 1993a-b, 1995a-b). Fixation neurons in the superior colliculus are probably involved in holding fixation at its current focus by inhibiting responses from other parts of the visual field. Saccade neurons are probably involved in disengaging fixation from its current location and moving the eyes to the location of the triggering stimulus. The signals for this disengage operation may also involve other brains structures besides the superior colliculus like the posterior parietal cortex (Andersen, 1989). Fixation is not necessarily coextensive with attention because it is possible for adults (Posner, Walker, Friedrich & Rafal, 1984) and infants (Clohessy, Posner & Rothbart, 1991; Hood, 1993) to attend to a location without necessarily making an eye movement to that location. Additionally, controversy remains about how much overlap there is between the processes that program saccadic eye movements and processes of visual attention (Danckert & Maruff, 1997; Stelmach, Campsall & Herdman, 1997). Nonetheless, I was interested in this work in what guides infants to look at a salient event or object within the first few seconds of its appearance in the visual field. The assumption here is that this looking behavior is a measure of the exogenous orienting of attention.

Nagata and Dannemiller (1996) developed a paradigm for studying this exogenous orienting during early infancy. In particular, they were interested in the extent to which such orienting involves stimulus competition within the visual field. There are many potential objects of attention in typical environments. How does the early visual system resolve the problem of where to look next in the face of such multiple targets? Understanding such behavior may help us to understand better why measures like visual preferences (Fagan & Singer, 1983; Bornstein & Sigman, 1986) and the lengths of visual fixations (Colombo, 1995) can predict cognitive performance in later childhood. Indeed, one suggestion in this regard is that such measures tell us something about the infant's ability to inhibit attention and eye movements to familiar or uninteresting objects in favor of attention to novel or interesting events (McCall & Carriger, 1993). Such inhibition may arise in the neuronal circuits that ultimately determine when and where to look next. I designed these experiments to examine a small piece of this picture; when multiple targets appear in the visual field, where do infants direct their initial fixations and attention?

## EXPERIMENT 1

All of the experiments in this study used the same paradigm. The infant was presented with a display in which many small vertical bars were present. One of these bars was moving. This movement sets this one bar apart from the other bars (a feature ‘‘singleton’’) and usually triggers a quick look in its direction. The important phrase here is ‘‘usually triggers.’’ By adjusting the strength of the motion signal, one can induce a competition between this moving bar (hereafter referred to as the ‘‘target’’) and the other static distractor bars. The goal in these experiments was to test a model of this competition and selectivity in exogenous orienting. To do this, I manipulated the colors and spatial distributions of these distractors. Previous work has shown that infants at approximately three months prefer red patterns to green patterns (Bornstein, 1975; Adams, 1987), so I exploited this preference to manipulate the relative saliences of the objects in the visual field. Pilot work showed that the red distractors appeared to be more salient to the infants at this age than the green distractors (Wagner, 1995).

3.5-month-olds participated in all of these experiments because in prior studies infants at this age have been relatively flexible in shifting their attention from one location to another (Bronson, 1994). Some of the problems in attentional disengagement characteristic of younger infants appear to be on the wane at this older age (Atkinson, Hood, Wattam-Bell & Braddick, 1992; Hood, 1993; Johnson, 1990; Johnson & Tucker, 1996). It is also true, however, that the fixational behavior of infants at approximately this age shows wide individual differences (Bronson, 1991). I also selected this age because the stimulus that triggered exogenous orienting—movement—is one that we have studied extensively at this age (Dannemiller & Nagata, 1995; Roessler & Dannemiller, 1997).

### *Method*

*Participants.* Infants were recruited from birth announcements in a local newspaper. Thirty-five infants were tested. Analyses were conducted on the data from 24 of these infants. The average age of these 24 infants was 100.9 days (range = 95–108 days). Data from the other 11 infants were excluded for the following reasons: prematurity greater than two weeks (n = 3), familial history of color blindness (n = 4), excessive crying, fussiness or inattentiveness (n = 1), birth complication severe enough to necessitate a stay in the intensive care unit (n = 2). Most of these 11 infants provided complete data sets (48 trials). The data from one infant were excluded from the analyses because there were no errors across 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) degrees. The background color of the stimulus field was white, and its luminance was 79.4 cd/$m^2$. The target and distractor bars were 5 deg vertically by 0.75 deg horizontally. These bars were either red or green (see below) 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 2.4 Hz with a peak-to-mean amplitude of 1.0 deg on each trial.

The display was situated at the infant's eye level in a matte black wall. To the infant's right of the display, there was a peephole that an observer used to watch the infant's eye and head movements and to make on-line judgments. The observer used a button box interfaced to a computer to start the trials and to register right and left judgments.

The target bar always appeared in one of two location on each trial: in the middle of the display vertically and either 10 deg to the right or to the left of the center of the display. There were 27 static distractor bars in all of the experiments reported below. The distractors could appear anywhere on the display with the following constraints. Thirteen of the distractors appeared on the same half of the display as the moving target. The remaining 14 distractors 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 distractors 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 24 infants who provided complete data had been randomly assigned to one of two conditions with 12 participants per condition. Infants in the *Prior* conditions saw all 28 of the bars appear on the screen prior to the onset of movement of the target bar. Infants in the *Simultaneous* condition saw all 28 of the bars appear on the screen simultaneously with the onset of movement of the target bar. The purpose of this manipulation was to determine if the presence of all of the bars in the visual field for a short time before the onset of motion had any effect on infants' tendencies to orient to the target. It may be easier to suppress attention to competing objects if they have been present in the visual field for some time before the stimulus (rapid movement) designed to produce exogenous orienting appears. Additionally, the colors of the bars may exert a measurable effect on orienting only after they have been present in the field for some time.

The period of time for which infants in the Prior condition saw all of the bars on the display prior to the start of the movement was not controlled, but ranged from approximately 0.5 sec to 4.0 sec across trials. This period depended simply on how long it took the observer to get the infant's attention back to the center of the screen after a trial had ended. After a trial ended, there was a very brief period of approximately 0.25 sec before the computer displayed all of the bars for the next trial. Once the observer had the infant's attention centered on the blue flashing bar, she began the next trial which removed the centering bar and caused one of the bars to start oscillating, so these bars were visible for varying lengths of time for each infant and across trials.

The infants in the Simultaneous condition saw all of the bars appear on the display simultaneously. As soon as all of the bars appeared one of them started to move. These bars appeared from a blank field set at the background luminance as soon as the blue centering stimulus was removed. The Simultaneous condition was most like the conditions typically presented in visual search tasks with adults in which the target and distractors appear suddenly from a blank field. The only difference between the Simultaneous and Prior conditions from the point of view of the infant is that all of the bars appeared during the intertrial interval in the Prior condition while in the Simultaneous condition, these bars were absent from the field. The only significant difference between the data from the Prior condition and the data from the Simultaneous condition was that infants tended to do slightly more orienting toward the target in the Prior condition, but this difference was not critical to the major arguments presented below.

The other variables were manipulated within subjects. There were a total of 48 trials presented to each infant. There were six different trial types comprising a 2 × 2 factorial design plus two additional conditions. The two additional conditions were homochromatic trials in which all of the bars on the display either were red, or all of the bars on the display were green. The 2 × 2 factorial design comprised two moving target colors, 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 distractors* 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 the display opposite to the moving target were red and the remaining three bars were green. On the other side of the display in this contralateral condition this proportion of red and green bars was flipped. Thus, on contralateral trials, 11 of the 14 putatively higher salience, red bars on the display were on the side of the display opposite to the side with the moving target, setting up the conditions for competition. 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 putatively weaker salience, green distractors. These manipulations generated data that were then fitted using the competition model described below. The percentage of correct judgments should be higher when most of the red bars fall on the same side as the moving bar. A schematic of the display is shown in Figure 1.

These trial types were randomly ordered within a block of six trials, and eight such blocks were presented to each infant for a total of 48 trials. The infant was seated in an infant seat approximately 50 cm from the display. Prior to the start of each trial a small blue flashing bar appeared in the center of the screen to attract the infant's attention. The observer also used various noise making toys to encourage the infant to orient to the display. 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.

Data were collected using the Forced-Choice Preferential Looking Technique (FPL; 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,

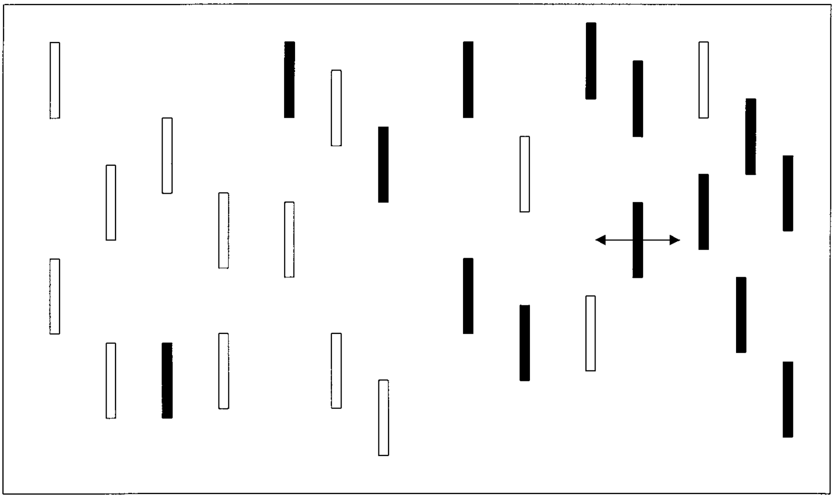

**FIG. 1.** Example of a heterochromatic display. In this example, the moving target bar is indicated by the arrows. Red bars are drawn as solid bars, green bars are drawn as open bars. This is an example of an ipsilateral trial with a red target with a ratio of 11:3 red:green on the side ipsilateral to the target. The ratio is the inverse on the side contralateral to the target.

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 onset of the motion stimulus. 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 1.5 to 2 s (see below), so I feel confident that this measure gives us information about orienting during the initial second or two after a strong motion stimulus appeared. 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.

## *Modeling*

I modeled the data using signal detection theory (Green & Swets, 1966) and a winner-take-all rule. Similar models have been used to account for visual search behavior with adults (Palmer, Ames & Lindsey, 1993) and visual saliency effects (Koch & Ullman, 1985). The goal of the modeling was to capture the competition effects observed in the data. There were several assumptions in the model:

1. Each object in the visual field produces an internal response the strength of which determines its likelihood of capturing attention initially after its appearance.
2. For chromatic displays, the strength of the internal response may depend on the color of the object.
3. Moving objects produce stronger internal responses than static objects.
4. These internal response are perturbed by noise. As in most signal detection models, I used Gaussian noise with a variance of 1.0.
5. The dominant direction of regard on each trial during the first few seconds following the appearance of the objects in the visual field or following the onset of motion is toward the object that produces the largest internal response (winner-take-all model or maximum-of model; Koch & Ullman, 1985; Palmer *et al.,* 1993).

Signal detection theory provides a natural way to model the effects of attention on detection. Sensitivity to the oscillating motion is limited by several factors: a) internal noise in the infant's visual system, b) temporary distraction by factors external to the experimental display, and c) signals from other objects (bars) in the visual field that compete with the oscillating bar for the infant's attention. Signal detection theory provides a way to incorporate these effects within one model. Noise is incorporated in the model by perturbing the internal response to each bar in the visual field by a random variable. Notice that this variance is really the summed effect of various sources of noise both internal and external to the infant. Noise sources include things like the random dropping of action potentials, temporary distractions by factors external to the stimulus display, and most importantly, variance in the responses to the bars caused by inhomogeneities in processing characteristics like color and contrast across the infant's visual field. In other words, the signal detection model incorporates these known but unparameterized stimulus effects into its noise term with all of the other unknown sources of noise. Further experimentation would be necessary to estimate these effects (e.g., retinal differences in the transduction of color, infants' tendencies to look at nearby contours over distant contours) and to remove them from the noise parameter in the model.

Model fitting proceeded in two steps. First, Monte Carlo simulations were used to estimate sensitivities to the moving target under the various stimulus conditions in the experiments with 2000 trials per condition. In other words, the simulations included trials in which all 28 of the objects in the field were red or all 28 were green (two homochromatic conditions), and trials in which the ratio of red to green bars on one side of the visual field took on values of 8:6, 11:3, and 13:1 with the inverse ratios on the other side of the display (four heterochromatic conditions for any ratio). The model had three free parameters: a) the mean of the normal distribution from which the internal responses to red moving objects were randomly sampled, b) the mean of the normal distribution from which the internal responses to green moving objects were randomly sampled, and c) the mean of the distribution from which the internal responses to static green distractors were randomly sampled. The mean of the distribution from which the internal responses to static red dis-

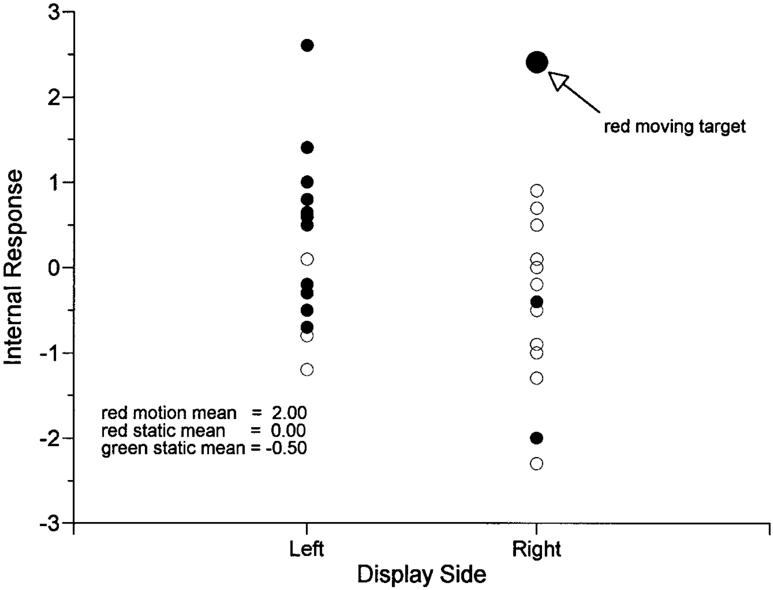

**FIG. 2.** Schematic of model simulation of a trial. In this example, the internal response to each of the 28 bars in the field is indicated by the symbol's ordinate. Fourteen of the bars were on the left side of the display, and 14 were on the right side of the display. Solid symbols represent the responses to red bars, and open symbols represent the responses to green bars. This is a heterochromatic trial with the majority of the red distractors contralateral to the moving target. The red:green ratio on this trial was 11:3 contralaterally, and 3:11 ipsilaterally. The internal response to the red moving target was drawn from a normal distribution with a mean of 2.0, the internal responses to the 14 green static distractors were all drawn from a normal distribution with a mean of $-0.50$, and the internal responses to the 13 static red distractors were all drawn from a normal distribution with a mean of 0.0. All these distributions had variances of 1.0. The internal response to the moving red target is shown by the large symbol. The model predicts orienting to the side contralateral to the motion on this trial because the largest internal response was to a static red distractor contralateral to the moving target. This trial would count as an error in the Monte Carlo simulations.

tractors were randomly sampled was set at 0.0 without loss of generality. On each simulated trial, a correct response was recorded if the maximum internal response across all 28 objects on the screen occurred on the same side as the moving target. An incorrect response was recorded if the maximum occurred on the side of the screen opposite to the moving target. This is the sense in which the model uses a winner-take-all or a maximum-of rule to generate a binary (left vs. right), forced-choice decision on each trial.

Figure 2 shows a simulated heterochromatic trial in which the moving target was red and 11 of the 14 bars on the side contralateral to the moving target were red (and 3 were green) while 11 of the 14 bars on the side of the screen ipsilateral to the moving target were green while the other three bars (one of which was the red moving target) were red. The mean of the red moving target distribution was assumed to be 2.0, and the mean of the green static distractor distribution was assumed to be −0.5. Recall that the mean of the red static distractor distribution was set to 0.0 by convention. Each point represents the initial internal response to one of the 28 objects on the display. The ordinate represents this internal response. Fourteen of these internal responses arise from objects on the left side of the display, and fourteen of them arise from objects on the right side of the display. The internal responses to red objects are represented with solid symbols, and the internal responses to green objects are represented with open symbols. The moving object is represented by the larger solid symbol on the right. This example shows that the largest internal response happened by chance to arise on this trial from a static red distractor on the side of the screen contralateral to the moving target. The model would predict that orienting would be to the side of the display contralateral to the movement on this trial resulting in an error (assuming that correct trials are referenced to the side with the moving target).

With the mean of the red distractor distribution set at 0.0 on each simulated trial, the mean of the green distractor distribution was allowed to take on values from −1.5 to +1.5. In other words, I did not force the red distractors to be more salient than the green distractors, but rather I let the data determine their relative saliences. Similarly, the mean internal responses of the red and green moving target distributions were allowed to vary from 0.75 to 3.0, so I did not force the red moving targets to be more salient than the green moving targets. I did force the moving targets to be more salient than the static bars because the mean percentages of correct judgments referenced to the location of the moving target were always above chance (50%).[1]

These parameter values were combined factorially to generate predicted percentages of correct judgments in all of the conditions across the four experiments reported below. In other words, for each combination of the three free parameters, and for each stimulus configuration (e.g., red homochromatic trials, 11/3 red/green split on heterochromatic trials with a red moving target), 2000 trials were simulated to estimate the mean percentage of correct judgments expected using this model. The observed data were then fitted by searching through all of the parameter combinations for that particular combination that produced predicted percentages of correct judgments closest in a least squared error sense to the observed data. The fits were done against the percentages of correct judgments averaged across subjects in each condition rather than against the data from individual subjects. The data from individual subjects were based on eight trials per condition and were likely to be highly

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[1] The validity of these various constraints can always be checked by making sure that none of the best fits ‘‘bumped into’’ the extreme values allowed for a parameter. None of the parameter estimates reported here fell at a boundary value on any parameter for any set of data.

variable because of binomial sampling error. The dashed lines in each of the figures below show the best fits of the model to the observed data.

### *Results and Discussion*

The primary dependent variable was the percentage of correct judgments in each of the six conditions. The graphs below report these mean percentages of correct judgments. 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 sample sizes (Thorpe, Trehub, Morrongiello & Bull, 1988). The percentage of correct judgments for each infant in each of the six conditions was based on eight trials—a situation that led occasionally to perfect percentages (100% correct) in a given condition. The $d'$ transformation was implemented by taking the number correct out of a total of eight possible in each condition, adding 0.5 to it, dividing the result by 9 and determining $d'$ based on this percentage.[2] These percentages were then converted into z-scores using a standard (0; 1) cumulative normal distribution, and this z-score was multiplied by the square root of 2 to convert it into a $d'$ measure of sensitivity appropriate to a two-alternative forced choice procedure. The $MS_{\text{error}}$ values reported below are for the $d'$ measure. Differences between the mean percentages of correct judgments in various conditions reported below may be converted to estimated effect sizes by first converting these means into $d'$ values as described above, and then using the reported $MS_{\text{error}}$ values. In all of the experiments reported below, the conclusions are the same when the ANOVA's are conducted on the raw percent correct measures.

Figures 3 and 4 show the average percentage of correct judgments in each condition for the Simultaneous and Prior groups, respectively. Chance behavior with respect to the moving target in this task is 50%, and performance was well above chance under all conditions. There were, however, clear effects of the spatial distribution of the distractors on performance. For both red and green moving targets and in both groups infants were less likely to orient toward the moving target when most of the red bars were contralateral to the movement. This is shown by the dip in the percentage of correct judgments between the ipsilateral and contralateral conditions.

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[2] There is no $d'$ value that corresponds to 100%. The calculation described sets 100% to 94.4% and computes $d'$ based on that value. Fifty percent correct remains at 50% correct ($d' = 0$) after this transformation. This type of correction for perfect scores is common in the signal detection literature. Notice that this transformation preserves the ordering of scores, and the variances are more likely to be homogenous after the $d'$ transformation. In other words, data based on the raw number or percentage correct will have greater variance near 50% correct than at either extreme, but data transformed into $d'$ will have variance that is independent of the mean $d'$ value.

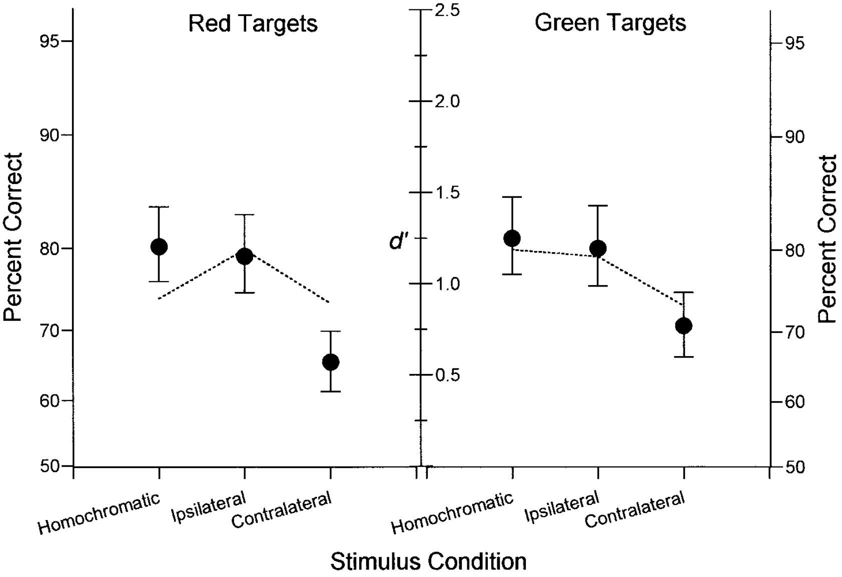

**FIG. 3.** Mean percent correct for infants in the Simultaneous group from Experiment 1. Chance is 50%. Data for red targets are shown on the left by the symbols, and data for green targets are shown on the right by the symbols. Dashed lines are best fits from the model described in the Discussion section. Error bars are ±1 SEM based on the appropriate ''subject × variable'' interaction error terms from the ANOVAs (see Loftus & Masson, 1994).

These observations were confirmed through an ANOVA on the $d'$ data. The data from the two homochromatic conditions were analyzed separately from the data from the 2 × 2 factorial, heterochromatic conditions. The ANOVA on the homochromatic data showed no effect of target Color (red vs. green) nor an effect of the Group variable (Prior versus Simultaneous). The percentage of correct judgments for red moving targets, $M = 81.2\%$, was similar to that for green moving targets, $M = 82.3\%$. The two groups also showed comparable mean percentages of correct judgments on these homochromatic trials ($M = 80.7\%$ versus 82.8% for Simultaneous and Prior groups, respectively). Sensitivity for the moving target was the same whether the moving bar was red or green when it was surrounded by like-colored static distractors.

The analysis of the heterochromatic trial data showed a different picture. This ANOVA used the between-subject variable of Group (*Prior* vs. *Simultaneous*) and the within-subject variables of target Color (red vs. green) and Distribution (most of the red distractors ipsilateral to motion vs. most of the red distractors contralateral to motion). There was a main effect of Group, $F(1,22) = 6.46$, $p = .019$, $MS_{\text{error}} = 0.81$). Sensitivity was higher for the moving target when all of the bars had been present for some time in the visual field (Prior condition $M = 83.3\%$) than when all of the bars appeared

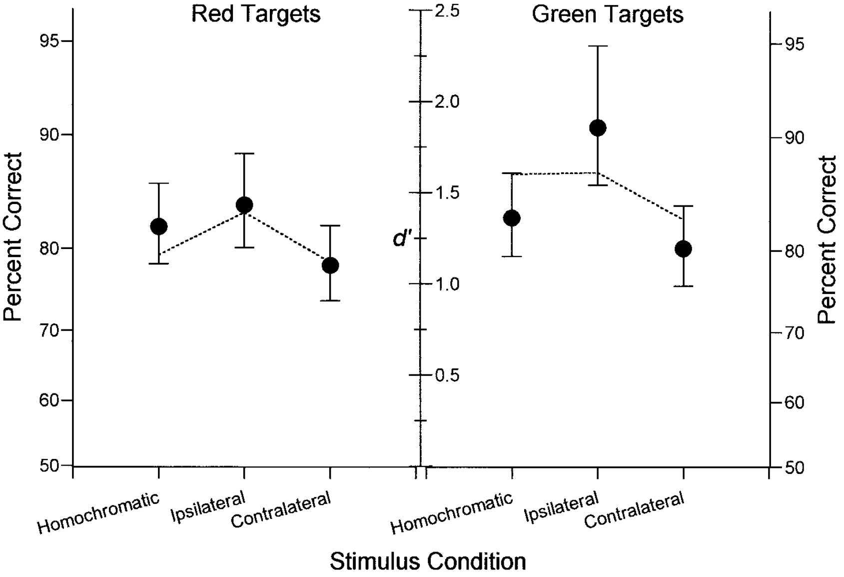

**FIG. 4.** Mean percent correct for infants in the Prior group from Experiment 1. Other conventions are the same as were shown in Figure 1.

simultaneously with the onset of motion (Simultaneous condition *M* = 73.9%). This cannot reflect a speed-accuracy tradeoff because the average latency to a judgment in the Prior condition was actually less (*M* = 1.83 s) than it was in the Simultaneous condition (*M* = 2.11 s). Sensitivity may be higher for this motion when infants have had a chance to see the distractors for a brief time before the target starts to move than when the appearance of all of the bars in the visual field coincides temporally with the onset of movement of the target.

This ANOVA also revealed a significant main effect of the Distribution variable, $F(1,22) = 10.56$, $p = .004$, $MS_{\text{error}} = 0.54$). When most of red distractors were ipsilateral to the moving bar, infants oriented correctly on 83.6% of the trials. In contrast, when most of red distractors were placed contralaterally to the moving bar, infants oriented correctly on 73.7% of the trials. This gives an estimated effect size of $d = 0.46$ for this Distribution effect.[3] In other words, sensitivity when most of red distractors were ipsilateral to the movement was shifted approximately one-half of a standard deviation higher than sensitivity when these red distractors were contralateral to the movement. There was no significant interaction of the Group variable or of target Color with this Distribution variable. These data show that sensitivity

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[3] The effect size measure *d* reported here should not be confused with the sensitivity measure *d′*.

to movement is affected by the spatial distribution of static, colored objects also in the visual field. One interpretation of this result is that it reflects a competition between this movement and other objects in the visual field for attention. This competition was selective; sensitivity to movement was affected by the colors of these additional objects and not just by their mere presence. Color can interfere with attention to movement, and red does so more effectively than green.

## EXPERIMENT 2

The main goal in the second experiment was to replicate the ipsilateral/contralateral distribution effect observed in Experiment 1 on another sample of infants. The replication included a minor stimulus variation by increasing the luminance contrast of the green bars in the visual field. It may be possible to make the green bars more salient relative to the red bars by increasing the luminance contrasts of the green bars.

### Method

*Participants.* Twenty-six infants were tested. Analyses were conducted on the data from 24 of these infants. The average age of these 24 infants was 101.0 days (range = 90–111 days). Data from the other 2 infants were excluded because they were born more than two weeks prematurely. These two preterm infants both completed 48 trials.

*Apparatus and stimuli.* The apparatus and stimuli were identical to those used in Experiment 1 with one exception. The luminances of the green bars in the display were decreased to 12.2 cd/m$^2$. Because the bars on the screen were darker than the white background, this increased the luminance contrasts of the green bars to 73% while the luminance contrasts of the red bars remained at their prior levels of 66%. The added luminance contrast of the green bars was expected to increase their salience making them compete more effectively with the red distractors to draw attention away from the moving target bar. Because this experiment served primarily as a replication of Experiment 1, I did not alter the balance between red and green luminances too drastically.

*Design and procedure.* The design and procedures were exactly the same as in the first experiment. Twelve of the infants saw all of the objects appear in the visual field simultaneously with the onset of the target bar movement. The other twelve infants saw all of the bars appear in the field for approximately two seconds prior to the onset of target bar movement.

### Results and Discussion

Figures 5 and 6 show the average percentage of correct judgments in each condition for the Simultaneous and Prior groups, respectively. The data in this sample replicated the prior effect. For both red and green moving targets and in both groups sensitivity in detecting the moving target was lower when

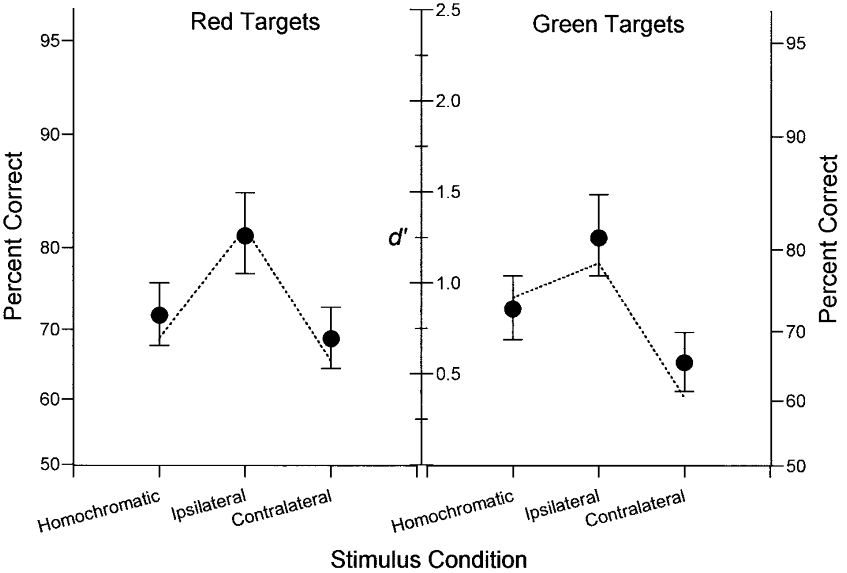

**FIG. 5.** Mean percent correct for infants in the Simultaneous group from Experiment 2. Other conventions are the same as were shown in Figure 1.

most of the red distractors were contralateral to the movement. This is shown by the dip in the percentage of correct judgments between the ipsilateral and contralateral conditions.

The ANOVA on the *d′* homochromatic data showed a main effect the Group variable (*Prior* versus *Simultaneous*), $F(1,22) = 6.09$, $p = .022$, $MS_{\text{error}} = 0.75$. Performance was slightly better when all of the bars were present in the visual field for a brief period before the onset of movement ($M = 79.0\%$) than when all of the bars appeared simultaneously with the onset of target movement ($M = 73.6\%$). This main effect was not significant in the first experiment, although the means were in this same direction. This may indicate a lack of power to detect this small effect consistently.

The analysis of the data from the heterochromatic trials showed a replication of the red/green distribution effect observed in Experiment 1. The effect of the Distribution variable was significant, $F(1,22) = 10.35$, $p = .004$, $MS_{\text{error}} = 0.76$. When most of red distractors were ipsilateral to the moving bar, the mean percentage of correct judgments was 81.0%. In contrast, when most of red distractors were placed contralaterally to the moving bar, this percentage dropped to 69.5%. This gives an estimated effect size of $d = 0.46$ for this Distribution effect. Experiment 1 yielded this same effect size. There was no main effect of the Group variable although the means were in the same direction as they had been in Experiment 1. There also was no main effect

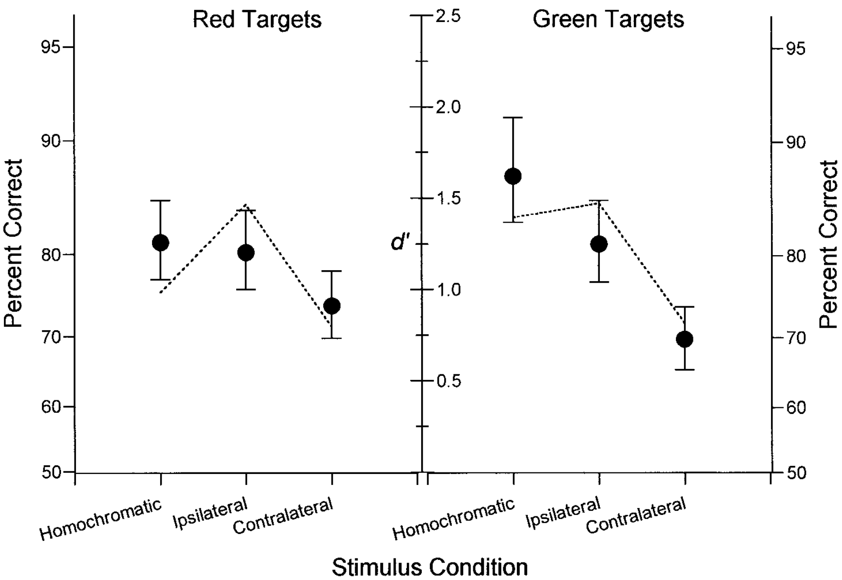

**FIG. 6.** Mean percent correct for infants in the Prior group from Experiment 2. Other conventions are the same as were shown in Figure 1.

of the Color of the moving bar, and neither the Group variable nor the target Color variable interacted with the Distribution variable.

To determine if there was any evidence that the luminance contrast manipulation affected the magnitude of the ipsilateral-contralateral performance difference, I combined the samples from Experiments 1 and 2 and conducted an ANOVA with Experiment (1 vs. 2) as a between subject variable. This ANOVA showed the spatial distribution affect present in both studies, $F(1,44) = 24.61$, $p < .001$, $MS_{\text{error}} = 0.44$). There was no main effect of the Experiment variable, and this variable did not interact significantly with the spatial distribution variable, $F(1,44) = 0.182$, $p = .672$). This combined analysis showed that the spatial distribution of the red and green distractors had similar effects in both experiments despite the luminance contrast difference in the green distractors between Experiments 1 and 2.

These data replicated the main features of the data from Experiment 1 in regard to competition between motion and color. Although the luminance contrast of the green bars was slightly higher in this experiment, sensitivity was still affected by the spatial distribution of red and green objects in the visual field. In particular, when most of red distractors were contralateral to the only moving object in the visual field, sensitivity to this movement was less than when these red distractors were ipsilateral to the moving bar—the same effect found in Experiment 1. The most plausible interpretation of these effects is that sensitivity to the movement is being affected by attention. Attention to red bars contralateral to the moving bar makes it less likely that infants will notice or orient to the movement.

It is possible that it is not the color difference that drives the selective failures to orient to the moving stimulus, but perhaps a brightness difference. To rule out brightness differences as the source of this selectivity it would be necessary to test for the ipsilateral-contralateral effect at many red:green luminance ratios closely spaced around the suspected brightness match. Nonetheless, it is probably the case that color per se is playing a role in this selectivity for several reasons. First, infants at this age can discriminate red from green (Hamer, Alexander & Teller, 1982). Second, the luminance ratio that creates a brightness match between red and green for adults also probably yield a brightness match for infants at this age (Maurer, Lewis, Cavanagh & Anstis, 1989), so the conditions in Experiment 1 were likely to have produced reasonably good brightness matches between the red and green targets. Third, I took care to eliminate infants with a familial history of color blindness from the data analysis. Such a deficit, if present could have rendered the brightnesses of the red and green bars substantially different for these infants. Fourth, the direction of the selective effects was predicted a priori based on data from other paradigms showing similar preferential looking to red and green patterns (Adams, 1987; Bornstein, 1975). Fifth, a 25% change in the luminance ratio between the red and green bars in Experiment 2 did not reduce or increase the size of the ipsilateral-contralateral effect observed in Experiment 1. For these reasons, although it remains a possibility that the stimulus selectivity effects demonstrated here might be caused by brightness differences between the two classes of objects, it is likely that color is playing a role as well.

## EXPERIMENT 3

The locations of the red bars affected sensitivity to the moving target in the first two experiments. The competition model described above makes the prediction that if the red bars are more salient than the green bars, then increasing the proportion of red bars contralateral to the target should produce a larger interference effect and decreasing this proportion should produce a smaller interference effect.

### *Method*

*Participants.* Fifty-eight infants were tested. Analyses were conducted on the data from 42 of these infants. The average age of these 42 infants was 105.0 days (range = 98–115 days). Data from the other 16 infants were excluded for the following reasons: fussiness or inattentiveness (n = 2), prematurity (n = 5), birth complications (e.g., ICU stay, n = 4), familial history of color blindness (n = 4), 100% correct (n = 1). I increased the sample size in this experiment because power calculations based on the effect

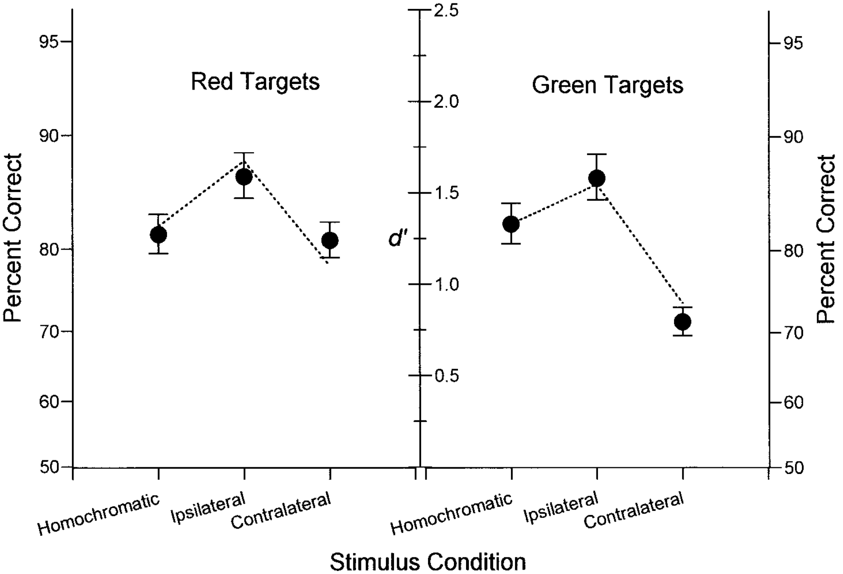

**FIG. 7.** Mean percent correct for infants in the 13:1 red:green ratio group from Experiment 3. Other conventions are the same as were shown in Figure 1.

sizes observed in Experiments 1 and 2 dictated larger samples to detect a predicted interaction.

*Apparatus and stimuli.* The apparatus and stimuli were identical to those used in Experiment 1. The contrasts of the red and green bars against the white background were once again set to equality because the manipulation of this contrast in Experiment 2 produced no detectable effect.

*Design and procedure.* All of the presentations in this experiment used the Simultaneous method from Experiments 1 & 2. In this method, all 28 of the bars appeared in the visual field simultaneously with the onset of motion of the target bar.

Infants were assigned randomly to two conditions with the final sample comprising 21 infants in each of these conditions. In the first condition (low imbalance) the ratio of red to green bars on one side of the field was 8:6 while on the other side of the field it was the inverse of this or 6:8. This represents only a slight imbalance in the spatial distribution of the red and green bars in the visual field. There should have been little if any effect of the spatial distribution variable (ipsilateral versus contralateral) in this condition. In the other condition (high imbalance), these ratios were set to 13:1 and 1:13 representing a strong imbalance. The effect of the spatial distribution variable in this condition should have been at least as strong as the effect observed in Experiments 1 and 2 in which the imbalance was 11:3.

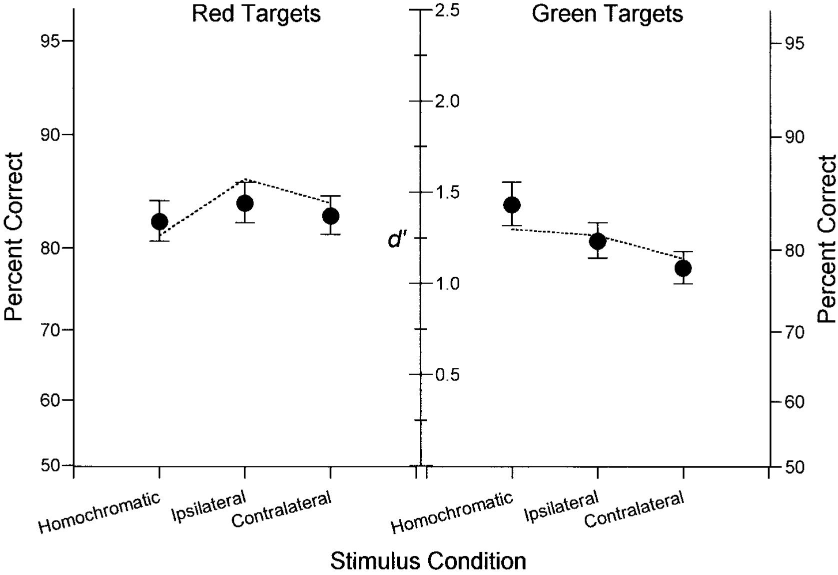

**FIG. 8.** Mean percent correct for infants in the 8:6 red:green ratio group from Experiment 3. Other conventions are the same as were shown in Figure 1.

### *Results and Discussion*

Figures 7 and 8 show the average percentage of correct judgments in each condition for the high imbalance and the low imbalance groups, respectively. The ANOVA on the data from the homochromatic trials showed no main effects of the Group variable (low vs. high imbalance) nor for the target color. One would not expect an effect of the Group variable in the homochromatic data because this distribution variable does not affect the display on homochromatic trials. The two groups are exact replicates of each other on these homochromatic trials. Once again, the color of the moving target did not exert an effect on performance when all of the objects in the field were the same color.

The analysis of the data from the heterochromatic trials showed a replication of the red/green distribution effect observed in Experiments 1 and 2. The effect of the Distribution variable was significant, $F(1,40) = 8.53$, $p = .006$, $MS_{\text{error}} = 0.35$), although this main effect was qualified by an interaction of the distribution variable with the degree of imbalance variable (see immediately below). There was also an effect of target Color with performance being slightly better with red moving targets than with green moving targets, $M =$ 83.9% and 79.3%, respectively, $F(1,40) = 4.95$, $p = .032$, $MS_{\text{error}} = 0.32$). This effect of the color of the moving target was not significant in the comparable conditions of Experiments 1 and 2. This target color effect also emerged in

Experiment 4 below with an even larger sample size, so its absence in Experiments 1 and 2 may have been because of lower power in those experiments.

The competition model leads to the prediction of an interaction between the degree of imbalance of the red green distractors (low imbalance, 8:6 versus high imbalance, 13:1) and the spatial distribution variable (majority of the red distractors ipsilateral to the movement versus majority of red distractors contralateral to the movement). This interaction was significant, $F(1,40) = 5.47$, $p = .024$, $MS_{\text{error}} = 0.34$). As shown in Figure 8 for the low imbalance group, there was little effect of the spatial distribution variable with performance under ipsilateral conditions being approximately equal to performance under contralateral conditions as predicted (effect size $d = 0.08$). In contrast, in the high imbalance group (Figure 7), performance under contralateral conditions was consistently worse than performance under ipsilateral conditions as it had been in Experiments 1 and 2. The effect size of this spatial distribution variable in this high imbalance group was $d = 0.80$. This effect size was larger than the effect size of 0.46 observed in both of the first two experiments. In other words, when the degree of imbalance of the red/green distractor distribution was increased from 11:3 to 13:1, the magnitude of the ipsilateral-contralateral performance difference increased as predicted. When the degree of this imbalance was decreased to 8:6, the magnitude of the ipsilateral-contralateral performance difference decreased approximately to zero as predicted.

## EXPERIMENT 4

The data from Experiment 3 once again showed that sensitivity to movement is higher when most of the red objects in the visual field are in the general vicinity of the moving object than when these red objects are located away from the position of the moving object. There was also a slight advantage overall on these trials for detecting red moving targets over green moving targets. I wanted to replicate both of these effects and to examine more closely how the degree of imbalance of the spatial distribution of red and green distractors affects sensitivity to the movement. I therefore repeated the 13:1 red:green ratio from Experiment 3 and the 11:3 ratio from Experiments 1 and 2 with larger samples.

There was a second reason for examining these two closely spaced ratios. It is possible that when the red:green ratio reaches its extreme value of 13:1, there may be a color contrast effect that works against the ipsilateral vs. contralateral effect. For example, on trials with a red moving bar when the ratio of red to green bars on the target side is 1:13, this red target is surrounded by 13 nearby green distractors potentially making it more salient. Although such contrast effects might also operate to some extent in the 3:11 condition, one would expect them to be weaker. If these color contrast effects operated, then one would expect to see an interaction between target color and the spatial distribution variable in the 13:1 condition.

## *Method*

*Participants.* Eighty-four infants were tested, and the data from 64 of these infants are reported below. The average age of these 64 infants was 103.2 days (range 92–113 days). The data from the additional 20 infants were excluded for the following reasons: strong right side bias (n = 1), prematurity (n = 11), familial history of color blindness (n = 5), birth complications (n = 2), 100% correct (n = 1).

*Apparatus and stimuli.* These were the same as in the prior experiments.

*Design and procedure.* All of the presentations were done using the Simultaneous method as described above. Half of the infants were tested in the 11:3 imbalance condition (n = 32), and the other half were tested in the 13:1 imbalance conditions (n = 32).

## *Results and Discussion*

The data from the homochromatic trials in both groups showed no significant effects of the distribution ratio, the target color or the interaction between these two variables. Once again, the distribution ratio variable is meaningless for homochromatic trials making the two groups replicates of each other on these trials. As in prior experiments, the color of the moving target exerted no significant effect on performance when all the bars in the field were the same color. The data from this experiment are shown in Figures 9 and 10.

The analysis of the heterochromatic trials data showed only two significant effects. The color of the moving target exerted a significant effect, $F(1,62) = 8.27$, $p = .006$, $MS_{\text{error}} = 0.41$. Red moving targets on heterochromatic trials produced higher percentages of correct judgments than green moving targets, M = 86.3% and 80.6%, respectively. This is a replication of the effect observed in Experiment 3. The Distribution variable once again produced a significant effect, $F(1,62) = 6.14$, $p = .016$, $MS_{\text{error}} = 0.37$. Performance was better with ipsilaterally placed red distractors, M = 85.5%, than with contralaterally placed red distractors, M = 81.3%. The interaction of the ratio variable with this spatial distribution variable was not significant. The magnitude of the ipsilateral-contralateral difference was comparable in the two groups.

Inspection of Figures 9 and 10 shows that the magnitude of the ipsilateral-contralateral difference in performance appears to be smaller for red targets than for green targets pulling the average ipsilateral-contralateral difference to a value somewhat lower than it had been in the prior experiments. This target color by spatial distribution interaction did not reach significance ($p = .122$). Nonetheless, the same trend was present in Experiment 3 with 13:1 ratio data suggesting that when there are differently colored objects in the visual field, not only do the red static objects exert a stronger affect on orienting than green static objects, but the magnitude of this effect is somewhat stronger when the moving target is the lesser preferred, green color. I

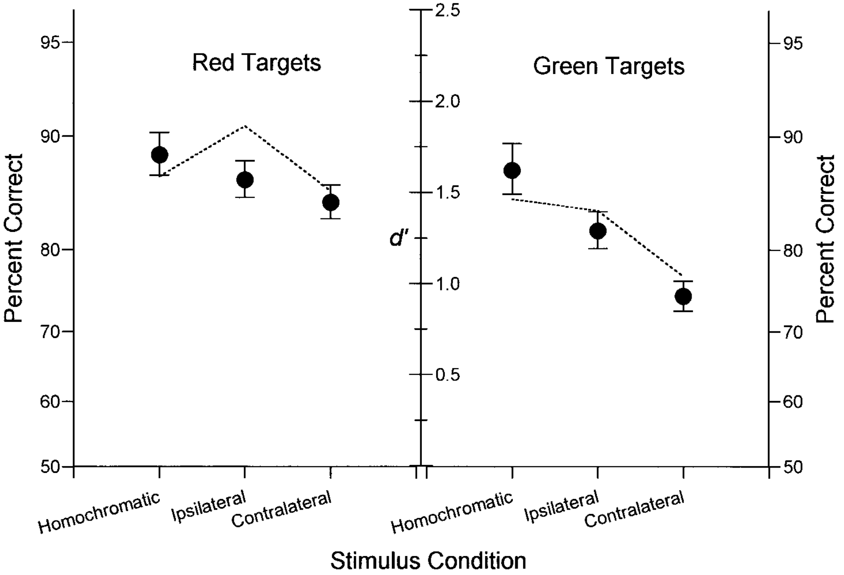

**FIG. 9.** Mean percent correct for infants in the 11:3 red:green ratio group from Experiment 4. Other conventions are the same as were shown in Figure 1.

tested the significance of this effect with more power by combining the samples from Experiments 3 and 4 (total n = 53). The first test used the heterochromatic data from Experiments 3 and 4 collected with the 13:1 red:green ratio. These infants received exactly the same stimulus conditions, so they represented replication samples. This ANOVA showed no main effect of experiment and no interaction of experiment with either the target color variable or the spatial distribution variable. As in Experiment 3, however, the magnitude of the ipsilateral-contralateral performance difference remained smaller for red targets than for green targets, but the *p* value (.12) fell short of significance.

Finally, I combined all of the heterochromatic data from Experiments 3 and 4 using the higher red:green ratios (13:1 and 11:3) and using this ratio as a between-subject variable in the analysis (total n = 85). The main effect of color (higher sensitivity to red targets) found in the separate experiments, $F(1,83) = 11.56$, $p = .001$, $MS_{\text{error}} = .38$, was present in the combined sample. I also found the spatial distribution effect present in the prior analyses, $F(1,83) = 12.50$, $p = .001$, $MS_{\text{error}} = .41$, with sensitivity being higher when most of the red distractors were ipsilateral to the moving target. The interaction between target color and the spatial distribution variable that was evident as a trend in the separate experiments now reached significance, $F(1,83) = 4.03$, $p = .048$, $MS_{\text{error}} = .351$). The magnitude of the ipsilateral-contralateral performance difference was smaller with red targets than it was with green targets

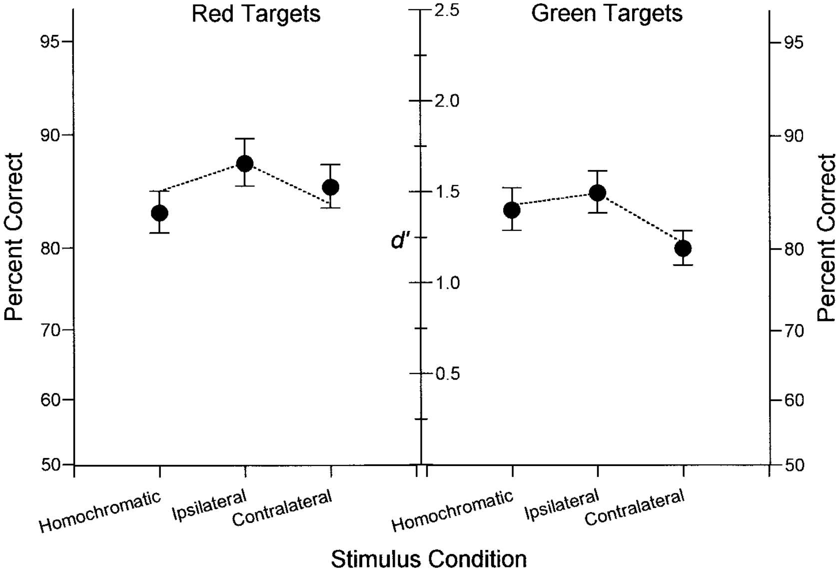

**FIG. 10.** Mean percent correct for infants in the 13:1 red:green ratio group from Experiment 4. Other conventions are the same as were shown in Figure 1.

in this combined sample. The estimated effect size with the red targets for this difference was *d* = 0.22. This estimated effect size was *d* = 0.78 for green targets. In other words the spatial imbalance of the red and green distractors exerted a significantly larger effect when the moving target was green (less salient) than when it was red (more salient). Sensitivity to the moving target is a combination of its movement per se, its color, and the spatial distribution of other differently colored objects in the visual field. The average response latency of these judgments was approximately 2 seconds which shows that these attentional effects on sensitivity to movement develop very quickly after the appearance of objects in the visual field or after one of the objects begins to move.

## RESULTS OF THE MODELING ANALYSES

Table 1 shows the best-fitting parameter estimates from all of the experiments using a least squared error criterion between the observed mean $d'$ values and the model's predicted mean $d'$ values. Note that estimates for a given parameter should not vary substantially across experimental conditions because they represent the mean internal responses for single items (moving or static, red or green). It was the number of such items, their colors and their spatial distributions that were varied in these experiments to test the predictions of the model. The one exception to this statement is perhaps that the estimates from the two conditions in which the bars were displayed prior

TABLE 1
Parameter Estimates from All Experiments

| Experiment | Sample *n* | Ratio[1] | Onset | Red motion | Red distractor | Green motion | Green distractor |
|---|---|---|---|---|---|---|---|
| 1 | 12 | 11:3 | Sim[2] | 2.00 | 0.00[3] | 2.00 | −0.25 |
| 1 | 12 | 11:3 | Prior | 2.25 | 0.00 | 2.50 | −0.25 |
| 2 | 12 | 11:3 | Sim | 1.75 | 0.00 | 1.50 | −0.50 |
| 2 | 12 | 11:3 | Prior | 2.00 | 0.00 | 2.00 | −0.50 |
| 3 | 21 | 13:1 | Sim | 1.50 | 0.00 | 1.00 | −0.50 |
| 3 | 21 | 8:6 | Sim | 2.50 | 0.00 | 2.25 | −0.50 |
| 4 | 32 | 11:3 | Sim | 2.75 | 0.00 | 2.25 | −0.25 |
| 4 | 32 | 13:1 | Sim | 2.00 | 0.00 | 1.50 | −0.25 |
| All | $N = 154$ | — | — | 2.09 | (0.00) | 1.88 | −0.38 |

[1] Red:Green bars on one side of the display for heterochromatic trials. The ratio was inverted on the other side of the display.

[2] Sim = target and distractors appeared simultaneously with onset of motion; Prior = target and distractors appeared prior to onset of motion.

[3] Constrained to be 0.00.

to the start of the trial might be expected to differ somewhat from those obtained when all of the bars appeared simultaneously with the onset of motion. This did not appear to be the case because the parameter estimates from these two conditions were very similar to the estimates from the other six conditions.

Examination of these parameter estimates shows that the mean internal response to the static green distractors was consistently lower by approximately 0.4 standard deviations than the mean internal response to the red static distractors despite the fact that it was allowed to take on values higher than the fixed value of 0.0 for the red distractors. This mean difference represents just under two steps of the parameter variation that was used in the Monte Carlo simulations. This consistency reflects the fact that in 14 of the 14 experimental conditions for red or green targets involving red:green imbalance ratios of 11:3 and 13:1 the mean percentage of correct judgments was higher when most of red distractors were ipsilateral to the moving target than when they were contralateral. It is worth noting that even in the condition in which the ratio of red to green bars on one side of the screen was 8:6, the parameter estimate for the mean of the green distractor distribution was still −0.50. The consistently negative estimates for the mean of the internal responses to the green static bars relative to the mean for the red static bars confirm prior work using a different paradigm and showing that infants at this age prefer red to green (Bornstein, 1975; Adams, 1987).

Finally, notice in Table 1 that the mean of the distribution for the red moving bar was approximately 0.2 standard deviations above the mean of the distribution for the green moving bar. This was within the minimum parameter variation (0.25 z units) used in the Monte Carlo simulations. There was less consistency in the relationship between these means for the red and green moving bars than there was in the relationship between the means for the red and green static distractors. For five of the eight conditions listed in Table 1, the estimated mean of the red moving target distribution was larger than the estimated mean of the green moving target distribution, for two conditions these estimated means were equal, and for one of the conditions the estimated mean of the green moving target distribution was larger than the estimated mean of the red moving target distribution. Recall that in both Experiments 3 and 4 there was a main effect of the color of the moving bar on performance, but this main effect was missing in Experiments 1 and 2. Slightly higher internal responses to the red moving bar would also produce slightly smaller ipsilateral-contralateral performance differences because the simulations showed that this difference depended both on the difference between the means of the red and green distractor distributions and on their distances from the mean of the moving bar distribution. This was observed in the combined analysis of Experiments 3 and 4 when moving target color interacted with the spatial distribution of the red and green distractors. The ipsilateral-contralateral performance difference was slightly less for red moving targets averaged across these two experiments than it was for green moving targets. The slight difference in the estimated means of the red and green moving target distributions is consistent with this interaction. The smaller red-green parameter difference for moving bars relative to static bars implies that when objects move, their colors have less of an impact on exogenous orienting; rather, it is their movements per se that attract attention.

It is worth noting that the distances between the estimated means of the target and distractor distributions were virtually the same for the red and green bars (2.09 vs. 2.26 for red and green, respectively). The equality of these distances has implications in the model for performance on homochromatic trials. If the distances were exactly the same, then the model predicts that performance would be identical on homochromatic trials. This is generally what was observed in the data. None of the analyses ever revealed a significant effect of target color on performance on homochromatic trials. When a difference in the means on homochromatic trials was observed, it was almost always in the direction of slightly better performance with green targets. The model predicts this slight difference when there is a slightly larger distance between the means of the target and distractor distributions for green objects (difference between estimated means = 2.26) than for red objects (difference between means = 2.09). The intuition here is that stronger motion signals (i.e., a larger difference between the mean of the motion response distribution and the mean of the static distractor response distribution) makes detection of the target more immune to interference.

Finally, what does it mean that the data can be modeled at this age by a winner-take-all or maximum-of model? First, given multiple potential targets of attention, the visual system must resolve the problem of where to look or to attend next. One method for resolving such a competition is to allow the region or object within the visual field that generates the largest response to inhibit or suppress responses from other regions of the visual field (Koch & Ullman, 1985). One can think of the signal detection model as resulting in a single ‘‘winner’’ toward which attention is drawn after responses from all of the other objects in the field have been suppressed. Such suppressive affects are common in neurons thought to be involved in visual attention (Robinson, 1993).

This winner-take-all or maximum-of model also resembles other models developed to explain visual preferences in young infants (Banks & Salapatek, 1981; Gayl, Roberts & Werner, 1983). The difference between the present model and these earlier models is that these models were designed to explain which of two global patterns was preferred while the present model treats all of the bars in the visual field as distinct objects. These earlier models were designed to predict visual preferences in the preference paradigm, while the present model was developed to account for how attention to movement is modulated by the presence and distribution of competing objects. Both types of models ultimately yield a winner, but noise plays a more prominent role in the current model than it does in previous models.

## GENERAL DISCUSSION

The major results of these experiments can be summarized succinctly. Attention to movement at 3.5 month is affected by the spatial distribution and colors of other objects in the visual field. This result may not appear at first to be too surprising. Placing another object in the visual field to compete for attention with the moving stimulus is likely to interfere with attention to the movement some percentage of the time. Indeed, this type of effect has been documented in the past in eye movement studies with young infants (Aslin & Salapatek, 1975). The real significance of the results is that a) this interference is selective for color without prolonged inspections of the objects in the field, b) the data permit a quantification of such interference effects for the first time with infants at this age, and c) the interference effect conforms to a simple signal detection model with multiple noise sources (distractors) and one signal.

Sensitivity was affected primarily by the placement of the red bars in the field. When attention was disengaged (the central fixation bar disappeared), it was re-directed most often toward the side of the display with the single moving object (mean performance was always above 50% correct), but it could also be re-engaged by one of the static objects on a nontrivial proportion of trials. It was more likely to re-engaged by a red object than by a green object. The particular colors involved in this effect are not as important as the fact that there was an effect of color. Multiple objects in the visual field compete to be the next object of regard, and the pathways that ultimately resolve this competition are influenced both by an object’s color and by whether or not it is moving.

Prior work has clearly shown the effectiveness of movement and temporal change in driving orienting (Cohen, 1972). The current work shows that this effectiveness is really the result of a competition for attention by multiple objects in the visual field. The effectiveness of moving objects and temporal change in drawing attention may reflect the privileged access of the magnocellular pathways to orienting mechanisms (Steinman, Steinman & Lehmkuhle, 1997). The magnocellular pathways carry information relevant to the movements and the spatial layout of objects in the visual field (Livingstone & Hubel, 1988). These results suggest, however, that orienting at this age is the end result of a neural decision that also involves color information. Chromatic information is thought to be carried primarily by the parvocellular pathways (Livingstone & Hubel, 1988). Additionally, neurons in the superior colliculus are very poorly selective for color (Marrocco & Li, 1977), so the results suggest that the chromatic salience effects that observed here may reflect cortical influence on these subcortical orienting mechanisms. There are multiple pathways by which cortical centers can influence subcortical centers such as the pathway through the frontal eye fields (Schall, Hanes, Thompson & King, 1995).

These data extend prior work using a similar methodology (Nagata & Dannemiller, 1996). In that work, the spatial distribution of the distractors in the heterochromatic conditions was not controlled; instead the distribution of red and green distractors on the screen varied randomly with the constraint that half the bars on the screen were red and half the bars on the screen were green. The inferences of competition and selectivity in these prior experiments rested on much smaller differences between performance on homochromatic and heterochromatic trials. These inferences were clearer in the current experiments because the spatial distribution of the distractors was manipulated. This manipulation made it clear that failures to orient to the moving bar were not entirely random.

There are several limitations of the present results that should be acknowledged. These include the nature of the FPL measure and the apparent similarity of this paradigm to the visual search paradigm with adults. Consider these limitations in turn.

In discussing these effects, I have used phrases such as ‘‘attention was drawn to the target’’ and ‘‘the infant oriented to the target.’’ What warrant is there for speaking of exogenous orienting given that the measure that I used—FPL—does not index discrete behaviors? Technically, the data show only that sensitivity to movement was affected by the positions of the red objects in the field relative to the green objects and to the target. The FPL observer is not constrained to use only a single behavior to make the judgments about the location of the moving target. I have described the results above somewhat neutrally in terms of effects on sensitivity, but I also should note that most of the FPL judgments do involve some type of orienting by the infant. These orienting movements involve behaviors such as directional eye and head movements and different estimated inspection times for one side of the screen versus the other. The FPL observer integrates this information from various cues and makes a directional judgment. On some percentage of the trials this information does not permit a clear judgment so the observer guesses. Notice, however, that if the observer were guessing on most of the trials and there were no valid orienting information, then performance should fall around 50%, and it does not. For this reason, while FPL does not tell us which discrete behaviors the infant exhibited, performance significantly above 50% does tell us that the infants as a group were signaling the location of the target to the observer, and it is this performance that provides the warrant to speak of exogenous orienting based on these data. These orienting cues toward the movement were stronger or more prevalent on trials on which most of the red bars fell on the same side as the movement, and they were weaker or less prevalent on trials on which most of the red bars fell on the side opposite to the movement.

There are several ways in which the strength of these cues could be affected by the spatial distribution of the red bars. Recall that the judgments of the FPL observer took approximately 2 s, so one could expect the infant to make several refixations within this period. Errors by the FPL observer could arise because a) infants initially fixated the red bars contralateral to the motion and did not disengage attention in time to look at the moving target, or b) infants looked briefly at the moving target, but then were drawn quickly to the other side of the display by the red bars. Eye movement data would be necessary to determine the causes of ‘‘errors’’ made by the FPL observer. One could also use the direction of first fixation away from the center of the screen to distinguish these alternatives.

Next, consider the apparent similarity of these results to the visual search paradigm used with adult observers (e.g., Triesman & Souther, 1985). Both paradigms use ‘‘odd’’ singleton targets to determine the extent to which observers can use various stimulus characteristics (e.g., color, orientation) to find a target among distractors. One should not push the analogy between the current results and the results with adults too far because of a fundamental difference between these two paradigms: infants cannot be instructed to direct their attention always to the moving target. In this sense, it is probably a misnomer to speak of targets and distractors. The infant is not really being ‘‘distracted’’ from attending to the moving target by the red bars because distraction implies that they know that their task is to find the moving target. Instead, it would be better to see these results as telling us something about which stimulus features compete to re-engage attention once it has been temporarily disengaged by the disappearance of a fixation target. It is tempting to see the red bars as ‘‘distracting’’ the infant, but in fact they are simply attracting the infant’s attention on some proportion of trials more effectively than is the moving target.

Mindful of these differences between this paradigm and the visual search paradigm with adults, the present results are similar in one respect to a well-known finding in the adult visual search literature. It has been demonstrated repeatedly that if attention is drawn to the location of a subsequently presented target (valid cue), detection of that target improves or latency to detect the target decreases. If, however, attention is drawn away from the location of the subsequently presented target (invalid cue), then detection deteriorates and latency increases (Posner & Petersen, 1990). One way to construe the current results is that the red bars are acting like valid (ipsilateral) and invalid (contralateral) cues to the location of the motion. The results show that sensitivity to movement can be affected by the spatial locations of static bars in infants just as detection of a target can be affected by the prior onset of valid and invalid spatial cues in adults.

This competition model could be easily extended to other types of displays in which objects with different saliences are substituted for the red and green objects in the current experiments. One example of this would be to use vertical and oblique bars. Past research shows that infants tend to look longer at vertical and horizontal than at oblique lines (Bornstein, 1978). Orientation is a feature that is extracted first at the level of the visual cortex in primates. A pattern of results similar to those that obtained here with the vertical bars playing the role of the red bars and the oblique bars playing the role of the green bars would extend the previous conclusion that cortical processes influence exogenous orienting at this age.

This winner-takes-all model is quite similar to other types of visual models in which a choice or decision is required. The decision in this case is where to move the eyes next, so it is perhaps not surprising that this model resembles models of saccadic selection (Sheinberg & Zelinsky, 1993). In these models, the goal of the model is to predict the target of a saccade given multiple potential targets. These models use a winner-takes-all strategy with the location in the visual field that produces the largest response inhibiting responding to other locations and ultimately triggering a saccade to that location. Koch and Ullman's (1985) model is noteworthy in this regard because prior to the stage at which the final decision is taken to move attention to the most salient location, the image is filtered along a number of dimensions such as color, contrast and movement. A similar salience-driven model of exogenous orienting has been proposed by Theeuwes (1992; 1994). In all of these models, the spatial distributions of objects and their colors are important in influencing the final choice of the most salient object. This is consistent with the above results showing that even at 3.5 months of age the colors of objects, their spatial distributions and their movements compete to drive attention to its next object or location.

Finally, it is worth noting briefly that these results have implications for interpreting experiments with infants in which various complex displays are used to infer the infant's knowledge of various physical properties of objects (e.g., Baillargeon & DeVos, 1991; Needham & Baillargeon, 1997; Spelke, Breinlinger, Jacobson & Phillips, 1993). These studies often contain displays with motion, color, texture and brightness differences. The competition model and the results above imply that looking in these experiments may be affected significantly by quite subtle changes in the distribution of colors across the visual field and by the salience of the movement relative to the color differences in the display. How resistant these tendencies are to habituation in these studies is an empirical question worth considering. The competition effects did not wane as the experiment proceeded. Analyses of the data blocked into the first 24 trials versus the last 24 trials seldom showed any main or interaction effects of the repeated exposure.

In summary, these results may show that refixations at this age may remain relatively sluggish (Hood, 1995). Infants at 3.5 months may still find it difficult to disengaging attention from its current focus. One of the explanations given for the lower sensitivity on contralateral trials than on ipsilateral trials was that infants may have difficulty disengaging attention from a contralateral red distractor to refixate the moving target (or they simply may not find the moving target as compelling on some proportion of trials). Previous studies have indicated clear development of the ability to disengage attention after two months (Atkinson, Hood, Wattam-Bell & Braddick, 1992), but the present results indicate that such a process may still be developing at 3.5 months. Disengaging attention is mediated in part by the parietal cortex (Posner & Petersen, 1990). This cortical area shows marked postnatal development (Chugani & Phelps, 1986), so our results are consistent with the proposition that disengagement processes are still developing at 3.5 months, or that engagement processes at this age already exhibit a form of competition between motion and color.

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