

## RESEARCH ARTICLES

---

# Relative Color Contrast Drives Competition in Early Exogenous Orienting

James L. Dannemiller

*University of Wisconsin–Madison*

Young infants typically orient to a moving object, but the strength of this tendency depends on what else is in the visual field, with some objects competing for attention more effectively than others. This competition was studied in 3.5-month-old infants by manipulating the colors and spatial distributions of static elements that appeared with a small moving probe. The hypothesis was that the competition from these static bars would depend on their color contrasts. Three different color pairings were used: red with green, pink with green, and red with pink. The results were generally consistent with the hypothesis that the competition from static elements in the visual field depends on their color contrasts. Orienting at 3.5 months is determined by competition mechanisms that weight motion and color and most probably other stimulus characteristics to produce a directional response.

Infants look selectively at objects and features in their visual fields. This selectivity is evident in initial orienting (Aslin & Salapatek, 1975; Richards & Hunter, 1997) and in prolonged scanning (Bronson, 1994; Haith, 1980). Selectivity is necessary because the visual field typically is populated with many different objects, and inhomogeneities in spatial resolution coupled with capacity limitations on object recognition require sequential foveation of selected image regions. A fundamental problem faced by infants and adults alike, therefore, is where to look first when multiple objects appear simultaneously in the visual field or when a refixation brings new objects into the field of view. This decision of where to look first

or next is resolved by endogenously (internal, goal-directed) and exogenously (stimulus-driven) controlled mechanisms within the visual system. Visual search for an object of a specific type or with a specific feature (e.g., a red object) is an example of endogenously controlled attention. A reflexive saccade to a suddenly appearing object in the peripheral visual field is an example of exogenously controlled orienting. Achieving a balance between these two methods of attentional control is certainly an important developmental task facing infants. The research in this report involves stimulus factors that influence exogenously controlled orienting. This has been referred to as attention-getting in the developmental literature (Cohen, 1973).

Exogenously controlled orienting is sensitive to the colors of small, discrete objects in the infant's visual field and to their spatial distributions (Dannemiller, 1998, 2000; Ross & Dannemiller, 1999). Attention is most often drawn to the hemifield with a small moving bar among static bars, but the strength of this tendency can be influenced by the spatial distribution of colored static elements. When most of the higher salience bars are placed contralaterally to the side of the display with the moving probe, orienting to the moving probe is weakened. This effect has been observed across the entire age range from 7 to 21 postnatal weeks (Dannemiller, 2000). This effect probably depends on the color contrasts of the static bars with their backgrounds (Ross & Dannemiller, 1999).

These prior results suggest the existence of competition mechanisms in the early postnatal visual system similar to those that have been hypothesized for the adult visual system (Koch & Ullman, 1985). Additionally, the sensitivity of these mechanisms to color may reflect the importance of color in image segmentation; that is, processes early in the visual pathway may use color to segregate different regions of the image for later object recognition. Prior research with infants also suggests that luminance contrast may play a role in image segmentation and perceptual grouping in 3-month-olds (Quinn, Burke, & Rush, 1993).

The purpose of these experiments was to provide converging evidence for the important role played by color contrast in this attentional competition process during the early postnatal months. The saturation of colors strongly influences newborns' abilities to discriminate color from achromatic stimuli (Adams & Courage, 1998). By presenting red and green bars against different backgrounds, Ross and Dannemiller (1999) were able to show that color contrast affects the strength of the competition process. Additionally, one of the conditions in Ross and Dannemiller (1999; red/green/yellow at nominal isoluminance) expected to equalize competition did not do so. It is useful, therefore, to have an alternative manipulation to test the color contrast hypothesis. In the following experiments, we used an alternate strategy of holding the background color constant (white) and directly manipulating the colors of the bars. A series of color comparisons was selected that permitted tests of the impact of color contrast on attentional competition.

To understand the hypotheses, it is necessary to understand the paradigm used to test for competition. Imagine being shown a display with 28 small bars scattered across it and no instructions on how to respond to the display. Any one of these small bars might serve as the target of a fixation when the bars first appear in the visual field. If one of the bars were moving, then it would be likely to elicit a brief fixation, as most featural singletons do (Nothdurft, 2000). If the movement were near threshold, then it would also be likely that on some presentations, one of the static bars in the visual field might draw a fixation, effectively competing with the weak motion signal. Static bars that contrasted strongly with their backgrounds would be more likely to draw a fixation than bars that were less visible (Zenger, Braun, & Koch, 2000). The paradigm that we have developed to study attentional competition in the early postnatal months is similar to this situation.

This paradigm that we use to test for competition involves oscillating a small bar and observing how orienting to this moving bar is affected by the colors and positions of 27 other static bars. A brief description of previous results with red and green bars on a white background will help to convey the operational definition of competition (Dannemiller, 1998). If infants show a greater tendency to orient to the moving probe when most of the red bars are placed on the same side as the probe than when most of the red bars are placed on the side opposite to the probe, then competition is inferred. There are always equal numbers of red and green bars on the display, so it is the uneven spatial distribution of the two colors that creates the conditions for competition. Red appears to be more effective than green in competing for attention with the probe because it has greater color contrast with the white background (Ross & Dannemiller, 1999).

With this brief description of the paradigm, it should now be possible to understand the hypotheses. Competition should depend on the relative saliences of the two colors used across trials. In the first experiment, two different color pairings were used for different groups of infants; red was paired with green, and pink was paired with green. Based on past results, red static bars should draw attention more effectively than green bars. Attention to the moving target should therefore be modulated by the spatial distribution of the red and green static bars. On trials when most of the red static bars appear contralaterally to the moving target, compared to trials on which most of the red bars appear ipsilaterally, the tendency to orient to the moving probe should be weaker. In contrast, when pink is paired with green, competition based on this spatial distribution of the two colors should favor the green bars. Pink is a desaturated form of red, so if competition depends on the color contrast of these bars against the white background, then green should increase in salience when it is paired with pink instead of with red. Attention to the moving probe should now be affected primarily by the location of most of the green static bars. These color pairings are discussed in more detail later.

A second hypothesis involves the (lack of) influence of the color of the moving target. There should be no effect of the color of the moving probe on sensitivity to motion. The basis for this null hypothesis is that sensitivity to the moving probe is determined mostly by its movement per se rather than by its color. Additionally, sensitivity to the movement is probably influenced mostly by the luminance contrast of the probe (Ross & Dannemiller, 1999), and all of the moving probes were presented with the same luminance contrast despite variations in color.

## EXPERIMENT 1

Both of the experiments in this study used the same paradigm that has been used previously in Dannemiller (1998, 2000) and in Ross and Dannemiller (1999).

### Method

*Participants.* Infants were recruited from birth announcements in a local newspaper. One hundred and four ( $N = 104$ ) infants (55 boys) provided complete data (60 trials). The average age of these 104 infants was 99.2 days (range = 91–107 days). Data from another 16 infants were excluded for the following reasons: excessive crying, fussiness or inattentiveness ( $n = 12$ ), birth complication severe enough to necessitate a stay in the intensive care unit ( $n = 2$ ), and prematurity greater than 2 weeks ( $n = 1$ ). Phone screening eliminated infants with a familial history of color blindness from the sample, although data from 1 infant were eliminated after later confirmation of a familial history of color blindness ( $n = 1$ ). The attrition rate, therefore, was 13.3%. The ethnic make-up of our sample in Experiments 1 and 2 reflected the local population, being mostly White. No specific information is available on the socioeconomic status distribution of our sample.

We tested 3.5-month-old infants to be able to compare these results specifically with prior results from similar age groups (Dannemiller, 1998; Ross & Dannemiller, 1999). Color also plays an important role in these experiments, and it is clear that by 3 months of age, if not before, infants possess trichromatic color vision (Teller & Bornstein, 1987).

*Apparatus and stimuli.* The displays were presented on a large monitor running at 60 Hz in a noninterlaced frame mode (50 cm diagonally; NEC JC-2002VMA-1).<sup>1</sup> The stimulus field was  $40^\circ$  (H)  $\times$   $31^\circ$  (V). The background color of the stimulus field was white (see later), and its luminance was

---

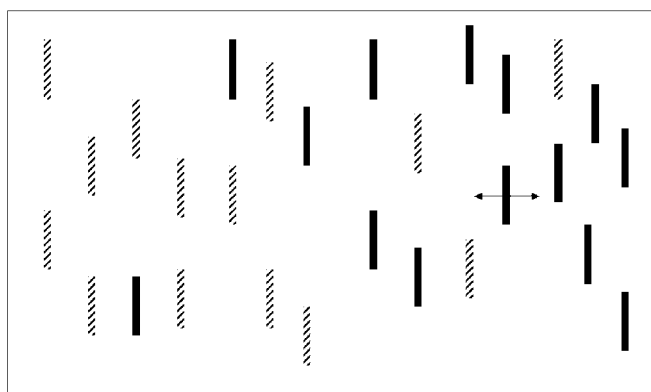
<sup>1</sup>In noninterlaced mode, a complete display is presented every 16.7 msec. In interlaced mode, every other scan line is presented every 16.7 msec, so a complete display requires 33.3 msec.

63.2 cd/m<sup>2</sup>. The target and static bars were 5° vertically by 0.75° horizontally. These bars were either red, pink, or green (see later), depending on the experimental condition, and the luminance of all bars was 13.1 cd/m<sup>2</sup>. 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%. Color was measured with a Minolta Chroma Meter (CL-100), and luminance was measured with a photometer with calibration traceable to the National Institute of Standards and Technology (Photo Research Corporation, Model UBD 1DEG). Stimuli were generated and displayed, and responses were collected using custom programming (C++) on a personal computer. A schematic version of the display is shown in Figure 1.

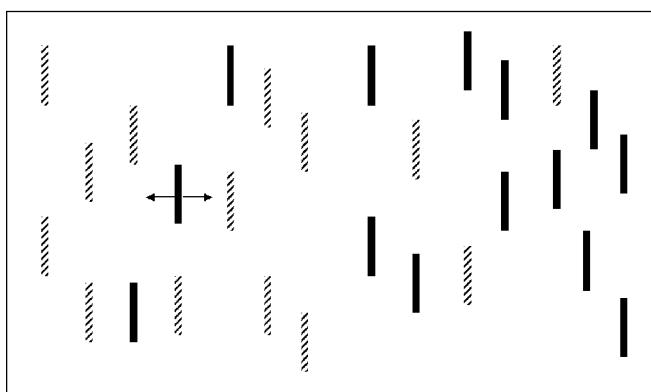
The moving target bar oscillated horizontally at 1.2 Hz with a peak-to-mean amplitude of 0.75° (lower amplitude condition,  $n = 40$  participants) or 1.0° (higher amplitude condition,  $n = 64$  participants) on each trial. The moving target bar is indicated in Figure 1 by the bar with the dual arrows (amplitude not drawn to scale). Amplitude was manipulated because modeling of the competition effect (Dannemiller, 1998) shows that its magnitude depends on the strength of the moving probe; that is, very strong probes always capture attention, leaving little room to observe competition effects produced by the static bars in the field. Two motion-probe amplitudes were used in hopes of finding at least one that produced above-chance data while not overwhelming competition effects, should they exist. It was also useful to have an estimate of the effect size of the amplitude manipulation with which to compare the effect of the color-contrast and competition manipulation.

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 online 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 locations on each trial: in the middle of the display vertically, and either 10° to the right or to the left of the center of the display. The target bar appeared equally often on the right and left sides of the screen within each of the six trial types (described later). The target position was determined pseudorandomly from trial to trial; it did not alternate sides regularly across trials. There were 27 static bars in all of the following experiments. These static bars are shown in Figure 1 by the bars without arrows. The static bars could appear anywhere on the display, with the following constraints: Thirteen of the static bars appeared on the same half of the display as the moving target, and the remaining 14 static 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 among 14 imaginary columns that divided the horizontal extent of the display into 14 equal



ipsilateral



contralateral

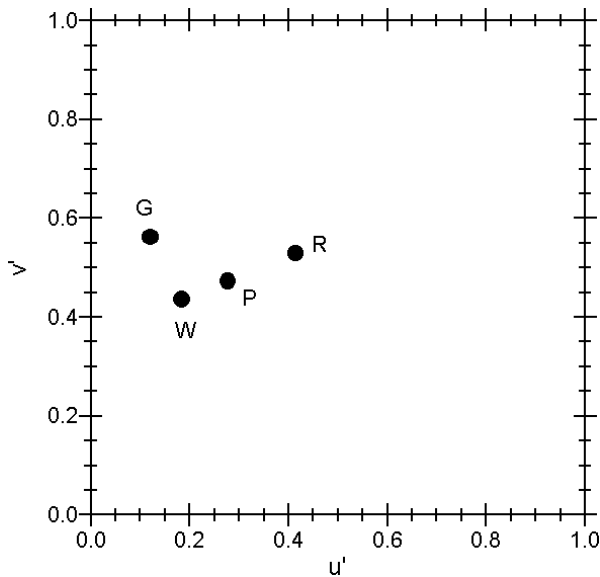
**FIGURE 1** Schematic representations of mixed displays from Experiments 1 and 2. In these displays, the black bars represent the red, pink, and red bars in the RG, PG, and RP conditions. The hashed bars, therefore, represent green, green, and pink bars in the RG, PG, and RP conditions. All colored bars in the actual displays were presented with the same luminance contrast (66%) embedded in identical white backgrounds. An ipsilateral display is shown on the top, and a contralateral display is shown on the bottom. The terms ipsilateral and contralateral always designate the location of most (11/14) of the red (in the red and green pairing), pink (in the pink and green pairing), or red (in the red and pink pairing) bars with respect to the side with the moving probe. If black is taken to be the more salient of the two bar types in these schematic displays, then the contralateral condition on the bottom would lead to lower levels of orienting to the moving probe than the ipsilateral condition on the top. The moving probe is indicated with the arrows in each panel. Spatial dimensions are not precisely to scale (see text for these details).

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 or her visual field.

*Colors.* The major hypothesis is that when bars of two different colors are present simultaneously on the display, the bars that have the greater color contrast against the white background will be more salient. Saliency is sometimes a circular concept, so in this work, saliency is identified with color contrast to remove the circularity. This doesn't completely solve the problem of how to determine which of two colors is the more salient for an infant because color vision at 3.5 months of age is undoubtedly different at least quantitatively from mature human color vision. As a working hypothesis, I assumed that color contrast metrics used for adults could also be used to give a first approximation to color contrast for 3.5-month-old infants. Human infants are trichromatic by at least 3 months, if not before (Teller & Bornstein, 1987). Additionally, Teller, Pereverzeva, Chien, and Palmer (2000) showed that isoluminance values for 3-month-old infants for red and green are very similar to adult values measured with a motion nulling technique, probably justifying the use of adult isoluminance values as good first approximations to the infant values. Of course, this may not hold exactly when the task differs from a motion-nulling task.

Given these assumptions, a standard color space used to represent color differences for adults was used to determine the approximate color contrasts of the three colors shown to the infants. The colors of the bars are shown in Figure 2. Color is plotted here in  $u'$ ,  $v'$  space. The color of the background was white on all trials. This white is also indicated in Figure 2.

Half of the infants were tested with the bars that were red or green (RG condition), whereas the other half were tested with bars that were pink or green (PG). The green was identical in both of these conditions. Notice in Figure 2 that red is farther from white than green, implying that the color contrast between the red bars and the white background is greater than the color contrast between the green bars and the white background. The Euclidean distance in this space between green and white is approximately 57% as large as the distance between red and white. If saliency is determined by color contrast, then the red bars should be more salient than the green bars, and, indeed, this is what has been found previously using this paradigm (Dannemiller, 1998, 2000; Ross & Dannemiller, 1999). Performance is worse when most of the red bars are placed contralaterally to the moving target than when they are placed ipsilaterally. Notice also that by the same logic, when the red color is desaturated to pink, then the green bars should become relatively more salient than they were when



**FIGURE 2** Locations of the colors used in Experiments 1 and 2 in  $u'$ ,  $v'$  color space. R = red, G = green, W = white, and P = pink. Human color vision is trichromatic, but in this color space two dimensions are sufficient to represent a color because the three values are constrained to sum to 1.0, so the third coordinate is implied by  $u'$ ,  $v'$ . The advantage of using this color space is that chromatic discriminability is related, albeit somewhat imperfectly, to distance in this space. Hence, red is farther from white than is green, and pink is closer to white than red, leading to approximate predictions of relative salience.

paired with the red bars. The Euclidean distance between pink and white in this space is approximately 71% of the distance between green and white. Thus, the spatial distribution effect observed repeatedly with red and green should be diminished or perhaps even reversed when green is paired with pink (with the spatial bias now favoring green).

*Design and procedure.* Within both the RG and the PG conditions, infants saw 10 blocks of six trial types. Four of these trial types (mixed trials) resulted from the  $2 \times 2$  factorial combination of two independent variables: moving target color and the spatial distribution of the two differently colored bars. The other two trial types (uniform trials) were constructed by presenting only bars of one color at a time on the screen: All bars on the screen were red, all bars were green, or all bars were pink on the uniform trials. These uniform trials are useful in modeling and parameter estimation. They do not bear directly on the color-contrast and competition hypothesis, but the following results are presented for completeness.



The infant was presented with two differently colored sets of bars mixed within the same display on the mixed trials. The spatial distribution of the bars with these two colors was manipulated to examine competition effects. The terms *ipsilateral* and *contralateral* always refer to the side of the display with most of the red (RG condition) or pink (PG) bars relative to the moving target regardless of the color of the moving target. The distribution of the two bar colors was always set at 11:3, as it was in our previous work. Thus, on the ipsilateral RG trials, there were always 11 red bars on the side of the screen with the moving target bar and 3 green bars on this side. The proportion was reversed on the other side of the display. On contralateral RG trials, there were always 11 red bars on the side of the display contralateral to the moving target and 3 green bars. For the PG condition, the red bars were replaced with pink bars. The six types of trials shown to each infant are listed in Table 1 with other details of the experimental design.

The trial types were randomly ordered within a block of six trials, and 10 such blocks were presented to each infant, for a total of 60 trials. The infant was seated in an infant seat approximately 50 cm from the display. Prior to the start of each

TABLE 1  
Experimental Design and Numbers of Participants in Experiments 1 and 2

Experiment	Amplitude (Degrees)	Color Pairing	Target	Static Bars	
				Target Side	Nontarget Side
1	0.75 ( $n = 20$ ), 1.0 ( $n = 32$ )	Red/green (RG)	R <sup>a</sup>	13R	14R
			R <sup>b</sup>	10R, 3G	3R, 11G
			R <sup>c</sup>	2R, 11G	11R, 3G
			G <sup>a</sup>	13G	14G
			G <sup>b</sup>	11R, 2G	3R, 11G
			G <sup>c</sup>	3R, 10G	11R, 3G
1	0.75 ( $n = 20$ ), 1.0 ( $n = 32$ )	Pink/green (PG)	P <sup>a</sup>	13P	14P
			P <sup>b</sup>	10P, 3G	3P, 11G
			P <sup>c</sup>	2P, 11G	11P, 3G
			G <sup>a</sup>	13G	14G
			G <sup>b</sup>	11P, 2G	3P, 11G
			G <sup>c</sup>	3P, 10G	11P, 3G
2	0.75 ( $n = 16$ ), 1.0 ( $n = 16$ )	Red/pink (RP)	R <sup>a</sup>	13R	14R
			R <sup>b</sup>	10R, 3P	3R, 11P
			R <sup>c</sup>	2R, 11P	11R, 3P
			P <sup>a</sup>	13P	14P
			P <sup>b</sup>	11R, 2P	3R, 11P
			P <sup>c</sup>	3R, 10P	11R, 3P

<sup>a</sup>These trials are uniform. All other trials are mixed. <sup>b</sup>Referred to as ipsilateral trial in text. <sup>c</sup>Referred to as contralateral trial in text.

trial, a small blue flashing bar appeared in the center of the screen to attract the infant's attention. The observer also used various centered noises to encourage the infant to orient to the display when necessary. The observer pressed a button to initiate the trial, and she could restart a trial if the infant looked away from the display at the start of the trial. All of the bars appeared abruptly in the visual field, and the probe began oscillating as soon as it appeared.

Data were collected using a speeded version of 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, audible beep. The FPL observer was instructed to make these judgments as quickly as possible while maintaining reasonably good accuracy because the focus was on orienting, or the dominant direction of regard, in the first 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 2 sec and often less, so this measure yields information about orienting during the initial second or two after the stimuli appeared.

The same observer was used to test all of the infants in both of these experiments. This same FPL observer has tested more than 1,000 infants over the last 6 years using this same paradigm, so her contribution to the data collected with this paradigm is stable and in a sense transparent. It might be true that a different observer could yield higher average percentages of correct judgments, but the conditions that test for competition effects are manipulated within subjects, so such interobserver differences are largely irrelevant. Notice, also, that observer 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. Reliability is often substituted for validity when duration judgments are used because there is no external validity criterion against which the judgments can be compared.

Forty of the infants provided complete data in the lower amplitude condition, and 64 of the infants provided complete data in the higher amplitude condition. The two conditions were run sequentially. More infants were tested at the higher amplitude because past testing and modeling showed that the color competition effects that underlie this paradigm are harder to observe with stronger motion probes. The two conditions are presented later as one experiment because analyses showed that the amplitude variable produced a main effect but no interactions. Within each of the two amplitude conditions, infants were randomly assigned to the two color-pairing conditions.

## Results and Discussion

The percentages of correct judgments were recorded for each of the six trial types (two uniform and four mixed). Each of these percentages was based on 10 trials. The statistical tests were conducted on  $d'$  (sensitivity to motion) transformations of these percentage correct measures. This transformation is monotonic with the percentage of correct judgments and is preferable with respect to the homogeneity of the variance assumption of analysis of variance (ANOVA) when percentages are based on small sample sizes (Thorpe, Trehub, Morrongiello, & Bull, 1988).<sup>2</sup>

Was orienting above chance? It is important to note that the mean  $d'$  values were significantly above chance ( $d' = 0$ ) on all six trial types for both the red/green and the pink/green color pairings at both amplitudes (least significant one-tailed  $p = .027$ ). This shows that orienting was driven most strongly to the side with the moving probe. As described later, the distribution of the static colored bars modulated the strength of this orientation toward the moving target.

*Analyses of data from uniform trials.* The data from the uniform trials were analyzed separately from the data from the mixed trials. The data from the uniform trials were analyzed using a  $2 \times 2$  mixed ANOVA. The between-subject factor was pairing (red and green vs. pink and green).<sup>3</sup> The within-subjects factor was color (red or pink vs. green). Recall that these were uniform trials, so the color variable refers to the color of all of the bars on the screen. The data from the uniform trials do not address the competition hypotheses because there were never two differently colored bars on this display simultaneously on uniform trials, as there were on mixed trials. Nonetheless, these uniform trials are useful for assessing the reliability of the data because identical trial types (e.g., all

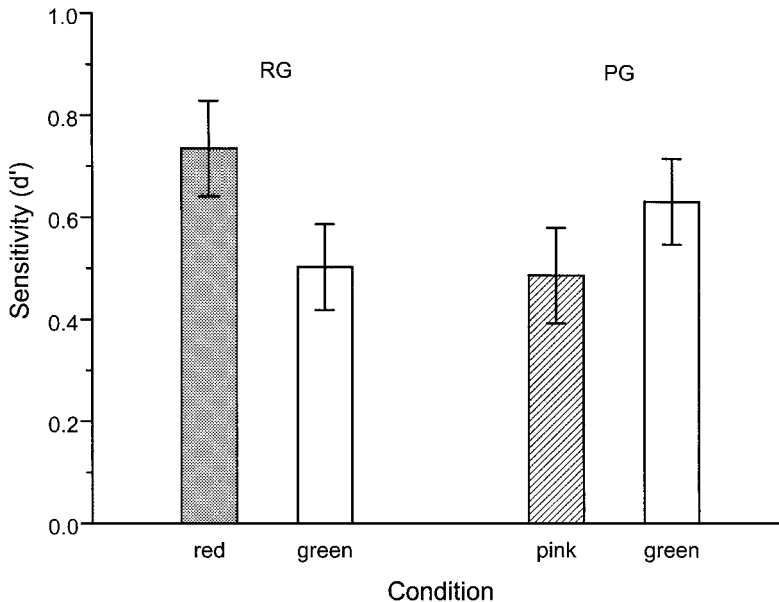
---

<sup>2</sup>The  $d'$  transformation was implemented separately for each trial type as follows. The number correct out of 10 was increased by 0.5, and this number was divided by 11. The  $z$  score corresponding to this percentage was then determined from a standard cumulative 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 0.5 and dividing by 11 was to handle occasional perfect scores: 10 of 10 correct. A  $z$  score is undefined for 100% correct, so this transformation maintains the rank orderings of all scores and represents perfect scores as  $d' = 2.39$ . Such a treatment of perfect scores is common in the signal detection literature. Chance (5 of 10 correct) on the original scale remains chance (5.5 of 11 correct) on the transformed scale and always corresponds to  $d' = 0.0$ .

<sup>3</sup>Amplitude was also manipulated as a between-subject independent variable ( $0.75^\circ$  vs.  $1.0^\circ$ ) both in Experiments 1 and 2. It generally behaved as expected, with  $d'$  values being significantly higher with the larger amplitude. This held true for all of the uniform and mixed conditions in Experiment 1, and for the mixed condition in Experiment 2, but not for the uniform condition in Experiment 2. The latter null effect may represent sampling error, given its effect in all of the other conditions. Because amplitude did not interact with other independent variables in any of these analyses, the data were collapsed across amplitude in all of the analyses.

green bars) occurred in different experimental contexts (e.g., red vs. green and pink vs. green).

There was a significant Pairing  $\times$  Color interaction,  $F(1, 100) = 5.42$ ,  $MSE = 0.325$ ,  $p = .022$ . This interaction is shown in Figure 3. Although the trend was toward lower sensitivity to motion with uniform pink displays (mean  $d' = 0.487$ ) than with uniform green displays (mean  $d' = 0.632$ ) in the PG pairing group, simple effects analysis showed that this difference was not significant,  $F(1, 100) = 1.60$ ,  $MSE = 0.325$ ,  $ns$ . In contrast, sensitivity to motion was significantly higher with uniform red displays (mean  $d' = 0.735$ ) than with uniform green displays (mean  $d' = 0.503$ ) in the RG pairing group,  $F(1, 100) = 4.09$ ,  $MSE = 0.325$ ,  $p = .046$ . Infants were most sensitive to the red moving probe in uniform red displays and less sensitive to the pink and green moving probes in uniform displays of those colors. Perhaps most important, sensitivity to motion with uniform green displays, which were identical in the two experimental groups, did not differ significantly,  $F(1, 100) = 1.28$ ,  $MSE = 0.325$ ,  $ns$ . In other words, when green uniform



**FIGURE 3** Sensitivity to motion on uniform trials in Experiment 1. Sensitivity to motion has been plotted on the y axis against the colors of the bars on the x axis for uniform trials from the RG pairing (left two bars) and the PG pairing (right two bars). The solid bar is for red targets with all red static bars, the open bars are for green targets with all green static bars, and the hashed bar is for pink targets with all pink static bars. Data from the two green trial types represent exact replications across two different samples. Data have been averaged over amplitude. Errors bars are  $\pm 1$  SEM.

displays appeared across trials mixed with other pink displays or with red displays, sensitivity to motion was similar in both experimental contexts.

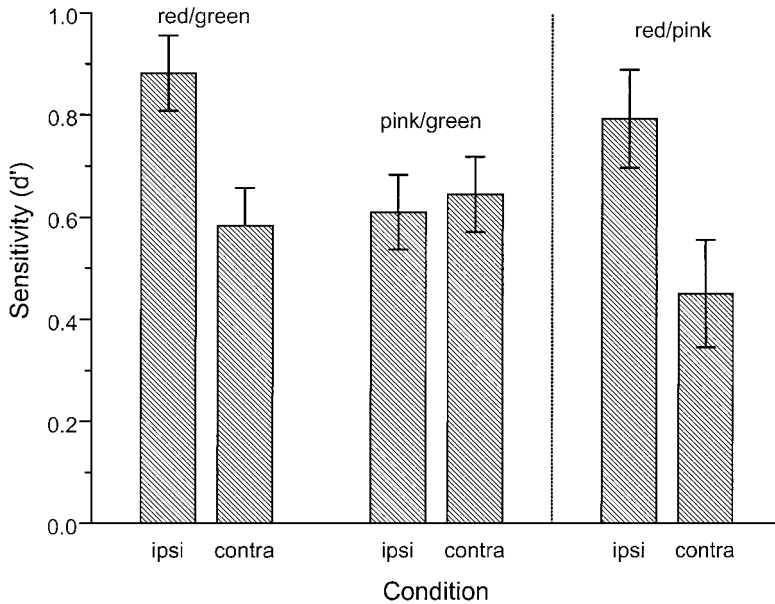
*Analyses of data from mixed trials.* As with the data from uniform trials,  $d'$  served as the dependent measure on mixed trials. These data were analyzed in a mixed  $2 \times 2 \times 2$  ANOVA. The between-subject factor was pairing (RG vs. PG). The within-subjects factors were color of the moving target (red or pink vs. green) and spatial distribution (ipsilateral vs. contralateral).

On mixed trials, infants again oriented to the side with the moving probe at levels above chance (mean  $d' = 0.58$ ,  $SEM = 0.069$  in the  $0.75^\circ$  amplitude group; mean  $d' = 0.781$ ,  $SEM = 0.054$  in the  $1.0^\circ$  amplitude group). These mean sensitivities are similar to those observed on the uniform trials (0.425 and 0.754 in the  $0.75^\circ$  and  $1.0^\circ$  conditions, respectively).

Competition was evident in the data from mixed trials. As predicted from the first hypothesis earlier, the effect of the spatial distribution variable depended on the particular color pairing used. There was a significant main effect of the spatial distribution variable,  $F(1, 100) = 5.27$ ,  $MSE = 0.323$ ,  $p = .024$ . This main effect was qualified by a spatial Distribution  $\times$  Pairing interaction,  $F(1, 100) = 8.43$ ,  $MSE = 0.323$ ,  $p = .005$ . This interaction is shown in Figure 4. On trials with red and green bars, sensitivity to motion was higher when most of the red bars appeared ipsilaterally (mean  $d' = 0.882$ ,  $SEM = 0.074$ ) to the moving probe than when they appeared contralaterally (mean  $d' = 0.584$ ,  $SEM = 0.074$ ),  $F(1, 100) = 7.15$ ,  $MSE = 0.323$ ,  $p = .009$ . In contrast, there was no significant effect of the spatial distribution variable when green bars were paired with pink bars,  $F(1, 100) = 0.099$ ,  $MSE = 0.323$ ,  $ns$ . Hence, one of the two predictions from the first hypothesis was supported (red > green), but the other prediction (green > pink) was not. Nonetheless, green was not inherently less salient; its salience depended on the color with which it was paired, as indicated by the interaction.

The second hypothesis predicted that the color of the moving probe would have no effect on sensitivity to motion on mixed trials, and this hypothesis was confirmed. The color of the moving probe did not produce any main effects or interactions. The basis for this prediction was that the motion per se draws attention to the probe independently of its color, especially when substantial luminance contrast is present.

Thus, attention to the moving target depended significantly on the composition of the visual field with competition effects evident. The spatial distribution effect with the red and green bars replicated the same effect observed previously at this age (Dannemiller, 1998; Ross & Dannemiller, 1999). Color contrast probably plays a role in this competition. Notice that this argument is based on the spatial distribution effect evident in the red and green data and is absent in the pink and green data. The spatial distribution effect implies that bars of one



**FIGURE 4** Spatial distribution effects on orienting in Experiment 1 (left of vertical dashed line) and Experiment 2 (right of vertical dashed line) from the mixed conditions. Sensitivity ( $d'$ ) is plotted on the  $y$  axis under ipsilateral (ipsi) and contralateral (contra) conditions on the  $x$  axis. Ipsi and contra refer to the locations of the majority (11:14) of the red, pink, and red bars in the red and green, pink and green and red and pink conditions, respectively. Data have been averaged over amplitudes and colors of the moving target. Errors bars are  $\pm 1$  SEM.

color more effectively compete with the moving probe for attention than bars of the other when both are present on the display simultaneously. This interpretation is inherently relative. It does not depend on the absolute sensitivities shown in the ipsilateral and contralateral conditions because to some extent those absolute sensitivities may depend on the characteristics of the moving bar as well. Rather, this argument relies on the fact that when the spatial balance between bars of the two colors is shifted, orienting to the moving probe also shifts. When most of the red bars in the red and green condition were shifted from the same side as the target to the opposite side, orienting to the side with the moving probe decreased (see leftmost panel in Figure 4). In contrast, when most of the pink bars in the pink and green condition were shifted from the same side as the target to the opposite side, orienting was unaffected (see middle panel in Figure 4). Green bars were only less effective in competing for attention when they were paired with red bars. When green bars were paired with pink bars, they competed as effectively, presumably because the color contrasts of the pink bars made them attract attention more weakly than the red bars.

## EXPERIMENT 2

Experiment 1 provided partial support for the hypothesis that static bars compete more effectively for attention with the moving target if they have more color contrast. Reducing the color contrast of the red bars by making them a less saturated pink eliminated the spatial distribution effect that was evident when red was paired with green. The distribution of the pink and green static bars did not affect the performance in the same way that the distribution of red and green bars did. Although the spatial distribution effect was not reversed as predicted for the pink and green pairing, it was eliminated. It is possible that hue differences (e.g., red vs. green) may have complicated the attempt to find evidence for the unilateral effect of color contrast. In other words, it is certain that desaturating a color while holding hue constant reduces the perceived color contrast with the white background, but comparing perceived color contrasts across different hues (pink vs. green) may be more complicated.

A more straightforward test of the color contrast hypothesis that does not involve hue differences would involve comparing red to pink. Hue is held constant in this comparison, and only color contrast against the white background or, alternatively, saturation differs in this pairing. As long as the red and pink are discriminable from each other (and this is an empirical question for infants at this age), it should be possible to observe a spatial distribution effect. The Euclidean distance between this pink and white in  $u'$ ,  $v'$  color space is approximately 40% of the distance between red and white. The prediction is that a spatial distribution effect should be observed in this experiment, with sensitivity to motion higher on ipsilateral trials (with most of the red bars ipsilateral to the moving probe and most of the pink bars contralateral to the moving probe) than on the complementary contralateral trials. Essentially, the pink bars in this experiment are predicted to play the role that the less salient green bars played in the red and green pairing of Experiment 1.

This experiment also permitted a test of the transitivity of salience relations and of the internal consistency of the results obtained with this paradigm. In the mixed conditions of Experiment 1, red was found to be more salient than green, and green and pink were found to be approximately equally salient. Therefore, transitivity in these relationships would predict that red should be more salient than pink. Comparing red to pink also permitted a check on the internal consistency of the results across experiments.

### Method

*Participants.* Thirty-two infants provided complete data for this experiment (60 trials). The average age of these 32 infants (20 boys) was 98.8 days

(range = 90–106 days). Data from another 5 infants were excluded because of excessive crying, fussiness, or inattentiveness. Phone screening eliminated infants from the sample with familial histories of color blindness. The attrition rate, therefore, was 13.5%, almost identical to the attrition rate of 13.3% in the first experiment.

*Apparatus and stimuli.* The apparatus and stimuli were identical to those used in Experiment 1. The red and pink colors from Experiment 1 were used. Bars of these two colors were presented with 66% luminance contrast against the same white background used in Experiment 1.

*Design and procedure.* The design and procedures were the same as in the first experiment. Half of the infants were assigned to be tested with the lower amplitude moving probe ( $0.75^\circ$ ), and half were randomly assigned to the higher amplitude condition ( $1.0^\circ$ ). The spatial distribution of the red and pink bars was manipulated within subjects. Each participant received 10 blocks with six trials in each block. The six trial types comprised two uniform trials (all bars on display red or all bars on display pink) and four mixed trials (two moving probe colors, red and pink; crossed with two spatial distribution trial types, 11:14 red bars ipsilateral to the moving probe vs. 11:14 red bars contralateral to the moving probe). Precise descriptions of the six trial types are shown in Table 1 under Experiment 2.

## Results and Discussion

Percentage correct values were converted to  $d'$  as discussed earlier, and  $d'$  was used as the dependent variable in all analyses. Was orienting above chance? As in Experiment 1, the mean  $d'$  values from all six trial types at both amplitudes were tested against chance ( $d' = 0$ ). Eleven of these 12 mean  $d'$  values were significantly above chance (least significant one-tailed  $p = .033$ ). In one condition, the mean  $d'$  (0.133) was not significantly above chance,  $t(15) = 0.654$ ,  $p = .26$ , one-tailed. This occurred in the low amplitude condition with a pink moving target on the contralateral trial. In other words, when most of the red static bars appeared contralaterally to the pink target moving with the lower amplitude, infants oriented randomly with respect to the side of the display with this moving target. This result could represent sampling error, or it could suggest that red static bars are salient enough to compete effectively with a weak moving target when most of those bars appear in the hemifield opposite to the moving target.

*Analyses of data from uniform trials.* The data from the two uniform conditions were analyzed using a within-subjects ANOVA. The within-subjects factor was color (red vs. pink). As in Experiment 1, the infants oriented toward the side



with the motion probe at levels above chance on these uniform trials. Sensitivity to motion with all red bars on the display (mean  $d' = 0.690$ ,  $SEM = 0.103$ ) was higher than with all pink bars on the display (mean  $d' = 0.445$ ,  $SEM = 0.101$ ),  $F(1, 30) = 4.32$ ,  $MSE = 0.223$ ,  $p = .046$ . This is similar to the results of Experiment 1 with uniform trials. In that experiment, uniform red trials yielded greater sensitivities than uniform green trials.

*Analyses of data from mixed trials.* The data from the mixed trials were analyzed with a  $2 \times 2$  within-subjects ANOVA. The color of the moving probe (red vs. pink) and spatial distribution (most of the red bars ipsilateral vs. most contralateral) were within-subjects factors. As in all previous conditions, infants oriented to the side with the moving probe at levels significantly above chance (higher amplitude mean  $d' = 0.786$ ,  $SEM = 0.114$ ; lower amplitude mean  $d' = 0.457$ ,  $SEM = 0.114$ ) when the data were averaged across the color of the moving probe.

Unlike the results from mixed trials in Experiment 1 with the red and green pairing, the color of the moving probe did affect orienting with the red and pink pairing. There was a main effect of the color of the moving target,  $F(1, 30) = 20.22$ ,  $MSE = 0.247$ ,  $p < .001$ . Sensitivity to motion was higher with the red moving probe (mean  $d' = 0.819$ ,  $SEM = 0.085$ ) than with the pink moving probe (mean  $d' = 0.424$ ,  $SEM = 0.098$ ). Apparently, in addition to motion parameters (amplitude) affecting sensitivity to motion on mixed trials, the color of the moving probe also affects sensitivity, with greater sensitivity to motion on trials with red moving probes than on trials with pink moving probes. The color contrast of the moving target in this case played a significant role in determining how often infants oriented to the side with the moving probe.

As predicted, sensitivity to motion was higher when most of the red bars appeared ipsilaterally to the moving probe (mean  $d' = 0.793$ ,  $SEM = 0.096$ ) than when most of the red bars appeared contralaterally to the moving probe (mean  $d' = 0.450$ ,  $SEM = 0.106$ ),  $F(1, 30) = 7.94$ ,  $MSE = 0.475$ ,  $p = .008$ . This spatial distribution effect is shown as the rightmost pair of bars in Figure 4. As in Experiment 1, relative color contrast played a significant role in modulating the strength of orienting to the moving probe, and the direction of this effect was as predicted, with red static bars being more effective than pink ones in competing for attention with the moving probe.

## GENERAL DISCUSSION

The major results of these experiments can be summarized succinctly. When a small moving object appeared with additional static objects in the visual field, infants generally oriented toward the side of the display with this moving bar. They did so more often when the bar oscillated with greater amplitude. The strength of this orienting, however, was modulated by the characteristics and distribution of the static objects. Static bars differed in how effectively they captured

attention depending on their color contrasts against the white background. In particular, orienting to the moving probe remained generally above chance, but the strength of this orienting was either enhanced or reduced depending on whether most of the bars with greater relative color contrast with the background color appeared ipsilaterally or contralaterally, respectively, with respect to the hemifield with the moving target. At 3.5 months of age, the problem of where to look first when many objects appear simultaneously in the visual field is resolved most often by looking toward a moving object, but these experiments also revealed that failures to orient to this moving probe were not always random. Objects with stronger color (greater color contrast against the background color) tend to draw orienting more often than objects with weaker color. This result held for two of the three color comparisons used across the experiments (red vs. green and red vs. pink but not pink vs. green).

It is important to emphasize that orienting was tempered by the relative color contrasts of the objects against their backgrounds. The same spatial distribution bias favoring red over green shown in Experiment 1 was also shown in our prior experiments (Dannemiller, 1998, 2000). It is possible to argue that this prior effect depends on some intrinsic preference for red over green, such as has been observed in chromatic preference experiments (Adams, 1987; Bornstein, 1975). These results and those of Ross and Dannemiller (1999) show that the explanation is a simpler one in this paradigm; green is not inherently less salient than red when both appear together. Rather, its salience depends on its color contrast with the background relative to the color contrasts of the other objects in the visual field. A 3.5-month-old's visual system apparently uses a competitive mechanism in overt orienting that gives greater weight to objects with greater color contrast, although it bears repeating that motion is still weighted heavily in this process.

Why might the relative color contrasts of the static bars modulate the tendency to orient to the moving probe? One answer is simply that objects with greater color contrast are more visible to the infant, and given a choice between looking at something that is more visible versus something that is less visible, the visual system at this early age resolves the choice naturally by favoring the more visible object. This is similar to other explanations that have been offered to account for visual preferences at this age (e.g., Banks & Ginsburg, 1985; Gayl, Roberts, & Werner, 1983). There is an important difference, however, between these prior preference experiments and the current data. Visual preferences at this age are usually tested by allowing prolonged inspection of two patterns and observing statistically greater total looking to one pattern over the other. In contrast, the data in this experiment were collected by observing initial orienting to displays with spatial distributions of small, discrete objects. The median judgment time was approximately 2 sec. These results suggest that mechanisms operate very quickly after the initial appearance of objects to guide infants toward the side with a moving probe, but even within approximately 2 sec of their

appearances, the characteristics of static elements also play a role in determining orienting.

This visibility hypothesis is consistent with other data shown in Ross and Dannemiller (1999). In two conditions from that experiment, bars of different luminance contrasts were used in place of color contrasts. In one of these conditions, bars with 66% contrast appeared with an equal number of bars with 50% contrast. In a second condition, bars with 33% contrast appeared with an equal number of bars with 20% contrast. There was no color contrast in either of the conditions. All other things being equal, one would expect higher contrast bars to be more visible than lower contrast bars. The modulation of orienting by the locations of the higher contrast bars was statistically significant in the 33% versus 20% condition, and the trend was in the same direction in the 66% versus 50% condition, although the effect did not reach conventional significance levels. Taken together with the color contrast results from the current experiment, these data suggest that visibility plays an important role in determining overt orienting at 3.5 months.

There were two other interesting effects observed in these experiments. First, in three of the four analyses, a small change in the amplitude of the moving probe from  $0.75^\circ$  to  $1.0^\circ$  led to a significant improvement in sensitivity to motion. This effect was expected, and it simply shows that stronger signals, whether ultimately motion or local temporal contrast, lead to more consistent orienting. This will not be discussed further. Second, the color of the moving probe also affected sensitivity to motion with the red and pink pairing. This effect was not expected. It is possible that this represents sampling error because it has been observed only occasionally in our prior work.

One way to estimate the amount of sampling error in these measures is to compare the results from identical trial types observed with different samples and in the context of different color pairings. There are two such trial types in this data set. Sensitivity to motion with displays having all red bars in Experiment 2 (mean  $d' = 0.690$ ,  $SEM = 0.103$ ) can be compared to the sensitivity with displays having all red bars from the RG group in Experiment 1 (mean  $d' = 0.735$ ,  $SEM = 0.094$ ). These two trial types are exact replications of each other, with 27 static red bars and one red moving probe. The mean sensitivities are clearly equal within experimental error, differing only by  $d' = 0.045$ . Similarly, the displays with all pink bars from the PG group in Experiment 1 are identical to the displays with all pink bars in Experiment 2, so sensitivities should be equal, providing another estimate of replicability and measurement/sampling error. The two mean sensitivities were  $d' = 0.487$  ( $SEM = 0.094$ , Experiment 1) and  $d' = 0.445$  ( $SEM = 0.101$ , Experiment 2). Once again, the difference was small,  $d' = 0.042$ , and almost identical to the difference between sensitivities to the all-red displays ( $d' = 0.045$ ). The reliability of these results makes sampling error an unlikely explanation for the unexpected result that overall sensitivity was higher in Experiment 2 on mixed trials with the red moving

probe than it was with the pink moving probe. This may be a real effect in which motion is combined with color contrast to determine the ultimate salience of a moving bar. These comparisons also argue that sensitivity to motion with uniform trial types is independent of the other trial types with which they are mixed in blocks of trials. In both of the cases above, the uniform trials were presented in blocks with different mixed trial types (e.g., red and green, pink and green, or red and pink), yet sensitivity to motion on uniform trials was independent of these differing experimental contexts.

One prediction from the relative color contrast hypothesis was not confirmed in the data. Based on adult color perception, we expected the pink bars to be less salient than the green bars when they appeared together in the mixed condition of Experiment 1. This was not the case. Instead, there was no spatial distribution effect. This lack of an effect implies that the pink and green that we used appeared approximately equally salient to these infants. There are several possible explanations for this result. First, the prediction that we made was based on adult color vision, so it is entirely possible that color vision in infants at this age differs enough from adult color vision to render the predictions only marginally accurate. In other words, although adults may perceive the pink bars to have less color contrast than green bars when both appear within the same white background, it is uncertain whether the same holds true for infants. A second possibility is that both pink and green bars appeared achromatic to these infants. Banks and Bennett (1988) proposed a model of color vision in early infancy that captured reasonably well much of the previous work on chromatic discriminations by infants at approximately 2 months of age. When the white, red, green, and pink colors are plotted on the diagram shown in Banks and Bennett (1988, Figure 11, p. 2069), only the red and white are clearly discriminable according to the color vision model proposed by Banks and Bennett. The green, white, and pink colors fall within the zone of nondiscrimination, although pink and white should clearly be less discriminable than green and white, given the probabilistic nature of such discriminations. The Banks and Bennett model represents discriminations of white from chromatic targets in the absence of luminance contrast. The bars in the experiments reported here also had considerable luminance contrast with the white background (66%), so the Banks and Bennett model provides only very weak support for the possibility that the green and pink bars appeared to these infants achromatic against the white background. If these bars did appear achromatic to these infants, then luminance contrast alone may have determined the relative saliences of the pink and green bars. Their luminance contrasts were equal, which is compatible with the lack of any spatial distribution effect. Further experiments are necessary to test this achromatic appearance explanation.

In previous work using this paradigm (Dannemiller, 1998, 2000; Ross & Dannemiller, 1999), orienting to the hemifield with the moving probe has been modeled using signal detection theory. The static bars and the moving probe are

assumed to lead to internal signals to orient, and these internal signals are perturbed by noise. Orienting is directed initially toward the hemifield containing the element that produces the largest internal response on each trial (winner-take-all or maximum-response model). A similar model has been used with adults to explain detection of signals in the presence of multiple noise samples (Foley & Schwarz, 1998; Palmer, Ames, & Lindsey, 1993). The color contrast competition effects in these data are assumed to reflect slightly different mean internal responses to the two color classes. Such a model predicts ipsilateral versus contralateral sensitivity differences like those observed here. By this model, the strength of the internal signal to orient to a static bar is influenced significantly by its color contrast.

As simple as this signal detection model is, it must be admitted that these experiments do not provide definitive evidence that it is correct. Without a direct manipulation of the number of static objects in the visual field, it is impossible to determine whether or not the discrete bars are being treated independently, as is required by the maximum response decision rule, or instead, if it is the spatially summed activity that biases attention to one side of the display or the other. In other words, it is possible that the mechanisms that determine exogenous orienting show large spatial summation areas so that a spatial imbalance in the distribution of the bars of different colors leads to gross, overall differences in the summed activity in the two hemifields. The side with more of the red bars may appear grossly more "reddish" to the infants than the opposite side of the display. Experiments are planned to distinguish these different models of the decision variable (maximum response vs. aggregate response) to which orienting is more closely related. Regardless of which of these decision rules is more closely related to behavior in this paradigm, however, the empirical results are robust and indicate that color contrast and motion have significant roles in the process.

In the maximum-response model described earlier, one of the assumptions is that all of the bars on the display lead to an internal response that is perturbed by noise. The maximum of these noise-perturbed responses then captures orienting. It is instructive to consider what this internal noise assumption implies about response variability in the early visual-attentional system. There are two possible implications of this assumption. One is that the noise that perturbs these internal responses is motion noise. The other is that the noise is not necessarily motion noise, but rather that it is noise that influences responses at some level of the visual system at or after which salience is computed. These two possibilities for the major sources of noise have different implications for early visual-attentional development. Consider these two possibilities in turn.

The signal detection model used previously is silent about the source of the noise that perturbs these internal responses (Dannemiller, 1998). All that matters is that the responses to all of these bars, moving or static, can be placed on a single, internal dimension that forms the basis of the decision to pick the maximum. One natural possibility is that this dimension represents motion strength.

The moving bar generally leads to the largest response, but given motion noise, occasionally one of the static bars may actually exceed the response to this moving target. In other words, this interpretation of the noise implies that there is enough internal motion noise in the early visual system that static bars occasionally appear to the infant to be moving with greater amplitude than the bar that is actually moving. This is really no different in principle than assuming that in the adult visual system, small eye movements and other sources of internal noise occasionally lead the adult to mistake a static bar for a bar that is moving near the threshold of movement. This possibility must be considered in light of the alternative interpretation of the noise.

The alternative interpretation of this internal noise is that it is not specifically motion noise. Rather, it is noise that is added at or after some stage in the visual pathway at which salience is computed. This salience computation is what determines initial orienting. To understand the necessity of postulating this stage of processing, consider the fact that most objects that we see are multidimensional; two objects may differ in color, size, movement, location, relevance for current behavioral goals, and so forth. If it is granted that exogenous orienting is not completely random, then some salience computation that differentially weights these multiple dimensions must be involved in determining which of the many objects that we see will garner the first look if several of them appear simultaneously. With this alternative interpretation of the noise source, all of the elements in the visual field are assumed also to lead to responses that can be distributed on a single dimension, but this dimension is not necessarily related exclusively to movement strength, as was assumed in the first alternative. The existence of a salience computation is prominently featured in many models of adult visual attention (Blaser, Sperling, & Lu, 1999; Koch & Ullman, 1985) and saccadic selection (Findlay & Walker, 1999), and it has been attributed to various brain structures such as the pulvinar (Robinson, 1993; Robinson & Petersen, 1992), the posterior parietal cortex (Taylor & Stein, 1999), and the lateral intraparietal area (Kusunoki, Gottlieb, & Goldberg, 2000).

Is it possible to decide among these alternative conceptualizations of the noise that affects exogenous orienting? This noise is not directly observable using behavioral methods such as those just listed. Nonetheless, it is possible to speculate that the second alternative makes more sense when all of the data from this and previous studies using this paradigm are considered. These results show that the color contrasts and luminance contrasts of the static bars in the visual field systematically affect the strength of orienting to the moving target (Dannemiller, 1998, 2000; Ross & Dannemiller, 1999). Unless one is willing to assume that greater color contrast leads to higher mean levels of internal motion noise, then the salience-noise model makes more sense than the motion-noise model. It is not difficult to imagine that greater levels of luminance contrast might lead to higher mean levels of motion noise. Motion is carried primarily by the magno-cellular

pathway (Maunsell, Nealey, & DePriest, 1990), and achromatic contrast significantly influences responses in this pathway in primates (Benardete, Kaplan, & Knight, 1992; Solomon, White, & Martin, 1999). Although it is true that some of the neurons in the magno-cellular pathway (e.g., the middle temporal area [MT]) respond to motion signaled by color differences alone, when both luminance and chromatic contrast are present, the chromatic contrast has little to no effect on the responses of motion-sensitive neurons in the MT (Thiele, Dobkins, & Albright, 1999). Rather than considering objects with greater color contrast to lead to greater levels of internal motion noise, it makes more sense to think of this effect as indicative of how color contrast gets weighted with other dimensions in a salience computation that ultimately resolves the problem of where to look first when multiple objects appear simultaneously or where to look next after fixation (Findlay, Brown, & Glichrist, 2001). Therefore, one interpretation of these and previous results is that objects with greater color contrast make better attentional and saccadic targets than objects with lesser color contrast.

There is one specifically developmental argument for the motion-noise interpretation that must be considered. Measures of sensitivity to movement direction early in postnatal life are compatible with the idea that stimuli defined by luminance contrast or those defined by chromatic contrast may be detected by mechanisms sensitive to the direction of motion (Dobkins & Teller, 1996). This is different from the fact that the detection of stimuli defined purely on the basis of color differences is mediated by mechanisms in adults insensitive to the direction of motion (i.e., nonmotion mechanisms). This difference between infants and adults could suggest that chromatic stimuli lead to more motion noise in the magno-cellular pathway early in life than later in life, especially if the color differences occur in the presence of luminance contrast. It is impossible at this point to decide between the motion-noise and the salience-noise interpretations of the signal detection model discussed earlier. Manipulation of other stimulus characteristics, such as size and orientation, may contribute to constraining the site of this response variability in the early visual-attentional system.

In summary, competitive mechanisms that determine overt orienting at 3.5 months of age (and earlier; Dannemiller, 2000) resolve the problem of where to attend initially on the appearance of multiple objects in the visual field by using color contrast as a relevant stimulus dimension. Objects with greater color contrasts against their backgrounds have a greater likelihood of capturing initial attention, although attention is most often drawn to the hemifield with a unique moving object. The influence of color contrast probably reflects a simple visibility effect; infants look first at what they can see best, and color contrast has a significant impact on what they see best at 3.5 months of age (see examples in Teller, 1997). The processes that determine overt orienting operate on relative color contrast so that the salience of a small object depends on the colors of the other objects with which it appears. Small green bars are less salient than small red bars,

but they are approximately equally as salient as small pink bars. Competitive mechanisms at this early age tend to guide orienting to parts of the visual field with the most visible objects. Finally, it is worth remembering that these results tell us only about some of the factors that affect initial orienting. The information that infants acquire visually also depends on subsequent scanning and prolonged inspection.

## ACKNOWLEDGMENTS

This research was supported by NICHD R01 HD32927 and a University of Wisconsin Vilas Foundation Fellowship to James L. Dannemiller. I thank Jackie Roessler for observing the infants, Megan Dunnigan and Manya Qadir for scheduling the infants, and Daniel Replogle for all of the computer programming.

## REFERENCES

- Adams, R. J. (1987). An evaluation of color preference in early infancy. *Infant Behavior and Development*, 10, 143–150.
- Adams, R. J., & Courage, M. L. (1998). Human newborn color vision: Measurement with chromatic stimuli varying in excitation purity. *Journal of Experimental Child Psychology*, 68, 22–34.
- Aslin, R. N., & Salapatek, P. (1975). Saccadic localization of peripheral targets by the very young human infant. *Perception and Psychophysics*, 17, 293–302.
- Banks, M. S., & Bennett, P. J. (1988). Optical and photoreceptor immaturities limit the spatial and chromatic vision of human neonates. *Journal of the Optical Society of America, Part A*, 5, 2059–2079.
- Banks, M. S., & Ginsburg, A. P. (1985). Infant visual preferences: A review and new theoretical treatment. In H. W. Reese (Ed.), *Advances in child development and behavior* (pp. 207–246). New York: Academic.
- Benardete, E. A., Kaplan, E., & Knight, B. W. (1992). Contrast gain control in the primate retina: P cells are not X-like, some M cells are. *Visual Neuroscience*, 8, 483–486.
- Blaser, E., Sperling, G., & Lu, Z. L. (1999). Measuring the amplification of attention. *Proceedings of the National Academy of Sciences of the United States of America*, 96, 11681–11686.
- Bornstein, M. H. (1975). Qualities of color vision in infancy. *Journal of Experimental Child Psychology*, 19, 401–419.
- Bronson, G. (1994). Infants' transitions toward adult-like scanning. *Child Development*, 65, 1243–1261.
- Cohen, L. B. (1973). A two process model of infant visual attention. *Merrill-Palmer Quarterly of Behavior and Development*, 19, 157–180.
- Dannemiller, J. L. (1998). A competition model of exogenous orienting in 3.5-month-old infants. *Journal of Experimental Child Psychology*, 68, 169–201.
- Dannemiller, J. L. (2000). Competition in early exogenous orienting between 7 and 21 weeks. *Journal of Experimental Child Psychology*, 76, 253–274.
- Dobkins, K. R., & Teller, D. Y. (1996). Infant motion:detection (M:D) ratios for chromatically defined and luminance-defined moving stimuli. *Vision Research*, 36, 3293–3310.



- Findlay, J. M., Brown, V., & Glichrist, I. D. (2001). Saccade target selection in visual search: The effect of information from the previous fixation. *Vision Research*, 41, 87–95.
- Findlay, J. M., & Walker, R. (1999). A model of saccade generation based on parallel processing and competitive inhibition. *Behavioral and Brain Sciences*, 22, 661–721.
- Foley, J. M., & Schwarz, W. (1998). Spatial attention: Effect of position uncertainty and number of distractor patterns on the threshold-versus-contrast function for contrast discrimination. *Journal of the Optical Society of America, Part A, Optics and Image Science*, 15, 1036–1047.
- Gayl, I. E., Roberts, J. O., & Werner, J. S. (1983). Linear systems analysis of infant visual pattern preferences. *Journal of Experimental Child Psychology*, 35, 30–45.
- Haith, M. (1980). *Rules that babies look by*. Hillsdale, NJ: Lawrence Erlbaum Associates, Inc.
- Koch, C., & Ullman, S. (1985). Shifts in selective visual attention: Towards the underlying neural circuitry. *Human Neurobiology*, 4, 219.
- Kusunoki, M., Gottlieb, J., & Goldberg, M. E. (2000). The lateral intraparietal area as a salience map: The representation of abrupt onset, stimulus motion, and task relevance. *Vision Research*, 40, 1459–1468.
- Maunsell, J., Nealey, T., & DePriest, D. (1990). Magnocellular and parvocellular contributions to responses in the middle temporal visual area (MT) of the macaque monkey. *Journal of Neuroscience*, 10, 3233–3334.
- Nothdurft, H. C. (2000). Salience from feature contrast: Additivity across dimensions. *Vision Research*, 40, 1183–1201.
- Palmer, J., Ames, C. T., & Lindsey, D. T. (1993). Measuring the effect of attention on simple visual search. *Journal of Experimental Psychology: Human Perception and Performance*, 19, 108–130.
- Quinn, P. C., Burke, S., & Rush, A. (1993). Part whole perception in early infancy: Evidence for perceptual grouping produced by lightness similarity. *Infant Behavior and Development*, 16, 19–42.
- Richards, J. E., & Hunter, S. K. (1997). Peripheral stimulus localization by infants with eye and head movements during visual attention. *Vision Research*, 37, 3021–3035.
- Robinson, D. L. (1993). Functional contributions of the primate pulvinar. *Progress in Brain Research*, 95, 371–380.
- Robinson, D. L., & Petersen, S. E. (1992). The pulvinar and visual salience. *Trends in Neurosciences*, 15, 127–132.
- Ross, S., & Dannemiller, J. L. (1999). Color contrast, luminance contrast and competition within exogenous orienting in 3.5-month-old infants. *Infant Behavior and Development*, 22, 383–404.
- Solomon, S. G., White, A. J. R., & Martin, P. R. (1999). Temporal contrast sensitivity in the lateral geniculate nucleus of a new world monkey, the marmoset *Callithrix jacchus*. *Journal of Physiology*, 517, 907–917.
- Taylor, K., & Stein, J. (1999). Attention, intention and salience in the posterior parietal cortex. *Neurocomputing*, 26, 901–910.
- Teller, D. Y. (1979). The forced-choice preferential looking procedure: A psychophysical technique for use with human infants. *Infant Behavior and Development*, 2, 135–153.
- Teller, D. Y. (1997). First glances: The vision of infants. The Friedenwald lecture. *Investigative Ophthalmology and Visual Science*, 38, 2183–2203.
- Teller, D. Y., & Bornstein, M. H. (1987). Infant color vision and color perception. In P. Salapatek & L. B. Cohen (Eds.), *Handbook of infant perception* (pp. 185–236). Orlando, FL: Academic.
- Teller, D. Y., Pereverzeva, M., Chien, S. H.-L., & Palmer, J. (2000). Are adult and infant isoluminance points the same? *Investigative Ophthalmology and Visual Science Supplement*, 41, S727.
- Thiele, A., Dobkins, K. R., & Albright, T. D. (1999). The contribution of color to motion processing in macaque middle temporal area. *Journal of Neuroscience*, 19, 6571–6587.
- Thorpe, L. A., Trehub, S. E., Morrongiello, B. A., & Bull, D. (1988). Perceptual grouping by infants and preschool children. *Developmental Psychology*, 24, 484–491.
- Zenger, B., Braun, J., & Koch, C. (2000). Attentional effects on contrast detection in the presence of surround masks. *Vision Research*, 40, 3717–3724.

## APPENDIX

Two-Dimensional Representations of Color:  $u'$ ,  $v'$  Color Space

The color space shown in Figure 2 is obviously two-dimensional. How is it possible to represent the effect of a color on a trichromatic visual system like that possessed by human adults with a two-dimensional space? Consider first the problem of representing color in a three-dimensional space. Given a trichromatic visual system, it would be possible to determine the responses of the three color mechanisms to a given wavelength distribution. For example, designate the three color vision mechanisms as short-wavelength sensitive, medium-wavelength sensitive, and long-wavelength sensitive. Now, given the wavelength spectrum of the stimulus in question, and given the sensitivities of these three mechanisms to the wavelengths in the visible spectrum (from approximately 400–700 nm), the absorptions produced in these three mechanisms by the wavelength distribution in question can be calculated. These three numbers define the effect of that wavelength distribution on this trichromatic visual system. They could be plotted in a three-dimensional space with axes that are the absorptions of the three color mechanisms.

Suppose that the wavelength distribution in question were simply increased in intensity by a factor of two. Now all of the absorptions would double, but the hue would still be the same.<sup>4</sup> Instead of representing the absolute absorption levels of the three mechanisms, all of these levels could be normalized by dividing each one by the sum of all three absorptions. Notice that when this is done, the three relative absorptions are now scaled to a value between 0 and 1, and the sum of these relative absorptions will always be 1.0 for any color. This normalization accomplishes two things. First, it permits a representation of color that is essentially independent of the absolute intensity of the stimulus. Second, it permits any color for this trichromatic visual system to be represented on a two-dimensional plot. The apparently missing third mechanism can be easily calculated by summing the ordinate and abscissa and subtracting this sum from 1.0. Thus, the effects of any color on this trichromatic visual system can be represented on a two-dimensional plot such as the one shown in Figure 2. This description is conceptually consistent with two-dimensional representations of color, although it is not precisely what is represented in  $u'$ ,  $v'$  color space.

There is a further advantage of plotting colors in this space. For adults, this color space is more uniform than other color spaces (e.g.,  $x$ ,  $y$ ). By uniform is meant that distance in this color space can be taken as an approximate index of discriminability; the farther apart two colors are in this space, the more discriminable they appear

<sup>4</sup>Hue does not always remain invariant with intensity, a phenomenon known as the Bezold–Bruecke hue shift, but this is beyond the scope of the current discussion.

to be. This is no guarantee that the  $u', v'$  color space is an accurate representation of color discriminability for these infants, but, as noted earlier, there is some empirical support for using this space as a first approximation to the color vision of infants at this age. What is most likely to differ between infants and adults is the size of the steps in this color space necessary to produce just noticeable differences in color. These steps are much larger for infants than for adults (e.g., see Banks & Bennett, 1988). This means that the discriminability of colors for infants may not exactly follow from the distance between two colors in this  $u', v'$  color space.