Developmental Science 8:6 (2005), pp 567–582

PAPER

Evidence against a maximum response model of exogenous visual orienting during early infancy and support for a dimensional switching model

James L. Dannemiller

Department of Psychology, University of Wisconsin – Madison, USA

Abstract

Very young infants orient overtly with eye and head movements to salient events in their visual environments, but those events rarely occur in the absence of competing visual stimuli. Two different models of how this kind of orienting is related to number and distribution of elements in the stimulus field were tested with infants across the age range from 2 to 5 months in four experiments. A set size manipulation in Experiments 1–3 produced data that were mostly inconsistent with the Maximum Response model proposed by Dannemiller (1998), especially at ages over 3 months. Experiment 4 produced data from 3.5-month-olds that were consistent with an alternative Dimensional Switching model that assumed that there was switching across trials in the stimulus dimension that drove orienting. This Dimensional Switching model can explain the small to nonexistent set size effects observed in the first three experiments as well as data from previous experiments using this paradigm. Factors that could produce this kind of dimensional switching over time were considered and other implications of this model for understanding the development of overt visual orienting were discussed.

Introduction

As vision develops over the first 6 postnatal months more and more information becomes available to the infant. For example, within a dimension like spatial frequency, increasing spatial detail becomes available (Skoczenski & Norcia, 1999). Within a dimension like movement, increasingly finer distinctions of direction become possible (Wattam-Bell, 1991). This additional information will be useful for tasks such as object recognition and event perception. Processes that link information across stimulus dimensions – the binding problem (Treisman, 1996) – will also have to change to accommodate this newly available information within each dimension. Perhaps as importantly as any of these quantitative changes within or between stimulus dimensions, however, is the increasing need for selectivity that they engender. At any given moment, the infant is confronted with a visual field that must be differentiated into surfaces and objects and from which one of these objects must be selected as the next focus of attention. How do these selection processes change across the first half year of life?

One attempt to answer such questions has been to generate models of preferential looking in young infants. These models have as their goal predicting at which of two patterns the infant will look longer, and in this sense, they are addressing the issue of selectivity at the level of the whole pattern (Banks & Ginsburg, 1985; Gayl, Roberts & Werner, 1983; Karmel, Lester, McCarvill, Brown & Hofmann, 1977). Changes in preferences across age in these models are accounted for by changes in the sensory processing that underlie the ultimate decision to look at one or the other pattern. These models generally use a Maximum Response (MR) decision rule to predict which of two patterns the infant will prefer. After filtering the patterns through a representation of the infant's spatial contrast sensitivity function, the pattern that produces the maximum response is predicted to be the one that the infant will prefer. The models can fail, however, because as the infant gains experience with certain classes of patterns (e.g. faces), s/he shows preferential orienting toward those patterns that is not predicted solely on the metrics incorporated in the models (Dannemiller & Stephens, 1988). The models can also fail because orienting at an early age might be governed by subcortical mechanisms with certain innate biases (Morton & Johnson, 1991).

Address for correspondence: James L. Dannemiller, Department of Psychology MS-25, Rice University, PO Box 1892, Houston, TX 77251-1892, USA; e-mail: dannemil@rice.edu

Another approach to studying the development of selectivity is to manipulate more local characteristics of the stimulus. Using a visual orienting paradigm, Dannemiller and colleagues were able to show that infants from 2 to 5 months of age were sensitive to the local distributions of bars that varied in color contrast, luminance contrast and luminance polarity when the positions of these bars were varied relative to a salient moving bar (Dannemiller, 1998, 2000, 2002; Dannemiller & Stephens, 2001; Ross & Dannemiller, 1999). Infants across the age range from 7 to 21 weeks of age showed these color/movement spatial distribution effects (Dannemiller, 2000). Interestingly, Dannemiller (1998) also used a Maximum Response model to account for these results. The model assumed that in a visual field with only a single moving bar and many static bars, it was this moving singleton that generally produced the maximum internal response on each trial. Occasionally, however, because of internal noise in the infant's nervous system, the maximum internal response could occur to one of the other static elements in the field. These latter occurrences were not completely random in the sense that when the moving bar failed to capture attention on a given trial, the infant's orienting was predictable based on the relative saliences of the remaining elements in the visual field. The MR model proposed by Dannemiller (1998) was based on a similar model of threshold visual search in adults proposed by Palmer, Ames and Lindsey (1993).

Both the preferential looking models cited above and Dannemiller's (1998) MR model assume that the infant either orients first or looks longer at the side of the visual field with the element or the pattern that produced the largest internal response. Because the idea of an internal response is a hypothetical construct, it is difficult to test this idea directly. There is, however, an alternative model of how selection might occur, especially in displays in which there is variation on multiple dimensions. Perhaps, rather than selection occurring at the level of the individual element in the visual field, selection first occurs for a class of elements sharing a given feature. Another way of saying this is that selection might occur first at the level of stimulus dimensions such as color, movement direction, orientation, etc. For example, all of the regions in the visual field that share the feature 'red' would get selected (Bichot, Cave & Pashler, 1999; Mounts & Melara, 1999). Further selection could then occur among all of the elements possessing this feature. The selected dimension could switch randomly across time, subject at least partially to endogenous factors or to short-term habituation of attention. I will refer to this alternative model as the Dimensional Switching (DS) model. I next contrast the predictions of these two models for a set size manipulation.

Predictions of the MR and DS models for a set size manipulation

The MR model

The Maximum Response (MR) model was presented in Dannemiller (1998). It is based on signal detection theory (Green & Swets, 1966) and a maximum response decision rule. The idea is quite simple. Consider a display in which there are multiple static bars and one moving bar such as the one shown schematically in Figure 1. Each of the bars on the display leads to an internal response that serves as a stimulus to orient. These internal responses are perturbed by noise. There is some mean internal response for all of the static bars, and the individual responses can be represented as deviating randomly with some variance around this mean. Similarly, there is some mean internal response to the moving stimulus, and the internal response to this stimulus on a given trial deviates

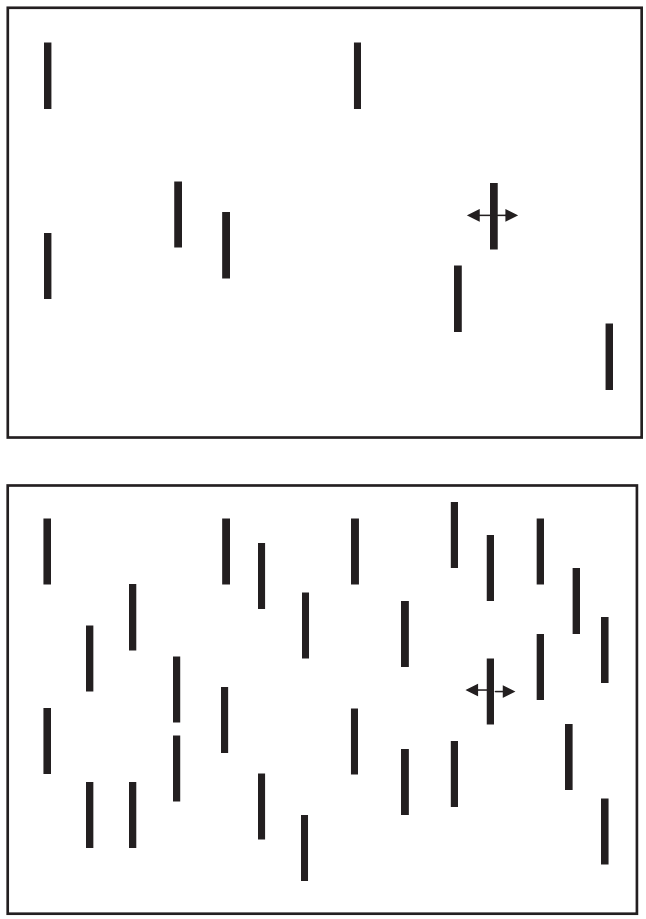

Figure 1 *Schematic versions of the displays with 8 bars (top) and with 28 bars (bottom). The dimensions are not drawn to scale (see text for actual dimensions). The arrows indicate oscillating movement.*

from this mean by some variance across trials. It is typically assumed that these variances are the same. Furthermore, past research (e.g. Dannemiller, 1998, 2000) shows that infants orient above chance levels to the side with the moving bar, so in this framework, this may be modeled as a greater mean internal response to the moving bar than to the static bars.

The noise that perturbs these responses in usually modeled with a Gaussian distribution. Yellott (1977) has shown that the computations are more tractable if double-exponential noise distributions are used instead. Double exponential cumulative distribution functions do not differ appreciably from cumulative normal distribution functions, so it probably makes little difference given the precision of the data below which of these two functions is used.

For ease of computation, it may be assumed that the mean internal response to the static bars is 0. The mean internal response to the moving bar may then be symbolized as μ_m. Yellott's development shows that the probability that the maximum response occurs on the side with the moving target is then:

$$percent\ correct_{observed} = \frac{e^{\mu_m} + g - 1}{e^{\mu_m} + 2g - 1} \quad (1)$$

In this equation, g represents the number of static bars on the side opposite to the moving target. The mean internal response to the moving target, μ_m, may be seen as the distance between the mean internal responses to the static and moving internal response distributions in units of their common standard deviation.

Once the mean internal response to the moving target, μ_m, is specified, the predictions of this equation for a set size manipulation are straightforward. Because this equation gives the probability that the maximum internal response will occur on the side with the moving target (not necessarily to the moving target), and because the MR model by definition assumes that orienting is determined by the element that produced the largest internal response, then $percent\ correct_{observed}$ in this equation may be interpreted as the predicted percentage of trials on which the infant oriented toward the side with the moving bar. Three different values of the μ_m parameter were used to generate the predictions shown in Figure 2. The exact values of this parameter are not important because (a) they are likely to vary across infants, and (b) it is the trend that is important for the prediction. As more static bars are added symmetrically to the two sides of the display, the percentage of correct judgments should decrease.

It is primarily the presence of substantial internal noise that leads to this prediction. The maximum

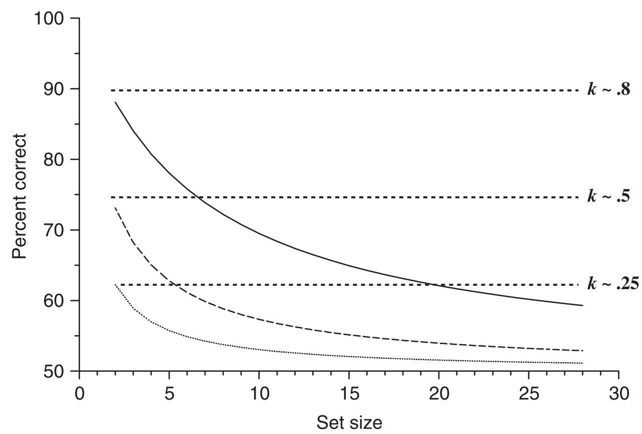

Figure 2 *Predictions of the MR and DS models. The smooth curves were generated from the MR model using three different values of the strength of the internal response to the moving bar (see Equation 1). The strength of this parameter is largest for the top curve and smallest for the bottom curve. The horizontal lines show the null set size effects predicted by the DS model. The value of* k *by each line represents the fraction of trials with orienting governed by movement (see Equation 2). On the remaining fraction (1 –* k*) orienting will be at chance, 50%, by experimental design, so the horizontal line is the weighted sum 100*k *+ 50(1 –* k*).*

response on the side with the moving bar is dominated by the response to that element and changes little as more static bars are added to that side of the display. In contrast, the probability that one of the internal responses from a static bar on the side contralateral to the moving bar will exceed the internal response to the moving bar increases substantially as more bars are added contralaterally.[1]

The DS model

This model assumes that the dimension that governs orienting switches randomly across trials. In a display with variation among the elements in movement and color, for example, on some trials, movement will govern orienting, but on some trials, color will govern orienting. In the set size experiments described below, the bars only differed on the dimension of movement, so while color could govern orienting on some proportion of trials, it could not *systematically* influence the direction of orienting because all of the bars in the field were the same color, and they were spatially distributed evenly across the two halves of the display.

[1] The behavior of this model reflects the statistics of maxima and minima rather than the statistics of central tendency on which the most familiar statistical tests are based.

To generate quantitative predictions from the DS model, suppose that the moving target governs orienting on a fraction, k, of the trials. By definition, when this occurs, orienting is driven to the side with the moving bar on 100% of these trials. On the complementary fraction of trials, $1 - k$, orienting is determined either randomly or by the characteristics of the static elements on the display. In Experiments 1, 2 and 3 below, the total number of bars on the display was always divided equally between the two halves of the display, and all of these bars were identical. Thus, on the fraction $1 - k$ of the trials, orienting will be random with respect to the location of the moving bar because there is nothing to distinguish the two sides of the display with the exception of small, random differences in the locations of the bars on each side of the display. The prediction for the observed percentage of correct judgments according to the DS model for the conditions of Experiments 1, 2 and 3 may be written as:

$$\textit{percent correct}_{observed} = 100k + 50(1 - k) \qquad (2)$$

Notice that the observed percentage of correct judgments is a mixture or weighted sum of two percentages, 50% and 100%, and it is independent of the number of bars on the display. For example, if movement governed orienting on 40% of all trials, and on the remaining 60% of the trials the infant attended to the colors of the bars, then the observed percentage of correct judgments would be $[(100 \times 0.4) + (50 \times 0.6)] = 70\%$. The prediction of the DS model for three different values of k, the fraction of trials on which orienting is governed by movement, are shown by the horizontal lines in Figure 2.

Thus, the set size manipulation should distinguish between the two models. The MR model predicts a sharp drop in orienting toward the moving bar as more static bars are added to the visual field. The DS model predicts no effect of this set size manipulation with the dimension that governs orienting randomly switching occasionally to force looks at the static bars on either the side ipsilateral or contralateral to the moving bar. Although this set size manipulation is sufficient in principle to distinguish between these two models, it must be recognized that the DS model is making a null prediction. This will be addressed in Experiment 4 in which the DS model is used to derive and test a non-null prediction.

Developmental implication of the MR and DS models

Several differences between these models are worth highlighting for their developmental implications.

1. The DS model could naturally incorporate processes known to be important in early perceptual and cognitive development such as habituation (Schoener & Thelen, in press; Sirois & Mareschal, 2004). What factors would cause shifts over time in the dimension to which an infant might attend? Certainly, short-term habituation could cause a type of switching over time in the dimension of a complex display that garnered initial attention. The MR model has no explicit place for incorporating such a process; rather, it is always a purely random event based on internal noise that determines which element in the visual field captures orienting. This kind of internal noise has been used previously to model infant visual exploration (Robertson, Guckenheimer, Masnick & Bacher, 2004). The DS model emphasizes the endogenous nature of the switching process, and there is evidence that some aspects of visual attention are coupled to endogenous factors like movement generation as early as 3 months (Bacher & Robertson, 2001; Robertson, Bacher & Huntington, 2001). The switching process in the DS model could also be related to the ease with which infants of different ages can disengage attention. Older infants typically disengage and shift attention more rapidly than younger infants (Colombo, Mitchell & Horowitz, 1988; Frick, Colombo & Saxon, 1999).
2. The increasing availability of stimulus detail might be expected to cause a shift from responding based on an MR-like model to responding based on a DS-like model. For example, as increasingly finer distinctions become available on a dimension like color, it could be possible that attention would naturally shift between different values on this dimension (i.e. different colors) over short periods of time in the service of exploration. Different rates of development across different stimulus dimensions (e.g. movement versus color sensitivity) could also influence how much switching between these dimensions occurred during a given attentional episode at a particular point in development. There is clear evidence that pathways subserving the processing of different stimulus dimensions mature at different rates (for reviews see Atkinson, 1992; Dannemiller, 2001).
3. The DS model contains the implicit assumption that elements in the visual field that share a common feature such as color are selected together. The MR model does not contain this assumption; all of the elements in the field are treated independently. Is there evidence for such grouping by feature similarity during this period? Three-month-olds can group spatially separated elements based on a common lightness feature (Quinn, Burke & Rush, 1993). Thus, there is empirical support that at least one of the component processes in the DS model, selection based on feature similarity, is in place by at least 3 month of age.

Experiment 1

The first two experiments comprised two different, within-subject set size manipulations. These experiments were conducted sequentially. Because no explicit statistical comparison is made between the results of these two experiments, they are described here as two different conditions of the same experiment.

Method

Participants

Infants were recruited from birth announcements in a local newspaper. A total of 223 infants participated in the two conditions described below. The infants in each condition ranged in age from 7 to 22 weeks. Age was sampled uniformly across this range for the purpose of using it as a covariate in regression analyses. Twenty-eight of these 223 infants failed to provide usable data for reasons that ranged from fussiness and sleepiness to prematurity greater than two weeks. The attrition rate was therefore 8%. Ninety-seven infants (44 females) provided complete data in one of the conditions described below, and 98 infants (52 females) provided complete data in the other condition.

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 moving bar and the static bars were 5 deg vertically by 0.75 deg horizontally. All the bars on the display were red with a luminance of 16.2 cd/m^2. Thus, in addition to the color contrast with the white background, these bars were darker than the white background providing a luminance contrast of 66% as well. The moving target bar oscillated horizontally at 1.2 Hz with a peak-to-mean amplitude of 0.75 deg on each trial. All of the bars in each condition described below appeared simultaneously from the uniform, white background, and the moving bar started to oscillate as soon as it appeared.

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 oscillating bar always appeared in one of two locations 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. One of the static bars always appeared on the opposite side of the display in the same relative position as the moving bar. This ensured that when only two bars appeared on the display, they did so symmetrically on either side of the center of the display. There were two conditions tested between-subjects: (a) Condition 2 + 28 (n = 98) and (b) Condition 8 + 28 (n = 97). In Condition 2 + 28 each infant was presented with 24 trials with two bars on the display and with 24 trials with 28 bars on the display. In Condition 8 + 28 each infant was presented with 24 trials with eight bars on the display and with 24 trials with 28 bars on the display. In all of these conditions, one of the bars was oscillating, and the others were always static. Schematics of the display with 8 and with 28 bars are shown in Figure 1.

The total number of bars on each display was always divided equally between the two halves of the display. The static bars could appear anywhere on the display with the following constraints. The bars were distributed between 14 imaginary columns that divided the horizontal extent of the display into 14 equal segments. No more than two bars could appear in each column, and no column received a second bar before all of the columns on that side of the display had already received one bar. This meant that when eight bars appeared on the display, the four bars on each side (including the moving bar) appeared in four different columns. When 28 bars appeared on the display, each of the 14 columns had exactly two bars. The vertical positions of the static bars in the columns were random with the constraint that the whole of a bar had to be visible and when two bars appeared in the same column, they could not overlap. All of the bars on the display appeared simultaneously at the start of a trial from the uniform background field, and the moving bar started oscillating as soon as it started to move. 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

Each infant was tested with two set sizes as previously described. These two set sizes (2 and 28 or 8 and 28) comprised a block of trials, and the order of the two set sizes within a block was randomized. Twenty-four 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, 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, so I feel confident that this measure gives us information about orienting during the initial second or two after a motion 'singleton' appeared. The primary dependent variable was the percentage of correct judgments made by the FPL observer. 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.

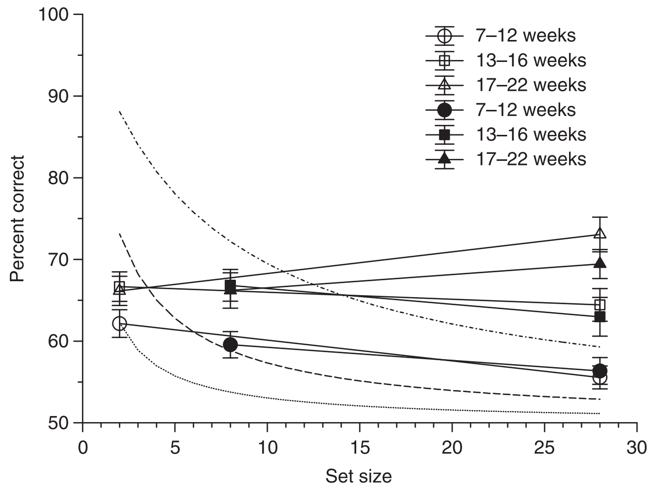

Figure 3 *Percentage of correct judgments for infants in the 2 + 28 group (open symbols) and the 8 + 28 group (closed symbols) divided approximately equally into three age groups as shown. Error bars are ±1 SEM. The curved lines are sample predictions from the MR model repeated from Figure 2.*

Results

The primary dependent variable was the percentage of correct judgments for each set size. Each of these percentages was based on 24 trials for each infant. The mean percentages of correct responses are shown in Figure 3 with infants grouped into three age groups for ease of exposition: 7–12, 13–16 and 17 to 22 weeks. Infants tested in the 2 + 28 condition are shown with open symbols, and infants tested in the 8 + 28 condition are shown with closed symbols. Lines connect the two means for each age group from each condition. The hypothetical curves from the MR model are also shown in Figure 3. It is evident that the results were more consistent with the DS model (cf. Figure 2) than they were with the MR model, perhaps with the exception of the data from the youngest infants who showed a slight tendency toward decreased orienting toward the movement as more bars were added to the visual field. In the oldest age group, there was some evidence that orienting toward the side with the moving bar actually increased slightly as set size increased.

A separate ANCOVA was computed for each sample (2 vs. 28 and 8 vs. 28) with age as a covariate and set size as a within-subject variable. Age was centered at the mean age before it was entered as a covariate. Age was a significant covariate in both ANCOVAs: $F(1, 95) = 30.4$, $p < .001$ and $F(1, 96) = 44.8$, $p < .001$. There was no main effect of set size in either sample, $ps > .2$. The interaction between age and set size was not significant in the 8 + 28 condition, $F(1, 95) = 2.39$, $p = .126$. The interaction between age and set size was significant in the 2 + 28 condition, $F(1, 96) = 13.84$, $p < .001$.

To understand this interaction, infants in the 2 + 28 condition were grouped into the three age groups shown in Figure 3: 7–12 weeks ($n = 33$), 13–16 weeks ($n = 30$), and 17–22 weeks ($n = 35$). A mixed ANOVA with set size as the within-subject variable and age group as the between-subjects variable showed the age group × set size interaction evident in the ANCOVA. The error term from this mixed ANOVA was used to compare the percentage of correct judgments in each age group for 2 vs. 28 bars. In the 7–12 weeks group, the percentage of correct judgments with 2 bars, $M = 61.24\%$, was significantly greater than the percentage of correct judgments with 28 bars, $M = 54.80\%$, $t(95) = 2.51$, $p < .02$. In the 13–16 weeks group, these two percentages did not differ significantly, $M = 66.94\%$ with two bars and $M = 65.28\%$ with 28 bars. In the 17–22 weeks group, infants actually oriented more often toward the side with the movement when there were 28 bars, $M = 71.55\%$, than they did when there were only two bars, $M = 66.43\%$, $t(95) = 2.06$, $p < .05$.

Figures 4A and 4B show the individual subject data with percent correct plotted as a function of age. The slope of the line relating age to percent correct was

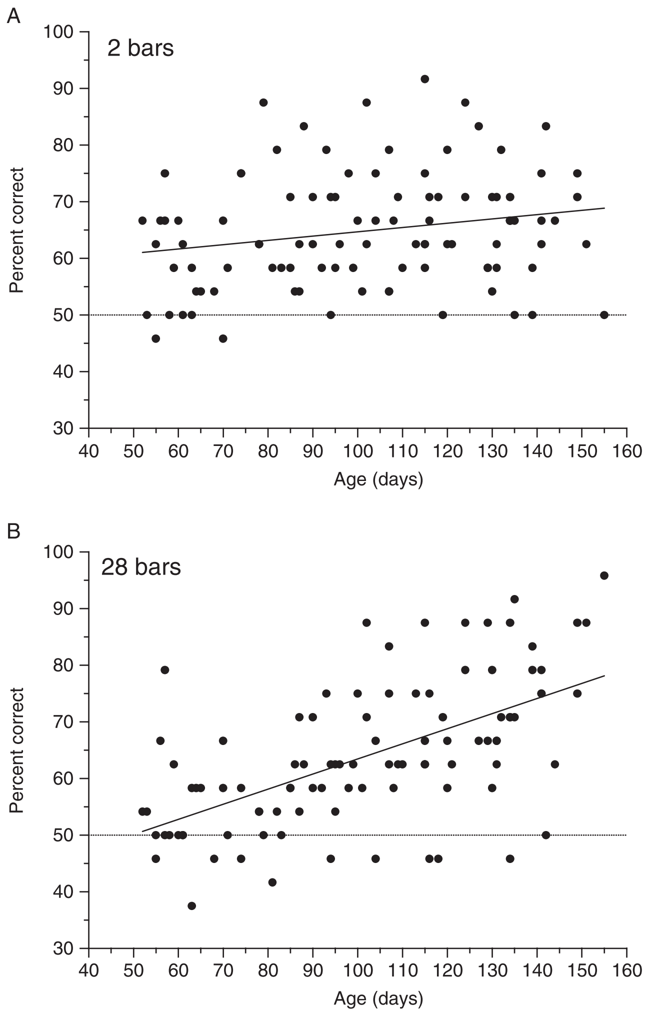

Figure 4 *The percentage of correct judgments with two bars (Panel A) and with 28 bars (Panel B). Each point represents one infant tested with 24 trials. The same infants were tested both with two and with 28 bars. The solid line is the regression line; the dashed line represents chance.*

higher with 28 bars than it was with only 2 bars. With only 2 bars in the field, one of which was moving and one of which was static, orienting to the movement only changed minimally between about 60% and 65% across the age range from 7 to 21 weeks. In contrast, with a much denser display, orienting started out at chance levels at 7 weeks (50%), but by 21 weeks it had improved to almost 80%. Although not shown in Figure 4, the data from the infants tested in the 8 + 28 condition confirm this strong age trend with the larger set size.

Discussion

Overall, the data do not support the MR model. They are much more consistent with the DS model that essentially predicts no relationship between set size and orienting to the moving bar. There were two slight exceptions to this statement. First, there was weak support for the MR model at the youngest ages (7–12 weeks). As more bars were added to the visual field, the youngest infants tended to orient less often toward the side with the moving bar as if their attention were being captured more often by one of the bars contralateral to the moving bar. While qualitatively consistent with the MR model predictions, the data from the youngest infants did not show as large a drop in orienting as would have been predicted by this model.

The second exception to the statement that the data were more consistent with the predictions of the DS model was that the oldest infants oriented slightly, but significantly more often toward the side with the moving bar with the larger set size. This is the antithesis of the prediction from the MR model, and it is not strictly predicted by the DS model. This could reflect a tendency of the static bars to begin to function like background texture at high densities making the movement of the single bar more visible or salient for the older infants.

Before accepting the DS model as being a better descriptor of the data certainly at the older ages, one must address the issue of power and null predictions. There are several aspects of the data that argue against this interpretation of the null to small set size effects. First, significant effects of set size in the direction *opposite* to the predicted direction were evident at the oldest ages and in the direction *consistent* with the predicted direction at the youngest ages. Second, the null results with infants at the intermediate ages appeared in the context of a significant interaction between age and set size for the 2 + 28 condition. Thirdly, the percentages of correct judgments with 28 bars in the two conditions (2 + 28 and 8 + 28) represent independent replications, and these percentages were equal to within a relatively small amount of error (<3%) for all three age groups (M = 54.8% and 56.3% at 7–12 weeks; 65.3% and 62.7% at 13–16 weeks; 71.5% and 68.8% at 17–22 weeks). It is unlikely that the null to small set size effects represent low power from highly variable data because this replication of results in independent samples (n = 97 and n = 98) would be unlikely if measurement or sampling error were playing a large role in determining the effects.

Experiment 2

Set size was tested as a within-subject variable in Experiment 1. As a check on replicability and to determine if the observed percentage of correct judgments for a given set size was independent of the experimental context in which it was observed, a sample of infants was tested with only eight bars. A second purpose of this experiment was to examine a possible reason for the significant increase in orienting toward the side with the moving bar observed at the older ages in Experiment 1. This could represent a density effect. As more bars were added to the display in a fixed area, the density of the bars necessarily increased. It is possible that this increased density made it easier for the older infants but not the younger infants to perceive the movement of the oscillating bar. This can be tested by examining the correlation between the local density of static bars near the moving bar and the probability of orienting toward the moving bar.

Method

Participants

Fifty-seven infants were tested. These infants were sampled from the ends of the age distribution used in Experiment 1. Forty-nine infants contributed complete data. The attrition rate was 14%. The mean age of the younger group (n = 25) was 61.4 days (range 51 to 73 days). The mean age of the older group ($n = 24$) was 133.0 days (range 118 to 145 days). Twenty-three of the 49 infants were females.

Apparatus and stimuli

The apparatus and stimuli were identical to those used in Experiment 1.

Design and procedure

The design and procedures were the same as in the first experiment with two exceptions. Each infant was only tested with eight bars, and 48 trials were presented.

Results

Percent correct

The mean percentages of correct responses with eight bars were $M = 53.8\%$ ($SEM = 1.4\%$) and $M = 66.5\%$ ($SEM = 1.6\%$) for the younger and older age groups, respectively. The corresponding means from the eight bar condition in Experiment 1 for infants with comparable ages were $M = 57.9\%$ ($SEM = 2.0\%$, $n = 27$) and $M = 66.8\%$ ($SEM = 2.1\%$, $n = 29$) for the youngest and oldest age groups, respectively. The age difference with eight bars between the youngest and oldest infant in Experiment 1 was replicated here (see Figure 3). Testing infants with two set sizes as in Experiment 1 or with only one set size as in this experiment did not appreciably change the observed level of orienting toward the side of the display with the moving bar when there were only 8 bars in the visual field.

Is trial-by-trial orienting correlated with the spatial proximities of static bars near the moving bar? In Experiment 1 the oldest infants oriented more often toward the side with the moving target when there were 28 bars perhaps because they benefited from the increased density of the static bars in the neighborhood of the moving bar. The positions of all of the static bars on every trial were recorded, and this afforded the opportunity of using trial-by-trial variation in the positions of static bars near the moving bar to examine age differences in this density effect at a finer-grained level of detail. The average Euclidian distance between the centers of the three ipsilateral static bars and the center of the moving bar was calculated and recorded on each trial. The average distance measure was inverted (to make it correspond in direction to density) and a simple point-biserial correlation was computed for each subject. This correlation estimated the relation between the density on the side with the moving bar (ipsilateral density) and the dichotomous orienting response toward or away from this side across trials. Responses toward the side with the moving bar (i.e. correct responses) were coded as 1 and responses away from the side with the moving bar were coded as 0. As ipsilateral density increased, one would expect the proportion of correct responses to increase. For each infant, this correlation was computed based on 48 trials, and these correlations were averaged to examine age differences.

Only the older infants showed the expected positive correlations with ipsilateral density. The mean correlation at the older age was $M = +.096$ (95%CI = +.026 to +.166). The mean correlation at the younger age was $M = -.027$ (95%CI = −.093 to +.039). This offers converging evidence for the facilitative effect of set size observed at the older age in Experiment 1.

Discussion

These data show that the null or small set size effects observed in Experiment 1 were not the result of testing set size within subjects. It is unlikely that the MR model failed in Experiment 1 because the within-subject design underestimated responding at the lower set sizes. Furthermore, the observed percentages of correct responses with eight bars in Experiment 2 replicated very closely these observed percentages from Experiment 1 for infants of similar ages. When coupled with the small standard errors this lends support to the earlier conclusion that the null results from Experiment 1 were unlikely to reflect low power.

The density analysis reinforced results from Experiment 1. In the previous experiment, the oldest infants actually oriented more often toward the side with the moving bar when there were 28 bars in the field than when there were only two bars in the field. The youngest infants, in contrast, showed a weak but significant trend in the opposite direction. In the current experiment, there were always eight bars in the field: four bars per side. The moving bar was always accompanied by three static bars whose positions were essentially random. The density analysis showed that the older infants oriented more often toward the moving bar when those three static bars were nearer to the moving bar than when they were distributed farther apart. The younger infants did not show this benefit from proximity of the three static bars to the moving bar. The results with the older infants are similar to those seen in Experiment 1. It is possible that the movement of the bar is more noticeable to the older infants when the static bars are closer to it. This could also explain why the results for the oldest infants deviated slightly in Experiment 1 from the null prediction of the DS model.

Experiment 3

At this point, the data for the older infants are more compatible with the predictions of the DS model than they are with the predictions of the MR model. In contrast, there was weak evidence that the younger infants behaved more in accord with the predictions of the MR model. Additionally, Experiment 2 showed that the slight deviation from the DS model's null prediction observed at the older ages could be the result of enhanced sensitivity to the movement when more static bars were near the moving bar. To find further support for the DS model, it was important to attempt a replication of the facilitative effect of the larger set size observed in Experiment 1.

It was also evident in Experiment 1 that the percentage of correct judgments was correlated more strongly with age for 28 bars but not as strongly with two bars in the 2 + 28 condition. When the correlations were examined between age and the percentage of correct judgments for the three age groupings used in the auxiliary analyses of Experiment 1, it was evident that much of the increase with age for the trials with 28 bars occurred for the oldest infants. Table 1 shows the correlations between age and the percentage of correct judgments for two and 28 bars for three age groupings from Experiment 1. With the exception of a marginally significant correlation between age and the percentage of correct judgments in the youngest group with two bars, the only significant correlation was in the oldest age group. Here, there was a significant correlation over a period of approximately 1 month (120 to 155 days) between age

Table 1 *Correlations (p values) between age (days) and the percentage of correct judgments in Experiments 1 and 3*

Experiment	Number of bars	Age group		
		<83 days	84 to 119 days	>119 days
1	2	.34 (.08)	.08 (.61)	−.198 (.29)
	28	−.20 (.32)	.16 (.34)	**.36** (.05)[1]
3	2	–	–	.17 (.36)
	28	–	–	**.48** (.01)

[1] Values significant by a two-tailed test are printed in **bold**.

and the percentage of correct judgments with 28 bars. This correlation speaks again to the possibility that density is playing a larger role in determining orienting to the moving bar for older infants. A replication of this effect was attempted in this experiment by testing older infants with two and 28 bars.

Method

Participants

Thirty-three infants were tested. Thirty infants (18 females) contributed complete data. The attrition rate was 9%. Age was uniformly sampled over the high end of the age range from Experiment 1. The 30 infants who produced complete data ranged in age from 120 to 155 days ($M = 135$ days).

Apparatus and stimuli

These were identical to those used in Experiment 1 in the 2 + 28 condition.

Design and procedure

Infants were tested with two and 28 bars randomly ordered within a block, and 24 blocks were presented.

Results

The correlations between age and the percentage of correct judgments with two and with 28 bars are shown in Table 1 under Experiment 3. The correlation was significant with 28 bars, but not with two bars. This replicates the same pattern seen over this upper age range in Experiment 1 and also is consistent with the density analysis from Experiment 2.

One aspect of the results from Experiment 1 did not replicate. In the 2 + 28 condition from Experiment 1 for the oldest age group (17 to 22 weeks), the mean percentages of correct judgments with two and with 28 bars were

$M = 66.4\%$ ($SEM = 1.2\%$) and $M = 71.5\%$ ($SEM = 2.2\%$), respectively. In the current experiment, these mean percentages were $M = 65.7\%$ ($SEM = 1.9\%$) and $M = 66.5\%$ ($SEM = 2.2\%$), respectively. The mean percentage with two bars replicated closely, but the mean percentage with 28 bars did not. In fact, the slight facilitation in the percentage of correct judgments with more bars noted in Experiment 1 for the oldest infants was not observed here.

Discussion

These data replicated the correlation between age and the percentage of correct judgments using 28 bars and the lack of a significant correlation between these variables using two bars. Over approximately a 1-month period from 17 to 22 weeks, age in days correlated with the percentage of correct judgments with an average Pearson correlation of +0.42. This could be the result of increases in sensitivity to small amounts of movement with age (Roessler & Dannemiller, 1997). It could also reflect the fact that orienting might simply be controlled more consistently across trials by movement for the oldest infants in this 1-month cohort.

The difference between the percentages of correct judgments with two versus 28 bars that was observed in Experiment 1 for the oldest infants was not observed here. In fact, the older infants in this experiment behaved almost exactly as would be predicted by the DS model: no effect of set size on orienting, but observed percentages of correct judgments that were well above chance. The facilitative effect of set size observed in Experiment 1 supported by a corroborating density effect observed in Experiment 2 was not observed in this experiment. Small differences in the exact distribution of ages in these two samples were not responsible for this discrepancy because when a subsample was selected from Experiment 1 to match exactly the age range used in the current sample (120 to 148 days), the difference between the data with two and with 28 bars remained in this matched subsample from Experiment 1. It may be that the superior performance with 28 bars compared to two bars is an individual difference in this age range, and that sampling error was responsible for the lack of replication. Nonetheless, the null set size effect in the current experiment, once again strongly argues against the MR model and in favor of the DS model.

Experiment 4

The DS model has emerged as a viable candidate for explaining the orienting behavior of the older infants, while the MR model appears to have some limited support in the data from the younger infants. The DS model can explain the null or near-null set size effects observed at the older ages, but there is an additional effect that has been repeatedly observed with this paradigm that would also have to be explained by the DS model. In previous studies, when the bars on the display were not all the same color, contrast or polarity (bright versus dark) there was evidence of competition between these static bars and the moving target in visual orienting. The evidence for this was that when the static bars were distributed unevenly across the display such that more of the higher salience bars appeared contralaterally to the moving target, then infants oriented on a smaller proportion of trials toward the moving target than when these bars appeared ipsilaterally to the moving target. For example, Ross and Dannemiller (1999) showed using 14 red and 14 pink bars, that when 11 of 14 red bars appeared contralaterally to the moving target and 11 of 14 of the pink bars appeared ipsilaterally to the target (with the remaining three bars of each color appearing on the complementary sides), infants oriented significantly less often toward the side with the moving bar than when the spatial distribution of these static bars was reversed. This effect is explained by the MR model if it is assumed that mean internal response to the red bars is larger than it is to the pink bars by virtue of the greater visibility, saturation or color contrast of the former against the white background. Given that the MR model fails to capture the data from the older infants, if the DS model is to remain a viable candidate, then it must also accommodate this robust spatial distribution effect.

As noted in the Introduction, it would be preferable to derive a non-null prediction from the DS model before accepting it as an explanation for the older infants. One can conceive of the DS model as postulating that infants are in one of *three* states when a trial starts: (a) motion-salient, (b) alternative-dimension-salient, or (c) random. The alternative-dimension-salient state is equivalent to the random state for the displays used in Experiments 1, 2 and 3 because of the identical nature of all of the bars on the display and because of their even distribution across the two halves of the display. A stronger test of the DS model would be one that allowed the static features of the display to exert a measurable effect on orienting. This was accomplished in Experiment 4 by creating an imbalance across the two halves of the display in the number of static elements. If the DS model is correct, then this imbalance should exert a measurable effect on orienting on some fraction of the trials. In Experiments 1, 2 and 3, when infants switched attention to some alternative feature of the bars on the display, this could only contribute a weighted 50% toward the observed percentage of correct judgments.

Method

Participants

Sixty-seven infants were tested. Sixty-one of these infants (32 females) provided complete data, and six did not because of problems with fussiness and sleepiness. The attrition rate was 9%. Only infants from 13–15 weeks were tested in this experiment because it was these infants who provided the clearest evidence that set size had no effect in Experiment 1. The mean age of the infants who contributed complete data was 98.7 days (range 91–105 days).

Apparatus and stimuli

The apparatus and stimuli were identical to those used in Experiment 1 with two exceptions. First, the number of bars on the display was changed to test the predictions of the DS model. Second, several of the trial types below did not have a moving bar, so there was no objective 'correct' side on the display. The observer was not given feedback on the correctness of her judgments in any of the conditions described below. For convenience, 'correct' on these trials without a moving bar refers to the side of the display with *more* static bars (see below). The observer was told to make her judgments similarly to the way in which she had made them in Experiments 1, 2 and 3.

Design and procedure

The procedure was the same as in the previous experiments.

There were two groups tested in this experiment: (a) a pop-out estimation group, and (b) a static imbalance group. The trials presented to each group are shown in Table 2. The pop-out estimation group was used to estimate k, the fraction of trials on which motion governed orienting. Examination of Equation 2 shows that for displays like those used in Experiments 1, 2, and 3 and for the pop-out group in the current experiment, the fraction k can be estimated simply from the observed percentage of correct judgments, pc, as:

$$k = \frac{pc - 50}{50} \tag{3}$$

This pop-out group received set sizes of 2, 6 and 22. Each set size appeared once in a block, and 12 such blocks were presented for a total of 36 trials. In addition to allowing the estimation of k, this group also served as a replication and extension of the data in Experiment 1 for the intermediate age group. When that age group was tested with set sizes of 2 and 28 or 8 and 28, there were no set size effects. We should expect to see above chance performance, but no set size effects in this group.

The static imbalance group had five different trial types.[2] One of these (Trial type 1: 11m/11) was identical to the set size of 22 bars in the pop-out estimation group. A second trial type had no bars at all on the display (Trial type 6). These trials were included to estimate bias (right versus left). No significant bias was seen in the group results, $M = 52.8\%$, $t(31) = 1.39$, $p = .17$, therefore these trials will not be discussed further. Two trial types both had a moving bar, and there were only 14 bars on the display, 11 on one side and three on the other. In one of these trial types the moving bar appeared on the side of the display that had only 11 bars (Trial type 2: 11m/3), and in the other trial type the moving bar appeared on the side of the display with only three bars (Trial type 3: 3m/11). The fourth and fifth trial types had 11 static bars on one side of the display and three static bars on the other side (Trial types 4 and 5 were identical: 11/3), but there was no moving bar. All these bars were identical in size, color and contrast. Trial types 2, 3 and 4(5) have a strong imbalance in the distribution of the static bars on the display. Trial type 4(5) is what the display should 'look like' to the infant when movement fails to capture orienting on trial types 2 and 3; that is, the display should effectively 'look like' a display with 11 static bars on one side and 3 static bars on the other – just the configuration that we presented to infants with Trial type 4(5). This trial type permitted us to estimate the probability of looks toward the side with more bars when orienting was governed by the static features of the display or when it was random.

Trial types 2 and 3 were the critical trials in Experiment 4. The DS model makes specific, quantitative predictions for these trials once several of its parameters have been estimated. The fraction of trials, k, on which pop-out

Table 2 *Trial types for Experiment 4*

Group	Trial type	Left side[1]	Right side	Total bars	Number of trials
Pop-out	1	1s[2]	1m	2	12
estimation	2	3s	2s + 1m	6	12
(n = 29)	3	11s	10s + 1m	22	12
Static	1	11s	10s + 1m	22	10
imbalance	2	3s	10s + 1m	14	10
(n = 32)	3	11s	2s + 1m	14	10
	4	11s	3s	14	10
	5	3s	11s	14	10
	6	0s	0s	0	10

[1] The same trials were also shown with the right and left sides of the display reversed.
[2] s = static bar; m = moving bar.

[2] Six trial types are listed in Table 4, but trial types 4 and 5 are identical.

occurred, was estimated from the pop-out estimation group. Orienting toward the side with more (11) of the static bars when pop-out failed to occur was estimated from Trial types 4 and 5 in the static imbalance group. Once these two quantities have been estimated, it is possible to make predictions for the observed mean percentage of correct judgments (orienting toward the moving bar) on Trial types 2 and 3. These predictions are (with no free parameters):

Trial type 2

$$percent\ correct_{observed} = 100k + s(1 - k) \tag{4}$$

Trial type 3

$$percent\ correct_{observed} = 100k + (100 - s)(1 - k) \tag{5}$$

Here s represents the percentage of trials on which infants oriented to the side with 11 static bars for trials on which the display consisted of 11 static bars on one side and three static bars on the other. This parameter represents both the random state and the state in which orienting is governed by the spatial imbalance of the bars on the display. These two states constitute the fraction $1 - k$ of the trials. The parameter s is like a visual preference; it represents the initial preference for the side of the display with more bars.

Results

The mean percentages of correct responses in the pop-out estimation group are shown on the right side of Figure 5. Once again, as in Experiment 1, there were no significant set size effects, but orienting toward the side of the display with the moving target was well above chance. Using Equation 3, pop-out was estimated to have occurred on approximately 46% of the trials. Notice that this percentage of trials should not be compared to 50% (chance); rather, it could range from 0 to 100%, and it represents the fraction, k, in the equations above.

The observed percentage of trials on which infants oriented toward the side with more (11) static bars when there was no moving bar is shown as the condition 11/3 on the x-axis. Infants oriented toward the side with 11 of the 14 bars on approximately 65% of the trials. This is the estimate of s in Equations 4 and 5, and it represents a type of initial preference for the side of the display with more bars.

These two parameter estimates can then be used with Equations 4 and 5 to predict the mean percentage of trials on which orienting toward the moving target occurred for Trial types 2 and 3. These predicted means are indicated by the short, horizontal lines above the conditions 11m/3 (Trial type 2) and 3m/11 (Trial type 3)

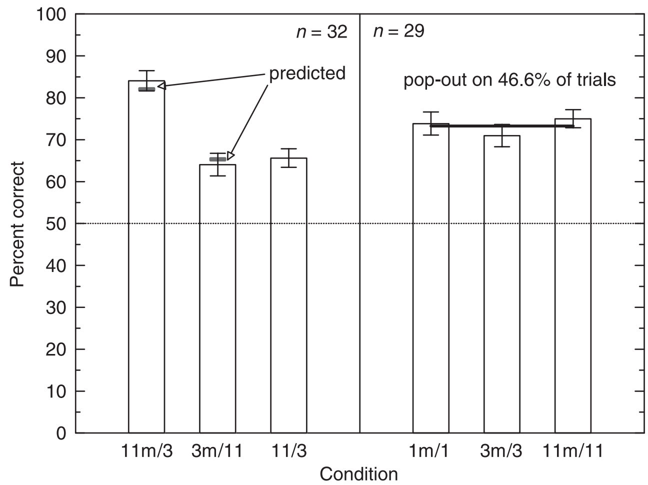

Figure 5 *Mean percentages of correct judgments in Experiment 4. Data from the pop-out estimation group are shown on the right, and data from the static imbalance group are shown on the left. The symbol 3m/3 indicates that there were six bars divided evenly between the two halves of the display, and one of the bars was moving. Similarly, the other symbols with the 'm' indicate the side on which the single moving bar was located when the bars were unevenly divided across the two halves of the display. The symbol 11/3 indicates that there were 14 bars divided unevenly with 11 on one side and 3 on the other, and none of the bars was moving. The predicted percentages of correct judgments using the DS model for the 11m/3 and the 3m/11 trials are shown by the short, horizontal lines. 'Correct' in the 11/3 condition indicates the percentages of looks toward the side with more (11 bars). Once the parameters* k *and* s *in Equations 3 and 4 were estimated from the data on the right and from the 11/3 data, there were no free parameters involved in the predictions. Error bars are ±1 SEM.*

in Figure 5. The observed percentages are also shown as vertical bars above these conditions. The agreement between the observed and predicted values is very good, differing by 0.87% and 2.43%. The observed means are within 1 standard error in both cases despite the difference of approximately 20% in the mean percentages of correct judgments in these two conditions and despite the fact that the proportion k was estimated using a different group of infants.

Discussion

No set size effects were observed for infants in the age range 13–15 weeks. This replicated the same result from Experiment 1. Additionally, this result was predicted by the DS model but not by the MR model. More critically, however, when non-null predictions were derived from the DS model and tested, they also were confirmed for this age group, the agreement between predicted and observed data being very good. The agreement was reassuring because the fraction of trials on which pop-out occurred was estimated from a separate sample of infants.

The major empirical feature of the DS model is that the observed percentage of trials on which infants orient toward the moving bar is a mixture of differently determined behaviors. On some fraction of trials, orienting is purely random. On some fraction of trials, orienting is driven by a strong movement signal from the oscillating bar. On the remaining fraction of trials, it is as if there is no movement at all yet the infant is still engaged with the display. On these trials, orienting is then determined by any spatial imbalance across the two halves of the display. There was no such imbalance in Experiments 1, 2 and 3 and in the pop-out estimation conditions of Experiment 4, but there was in the static imbalance conditions of Experiment 4. When this imbalance was present, it was clear that orienting was not entirely random on the complementary $1 - k$ of the trials, but rather that it was determined partially by this imbalance. Infants were orienting toward the side of the display with more of the static bars on some fraction of the trials. The dimension controlling orienting switched across trials.

General discussion

The major results of these experiments can be summarized succinctly. The visual orienting of younger infants (12 weeks of age or younger) toward a salient moving bar was disrupted slightly by the addition of more static bars to the visual field. In contrast, older infants were unaffected by the addition of these static bars or even slightly increased their orienting as more bars were added to the field. These basic results could signal a transition somewhere around 12 weeks of age in the type of mechanism that governs selective visual orienting. Prior to 12 weeks of age, a Maximum Response model qualitatively if not quantitatively captures the behavior of these infants. They orient to the element in the visual field that produces the largest internal response. This is usually a moving object, but because of noise in the visual pathways, other objects in the field will occasionally capture orienting. After 12 weeks of age, the mechanism appears to be different. Across time, the dimension of stimulation that controls orienting switches. Observed orienting behavior at these older ages is then a mixture of epochs in which several stimulus dimensions fluctuate in their control of selective orienting.

This interpretation of the data in terms of a qualitative shift in the underlying mechanism governing selection and orienting could be criticized as follows. The interaction in Experiment 1 between age and set size was one in which the results at the intermediate ages, 13–16 weeks, fell smoothly between the results at younger, 7–12 weeks, and older, 16–21 weeks, ages. In other words, an alternative interpretation of the data is that the mechanism that governs orienting is basically the same across this age range, but secondary factors shift the balance from a slightly interfering effect of increasing set size to a slightly facilitative effect of increasing set size. There are two arguments in favor of this more continuous interpretation of the age differences. First, the results of Experiment 2 showed that the facilitative effect observed for older infants was probably a density effect perhaps resulting from enhanced sensitivity to movement in the presence of nearby static elements. So the lack of this effect at the youngest ages could represent a quantitative change in the parameters that govern sensitivity to stimulus movement. Second, the amplitude and temporal frequency of the movement were held constant across age. This produced large age differences in the overall level of orienting toward the moving bar. Younger infants are less sensitive to movement (Roessler & Dannemiller, 1997), so perhaps the moving bar was nearer to threshold for these infants. Would the younger infants show a more facilitative effect of increasing set size if the moving stimulus were equated for them in detectability with that shown by the oldest infants? This clearly requires an additional experiment, but it remains a possibility that the age differences in the small effects of set size were a function of age differences in the overall detectability of the moving bar.

The strongest evidence in favor of the DS model at the older ages came from Experiment 4. In this experiment, predictions from the DS model were derived assuming that on some fraction of trials orienting was not automatically captured by the moving bar, but rather that it was captured by some alternative stimulus dimension associated with the static bars. Using a strong spatial imbalance in the distribution of these static bars on the two halves of the display made it possible to observe the effects of orienting governed by an alternative stimulus dimension. Was it the colors of the bars, their sizes, shapes or locations that represented this alternative dimension? It is not possible to say from the design of Experiment 4 which of these or other dimensions of stimulation might have occasionally governed orienting. This will await additional experiments in which these dimensions can be manipulated experimentally. Previous experiments with this paradigm, however, show that color contrast and luminance polarity can play this role (Dannemiller, 2002; Dannemiller & Stephens, 2001; Ross & Dannemiller, 1999).

These data argue that the MR model (Dannemiller, 1998) used to explain previous competition effects only applies with infants less than approximately 12 weeks of age. After this age, it would be more parsimonious to explain these and previously published results using the DS model. What might explain the transition from an MR model to a DS model over this age range? One possibility mentioned briefly in the Introduction is that older infants could show a more pronounced form of short-term habituation. Short-term here refers to habituation across only several trials. The idea is that for several trials one dimension such as color could attract attention and govern orienting. After several trials on which the infant looks initially at the bars and processes their colors, short-term habituation takes place and attention switches to some other dimension such as movement. This kind of repetitive, short-term habituation could induce the kind of mixed responding characteristic of the DS model. Its apparent absence at the younger ages would be explained by arguing that the time course of short-term habituation is longer for the younger infants.

There is one other possible explanation of the switching that is postulated by the DS model. Consider the possibility that Inhibition-Of-Return (IOR) might be responsible for some of the switching in the DS model. IOR refers to the fact that after attention is drawn either overtly or covertly to a location in space, it is less likely to return to that location during a short refractory period (for a review see Klein, 2000). IOR typically operates to block return to specific *locations*, but there is some evidence that it can also inhibit the return of attention to specific stimulus *features* such as color and orientation (Pratt & Castel, 2001). Feature-based IOR in the present context could make dimensional switching more likely by making it less likely that orienting would be governed by the same stimulus dimension across long sequences of trials. Location-based IOR has been observed in infants as early as the neonatal period, but feature-based IOR has not been formally studied during this age period (Valenza, Simion & Umiltà, 1994). The switching across dimensions inferred from the results with the older infants could reflect increases after 3 months of age in feature-based IOR.

One assumption in the DS model is that infants are in one of three states on each trial: motion-salient, static-salient or random. Using the data from Experiment 4 it is possible to estimate the proportions of these states as 48%, 24% and 28%, respectively, at approximately 3.5 months of age. Why would orienting be apparently random on approximately a fourth of all trials? There are several potential answers to this question. First, perhaps the FPL observer is insensitive to the infant's cues, and orienting is actually controlled on a larger proportion of trials by the movement or by the other features of the display. In this case, it would be the FPL observer adding noise to the judgments. This could be assessed by having the FPL observer make two passes through the same set of (videotaped) trials and calculating the agreement between the forced choices. Because reliability has not been an issue in using FPL to measure thresholds for individual infants, such intra-observer consistency calculations have not been done in the past. These will clearly be necessary now to estimate the contribution of the FPL observer to the random component of the DS model. Alternatively, this estimate of the random component of orienting at this age may be correct, and all or most of this randomness may reflect factors intrinsic to the infant. Consider this last explanation in more detail.

Hood and Atkinson (1993) presented data from a simple visual orienting (fixation followed by refixation) task with 3-month-old infants. One of the conditions involved a temporal overlap between the fixation pattern in the center of the display and the refixation target that appeared peripherally. In other words, when the peripheral orienting target appeared, the infant was fixating a competing target in the center of the display. This competition condition in Hood and Atkinson (1993) is closest to the conditions above in which there were multiple potential refixation targets on the display simultaneously. Hood and Atkinson found that at 3 months of age, 16.7% of the first refixations away from the centrally fixated target were toward the side of the visual field without the peripheral refixation target. There was nothing on the side of the visual field contralateral to the refixation target which was quite large (12 by 32 degrees), high contrast (50%) and polarity-reversing at 6 Hz. Infants made approximately 16% of their initial looks toward the side of the display that had nothing on it! Even as late as 6 months, 13.25% of these initial refixations were toward the empty side of the visual field. It is perhaps not surprising, then, that approximately one-quarter of all trials in Experiment 4 involved apparently random orienting with respect to the small (0.75 by 1 deg) bar oscillating in place at 1.2 Hz. Under these circumstances, what is remarkable is rather that approximately three-quarters of all trials orienting was governed systematically by various stimulus dimensions (e.g. movement, etc.).

Robertson, Bacher and Huntington (2001) have shown recently that gaze shifts in 1- and 3-month-old infants in a free-viewing situation are tightly linked to body movements. In particular, for 3-month-olds, gaze shifts were immediately preceded by increases in body movements as if these movements unlocked gaze to shift to a new position. Given that the stimuli in the experiments reported above were not delivered in any way explicitly coupled to the infant's body movements, it is possible that some of the randomness that was observed could have resulted from this inconsistent timing of stimulus delivery with respect to spontaneous changes in overt attention. It is true that the FPL observer started a trial only when the infant was looking toward the center of the display, but this does not guarantee any necessary relationship between body movement and stimulus delivery. Future experiments will examine this issue by coding body movement prior to the onset of the orienting display.

It should also be noted that there is another interpretation of the proportions estimated using the DS model. Rather than interpreting these proportions as reflecting a mixture of different types of trials, they might also be interpreted as representing a fixed set of 'weights' applied consistently to the different dimensions on every trial (see Lutfi & Wightman, 1995, for a similar argument in psychoacoustic work with infants and children). In other words, motion gets weighted more heavily (48%) on each trial than static, spatial characteristics (24%) in determining the initial direction of orienting, and other, apparently random factors receive an aggregate weight of 28%. It must be admitted that the data are also compatible with this alternative, fixed-weights model. One argument in favor of the mixture interpretation, however, is that it is a natural extension of similar models that have been used to explain infant psychophysical data (Viemeister & Schlauch, 1992). Typically, the upper asymptote on infant psychometric functions does not reach 100% even with a very strong, suprathreshold stimulus. This has been explained by appealing to the idea that on some proportion of trials, the infant is simply not 'attending' to the stimulus and is responding randomly (Viemeister & Schlauch, 1992). Thus, the observed psychometric function is a mixture of two functions, one of which is at chance regardless of the intensity or strength of the stimulus. The DS model is an extension of this type of mixture model. The preference for the dimensional switching interpretation will need to be challenged by designing experiments that distinguish these two interpretations.

What implications might this dimensional switching behavior have for other perceptual and cognitive work with infants? Consider an habituation experiment with a rich, multidimensional stimulus or event as the habituation stimulus. The above results imply that when the stimulus first appears on every trial, the dimension of the stimulation that initially captures looking will vary from trial to trial. On one trial, it may be the color that is most salient, and a region with strong color captures the first look. On another trial, it may be movement or shape that is most salient, and color no longer captures the initial look. This kind of inconsistency across trials in the most salient dimension could slow down the overall rate of habituation, and it may play some role in explaining individual differences in looking patterns during habituation (Colombo, 1995). It may also underlie the typically large amount of variability in responding seen during test trials after habituation. It must be noted that these comments only apply to the initial orienting on each trial. Habituation typically involves extended fixations, so to the extent that these subsequent fixations are determined by dimensions other than the one that captured the first look, then the dimensional switching behavior observed above may be less relevant for habituation studies with infants at these ages. Careful observation of the relations between the first and subsequent fixations in such experiments could help to address this issue.

Finally, the conclusion that orienting is governed by shifts across trials in the dimensions that are most salient may be an indication that these experiments are not just telling us about overt, exogenously controlled orienting, but also about internally controlled, endogenous attentional processes. Unlike the case with adults who can control attention voluntarily, stimuli are not delivered only when the infant is ready for them attentionally. The infant's attention may be directed internally toward bodily functions or toward other aspects of the situation that are outside of the experimenter's control. Identical stimuli delivered on two different occasions when the infant is apparently attending to the center of the display may not yield identical responses because endogenous processes are different on the two occasions. One solution to this problem is to use physiological measures to assess the internal or endogenous state of attention (e.g. Richards & Hunter, 1997), but these measures are certainly imperfect indicators of such internal states. The apparently random component of orienting at these ages may reflect the interplay between endogenous and exogenous attentional control processes as they develop over this period. A decrease in the random component with age would then reflect an increase in the efficiency with which a strong stimulus interrupts ongoing, internally controlled attentional processes.

Acknowledgements

This research was supported by NICHD R01 HD32927 to JLD. I thank Jacqueline Roessler for observing the infants, Manya Qadir for scheduling the infants, and Daniel Replogle for all of the computer programming. Pat Klitzke helped in the preparation of the manuscript. Bob Lutfi provided helpful discussion on the dimensional switching model.

References

Atkinson, J. (1992). Early visual development: differential functioning of parvocellular and magnocellular pathways. *Eye*, **6**, 129–135.

Bacher, L.F., & Robertson, S.S. (2001). Stability of coupled fluctuations in movement and visual attention in infants. *Developmental Psychobiology*, **39**, 99–106.

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 Press.

Bichot, N.P., Cave, K.R., & Pashler, H. (1999). Visual selection mediated by location: feature-based selection of noncontiguous locations. *Perception and Psychophysics*, **61**, 403–423.

Colombo, J. (1995). On the neural mechanisms underlying developmental and individual differences in infant fixation duration: two hypotheses. *Developmental Review*, **15**, 97–135.

Colombo, J., Mitchell, D.W., & Horowitz, F.D. (1988). Infant visual attention in the paired-comparison paradigm: test-retest and attention-performance relations. *Child Development*, **59**, 1198–1210.

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.

Dannemiller, J.L. (2001). Brain–behavior relationships in early visual development. In C.A. Nelson & M. Luciana (Eds.), *Handbook of developmental cognitive neuroscience* (pp. 221–235). Cambridge, MA: MIT Press.

Dannemiller, J.L. (2002). Relative color contrast drives competition in early exogenous orienting. *Infancy*, **3**, 275–301.

Dannemiller, J.L., & Stephens, B.R. (1988). A critical test of infant pattern preference models. *Child Development*, **59**, 210–216.

Dannemiller, J.L., & Stephens, B.R. (2001). Asymmetries in contrast polarity processing in young human infants. *Journal of Vision*, **1**, 112–125.

Frick, J.E., Colombo, J., & Saxon, T.F. (1999). Individual and developmental differences in disengagement of fixation in early infancy. *Child Development*, **70**, 537–548.

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.

Green, D.M., & Swets, J.A. (1966). *Signal detection theory and psychophysics.* New York: Wiley.

Hood, B.M., & Atkinson, J. (1993). Disengaging visual attention in the infant and adult. *Infant Behavior and Development*, **16**, 405–422.

Karmel, B.Z., Lester, M.L., McCarvill, S.L., Brown, P., & Hofmann, M.J. (1977). Correlation of infants' brain and behavior response to temporal changes in visual stimulation. *Psychophysiology*, **14**, 134–142.

Klein, R.M. (2000). Inhibition of return. *Trends in Cognitive Sciences*, **4**, 138–147.

Lutfi, R.A., & Wightman, F.L. (1995). Guessing or confusion?: Analytic predictions for two models of target-distracter interference in children. Paper presented at the Association for Research in Otolaryngology, 19th Midwinter Meeting, Clearwater, Florida.

Morton, J., & Johnson, M.H. (1991). CONSPEC and CONLEARN: a two-process theory of infant face recognition. *Psychological Review*, **98**, 164–181.

Mounts, J.R.W., & Melara, R.D. (1999). Attentional selection of objects or features: evidence from a modified search task. *Perception and Psychophysics*, **61**, 322–341.

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.

Pratt, J., & Castel, A.D. (2001). Responding to feature or location: a re-examination of inhibition of return and facilitation of return. *Vision Research*, **41**, 3903–3908.

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.

Robertson, S.S., Bacher, L.F., & Huntington, N.L. (2001). The integration of body movement and attention in young infants. *Psychological Science*, **12**, 523–526.

Robertson, S.S., Guckenheimer, J., Masnick, A.M., & Bacher, L.F. (2004). The dynamics of infant visual foraging. *Developmental Science*, **7**, 194–200.

Roessler, J., & Dannemiller, J. (1997). Changes in infants' sensitivity to slow displacements over the first 6 months. *Vision Research*, **37**, 417–423.

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.

Schoener, G., & Thelen, E. (in press). Using dynamic field theory to rethink infant habituation. *Psychological Review*.

Sirois, S., & Mareschal, D. (2004). An interacting systems model of infant habituation. *Journal of Cognitive Neuroscience*, **16**, 1352–1362.

Skoczenski, A.M., & Norcia, A.M. (1999). Development of VEP vernier acuity and grating acuity in human infants. *Investigative Ophthalmology and Visual Science*, **40**, 2411–2417.

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.

Treisman, A. (1996). The binding problem. *Current Opinion in Neurobiology*, **6**, 171–178.

Valenza, E., Simion, F., & Umiltà, C. (1994). Inhibition of return in newborn infants. *Infant Behavior and Development*, **17**, 293–302.

Viemeister, N.F., & Schlauch, R.S. (1992). Issues in infant psychoacoustics. In L.A. Werner & E.W. Rubel (Eds.), *Developmental psychoacoustics* (pp. 191–209). Washington, DC: American Psychological Association.

Wattam-Bell, J. (1991). Development of motion-specific cortical responses in infancy. *Vision Research*, **31**, 287–297.

Yellott, J.I. (1977). The relationship between Luce's choice axiom, Thurstone's theory of comparative judgment, and the double exponential distribution. *Journal of Mathematical Psychology*, **15**, 109–144.

Received: 14 June 2004
Accepted: 20 May 2005