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REPORT

The dynamics of infant visual foraging

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Abstract

Human infants actively forage for visual information from the moment of birth onward. Although we know a great deal about how stimulus characteristics influence looking behavior in the first few postnatal weeks, we know much less about the intrinsic dynamics of the behavior. Here we show that a simple stochastic dynamical system acts quantitatively like 4-week-old infants on a range of measures if there is hysteresis in the transitions between looking and looking away in the model system. The success of this simple three-parameter model suggests that visual foraging in the first few weeks after birth may be influenced more by noise and hysteresis in underlying neural mechanisms than by how infants process visual information after a look begins.

Introduction

During the first few weeks of postnatal life, humans are active 'looking machines' (Posner, 1993). Their aggressive visual foraging has enormous adaptive significance because it provides detailed information about the external world integrated with spontaneous body movement and goal-directed action during a period of rapid brain development (Atkinson, 2000; Bertenthal, 1996; Johnson, 2001; Posner, Rothbart, Farah & Bruer, 2001; Robertson, Bacher & Huntington, 2001a). In spite of the importance of free-looking behavior in the early postnatal period, and although there is a good understanding of the features of visual stimulation that influence it (Atkinson, 2000; Banks & Salapatek, 1983; Haith, 1980), its intrinsic dynamics are unknown. Our goal was to determine what dynamical properties could account for the main characteristics of early visual foraging.

We began with just two assumptions. First, we assumed that in the simplest case a useful model system must have two stable states, corresponding to an infant looking at and away from a visual stimulus, with the possibility of bias toward one of the two states. In infants, bias toward looking or looking away presumably reflects the joint influence of many factors, including stimulus characteristics such as contrast and spatial frequency, the intrinsic sensitivities of the visual and attentional systems, memory, and global factors such as hunger and arousal (Atkinson, 2000; Bornstein, 1985; Fantz, 1964; Gardner & Karmel, 1995). The bias in our model therefore represents a deliberate simplification which summarizes a complex set of organism and environment characteristics and the interactions among them that are likely to occur during visual foraging by young infants.

Second, because noise is common and functionally significant in a wide range of biological systems (Krakauer & Sasaki, 2002; Mainen & Sejnowski, 1995; Shinbrot & Muzzio, 2001; Wiesenfeld & Moss, 1995), we included it in our model of infant visual foraging. In addition to stochastic neural activity within sensory, perceptual-cognitive and motor systems, sources of noise that might be relevant to early visual foraging include the perturbations that arise from the coupling between these systems (Bacher & Robertson, 2001). As with bias, the noise in our model is a simplification that summarizes the combined influence of potentially diverse sources of unpredictable activity on gaze shifts during visual foraging.

We chose a simple dynamical system that satisfies our starting assumptions and has been used to model other

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bistable, stochastic physical and biological processes (Zhou, Moss & Jung, 1990; Longtin, Bulsara, Pierson & Moss, 1994). The model was evaluated by comparing its behavior with that of 4-week-old infants who were allowed to look freely at interesting objects. Based on the particular manner in which the model failed, we added a small amount of hysteresis to the transitions between the states corresponding to looking and looking away and reevaluated the model's behavior.

Model I

We used the following stochastic dynamical system:

$$du(t) = (u(t)(1 - u^2(t)) + a)\,dt + s\,dW(t). \tag{1}$$

In this system, $u > 0$ corresponds to looking at a visual stimulus (ON) and $u \leq 0$ corresponds to looking away (OFF), a is a constant bias ($a > 0$ corresponds to a bias toward looking at a visual stimulus) and s is the magnitude of the noise, $dW(t)$. $W(t)$ is a standard Weiner process in which $W(t') - W(t)$ is distributed as $N(0, t' - t)$ (Gaussian white noise with zero mean and variance = $t' - t$). The system is bistable (it can settle in either the ON or OFF state) when the magnitude of the bias is small. For $a = 0$, there are stable fixed points at $u = \pm 1$ and an unstable fixed point at $u = 0$. As the magnitude of the bias is increased, the stable fixed point in the non-biased state and the unstable fixed point approach each other until they coincide when $|a| = 2/(3\sqrt{3}) \cong 0.385$. For larger amounts of bias, there is only one stable fixed point, which is in the biased state.

Methods

Model

The behavior of Model I was estimated by averaging the results of 24 simulations for each combination of bias and noise. The simulations were programmed in LabVIEW v. 6.1 (National Instruments, Austin, TX). Time in the stochastic differential equation (1) was discretized. The update formula,

$$u_{j+1} = (u_j(1 - u_j^2) + a)\Delta t + s\xi_j, \tag{2}$$

used a fixed time step, $\Delta t = 1/60$ s, corresponding to the sampling interval in the infants' data. For each simulation, a different sequence of random numbers, ξ_j, was drawn from $N(0, \Delta t)$ (Wichmann & Hill, 1982). Bias, a, ranged from −1 to +1 in increments of 0.02. Noise magnitude, s, ranged from 0.4 to 1.3 in increments of 0.013. The length of each simulation corresponded to the average length (8 min) of the infants' data. Incomplete periods in either state at the beginning or end of a simulation were discarded.

Infants

The 4-week-old infants (12 males, 12 females, 26–32 days after birth) were full term and healthy with no known vision problems who had been studied previously (Robertson *et al.*, 2001a). They were allowed to look *ad libitum* at a static array of four identical, complex three-dimensional objects (commercially available Big Bird toys with bright yellow head and body, orange feet, pink eyelids, blue eyelashes and large black pupils) mounted in front of a black cloth screen 100 cm in front of them until they showed any evidence of becoming fussy or drowsy. The objects subtended 7 × 9 deg of visual angle and were separated by 21 deg. Multiple, complex objects were used to maintain interest and increase the number of gaze shifts to analyze. The objects were identical to minimize preferences for any particular object based on its physical properties, but they were complex enough to maintain active visual foraging behavior for 8 ± 3 min (mean ± SD). The infants' direction of gaze was determined from corneal reflections of the objects recorded on videotape from a camera behind the screen in the center of the stimulus array.

Transitions between looking at and away from any of the objects were identified on the videotape to the nearest 1/60 s. Incomplete periods of looking or looking away (at the beginning or end of data collection) were discarded. The mean durations of periods of looking and looking away did not differ between the first and second halves of data collection (looking: 6.19 ± 0.67 vs. 5.91 ± 0.68 s, mean ± SEM, $t(23) = .35$, $p = .73$; looking away: 2.12 ± 0.41 vs. 2.29 ± 0.56 s, $t(23) = -.25$, $p = .80$). Independent coders determined the durations of 157 looking periods and 157 looking away periods from six infants. For both looking and looking away periods, the intercoder correlations exceeded .99 and the median absolute differences between the coders were 1/60 s.

Model-infant comparisons

The following seven measures were used to compare Model I and infant behavior: (i) The transition rate between ON (corresponding to looking at a visual stimulus) and OFF (corresponding to looking away from a visual stimulus) was used as a global measure of switching activity. (ii) The median duration of ON periods, and (iii) the median duration of OFF periods, were used as separate measures of the typical amounts of time spent in each state before switching to the other. (iv) The proportion of ON periods shorter than 1 s, and (v) the proportion of OFF periods shorter than 1 s, were used to measure the relative frequency of short times spent in each state; 1 s is commonly used as a criterion for defining behaviorally relevant periods of looking or looking away (Colombo & Horowitz, 1985; Richards & Gibson, 1997). (vi) The proportion of ON periods longer than 10 s, and (vii) the proportion of OFF periods longer than 10 s, were used to measure the relative frequency of extended times spent in each state; 10 s was chosen because it is an order of magnitude larger than 1 s and is commonly considered to indicate sustained looking or looking away (Richards & Gibson, 1997; Richards & Casey, 1992).

For each measure, model error was calculated as the difference between the model and infant means. Model error was expressed as a fraction of the standard deviation of the infants' measure so that the performance of the model could be assessed independently of the specific units of each measure.

Results and discussion

There are combinations of bias and noise for which Model I behaves like 4-week-old infants (model error near zero) on most of the measures if each measure is considered separately (Figure 1A). However, there are no combinations of bias and noise for which the model behaves like infants on all measures simultaneously (Figure 1, B and C). For example, there are regions in the bias × noise plane where model and infant behavior are similar on the global measure of switching activity (transition rate) and the median durations of time spent in each state (looking and looking away), but there are no regions where model and infant behavior are similar on

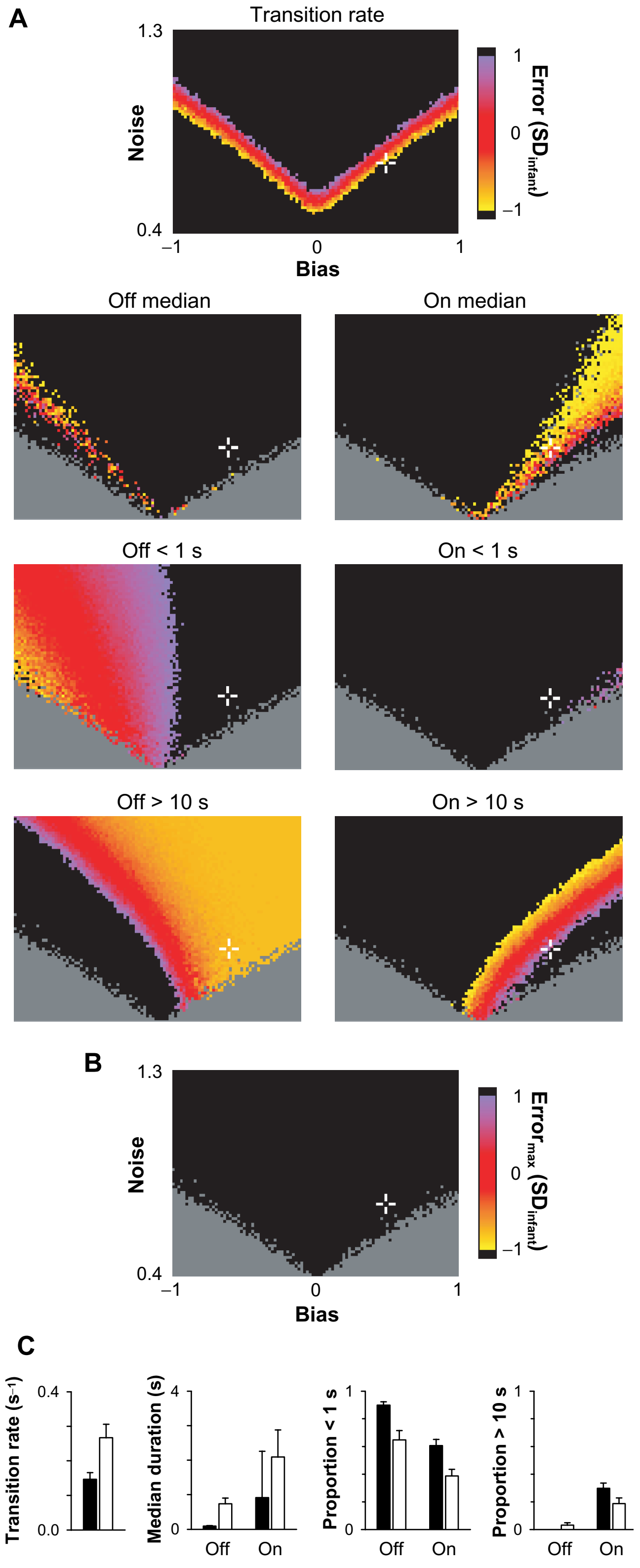

Figure 1 *(right) Comparisons of Model I and infant behavior. ON corresponds to looking and OFF corresponds to looking away. Red indicates that the model results are the same as the infant results (the model error is zero); purple (yellow) indicates that the model results are greater (less) than the infant results by 1 standard deviation of the infant's measure. Black indicates that the model and infant means differ by more than 1 standard deviation. Gray indicates that one or more of the measures are undefined because no complete period in one or both states occurred during the simulation. (A) Model error for each measure. (B) Maximum error for the set of 7 measures. The cross indicates the combination of bias and noise for which the maximum error is smallest (*$| error_{max} | = 1.7$*). (C) Means and 95% confidence intervals for each measure from 24 simulations of the model (filled bars) at the point indicated by the cross in panels (A) and (B), and the 24 infants (open bars).*

all three measures. Instead, if the model behaves like infants on transition rate and one of the median duration measures, it severely underestimates the other median duration measure.

The model fails to behave like infants on both median duration measures because repeated sequences of very short ON and OFF periods occur when the model system is near the boundary between the states. Larger bias can compensate for this chatter by producing longer periods in one of the states, but large bias cannot produce longer periods in *both* states.

The repeated sequences of very short periods in each state that are responsible for the model's failure occur because the transition between states happens at the same point ($u = 0$) regardless of the direction of the transition. However, dependence on the direction of change (hysteresis) is a property of many neural and behavioral systems (Farrell, 1999; Kelso, Case, Holroyd, Horvath, Raczaszek, Tuller & Ding, 1995; O'Reilly & Munakata, 2000). We therefore added hysteresis to the model system and reevaluated its behavior.

Model II

Hysteresis was added to the model system, equation (1), by redefining the transition point between the ON and OFF states so that it depends on the direction of the transition. In Model II, the transition from OFF to ON occurs when $u > h/2$, and the transition from ON to OFF occurs when $u \leq -h/2$, $h \geq 0$. When $h = 0$ there is no hysteresis, in which case transitions in both directions occur at $u = 0$ and Model II is identical to Model I. As with bias and noise, the hysteresis in Model II is assumed to summarize the many possible sources of hysteresis in the transitions between looking at and away from stimuli during visual foraging.

Methods

The behavior of Model II was estimated for values of hysteresis, h, between 0 and 0.5, at increments of 0.05, using the same methods, the same update formula (2), and the same values of bias and noise used for Model I.

Results and discussion

With the addition of hysteresis, there are combinations of bias and noise for which the model behaves like 4-week-old infants (the model error is near zero) on all seven measures at the same time (Figure 2A–C). The close similarity to infant behavior occurs over a range of hysteresis (Figure 3), but only if the bias in the model favors the ON state ($a > 0$, Figure 2B). The model behaves most like infants when the positive bias is also small enough that the system remains bistable ($a < 0.385$, Figure 2B). Under these conditions, the model can settle in the OFF state as well as the ON state, especially during transient periods of low noise.

General discussion

The results demonstrate that a stochastic dynamical system and free-looking 4-week-old infants exhibit very similar behavior if there is hysteresis in the transitions between the model states that correspond to an infant looking at and away from a visual stimulus. Importantly, the noise and hysteresis in the model system operate on a time scale that is 1 to 2 orders of magnitude shorter than the typical duration of ON and OFF states. That is, the macroscopic behavior of the model that matches infants' free-looking behavior is not represented directly in the model's free parameters. Rather, the model's infant-like behavior on a time scale of seconds emerges from governing dynamics defined on a time scale of a few hundredths of a second. These findings suggest that noise and hysteresis might be key properties of the neural dynamics underlying visual foraging in young infants.

The results do not point to specific sources of noise or hysteresis in the systems controlling attention and gaze. However, the evidence from 1-month-olds that spontaneous gaze shifts are coupled to intrinsic fluctuations in body movement (Robertson *et al.*, 2001a), which in turn have chaotic properties (Robertson, Bacher & Huntington, 2001b), points to general motor activity as one possible source of noise in the dynamics of visual foraging. There is also some evidence that characteristics of the young infant's visual system might result in hysteresis in the transitions between looking and looking away. During the first few postnatal months, looking away from one object and then toward another takes longer if the first object remains visible (Atkinson, Hood, Wattam-Bell & Braddick, 1992). This effect is thought to arise in part from the relative inability of immature cortical inputs from frontal and parietal regions to suppress the tonic inhibition of saccadic eye movements by the substantia nigra (Johnson, 1995). Because visual foraging requires repeated gaze shifts from one object or patch of information to another while at least some of the previous targets of attention remain visible, the durations of periods of looking and looking away are likely to be influenced by any stickiness of gaze.

The model system that we studied was selected because it satisfies the assumptions (bistable, stochastic) relevant for infant visual foraging with a minimal set of

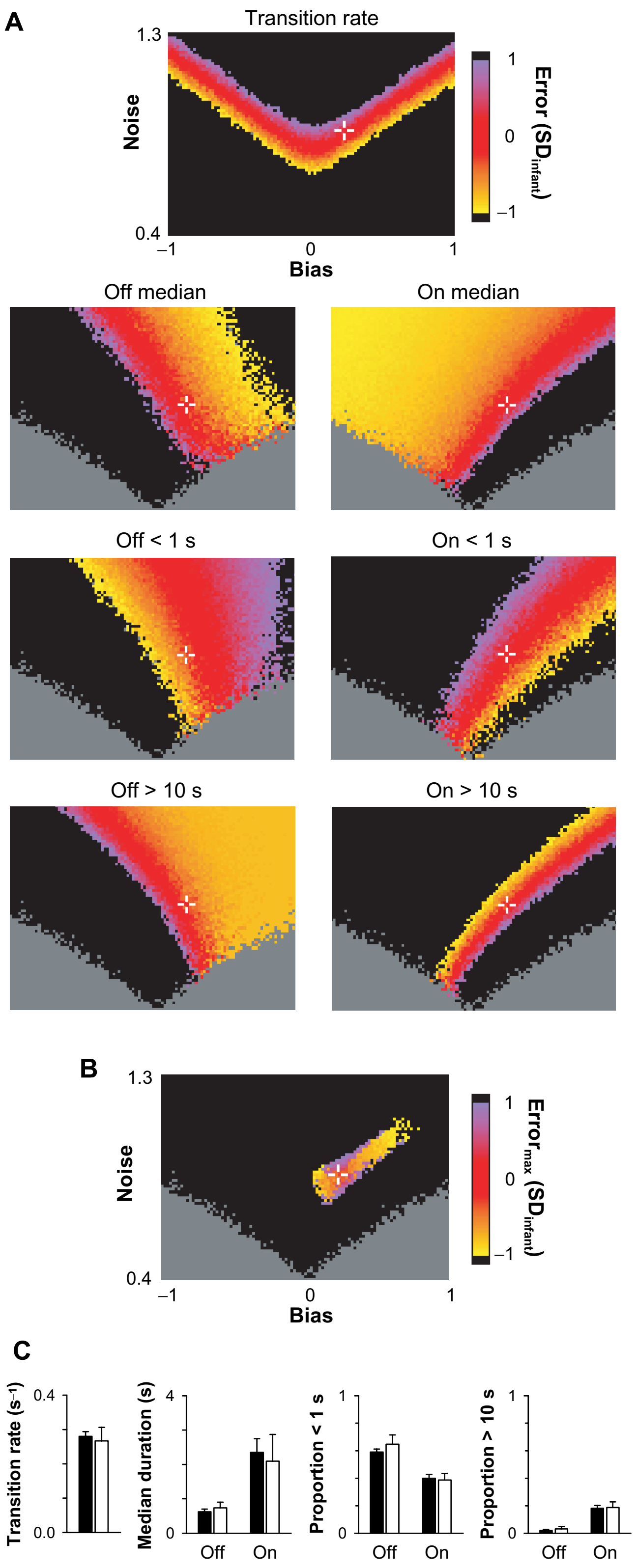

Figure 2 *(left) Comparisons of Model II (*h = *0.3) and infant behavior. See Figure 1 for explanation of colors. (A) Model error for each measure. (B) Maximum error for the set of 7 measures. The cross indicates the combination of bias and noise for which the maximum error is smallest* ($|\text{error}_{max}| = 0.30$)*. (C) Means and 95% confidence intervals for each measure from 24 simulations of the model (filled bars) at the point indicated by the cross in panels (A) and (B), and the 24 infants (open bars).*

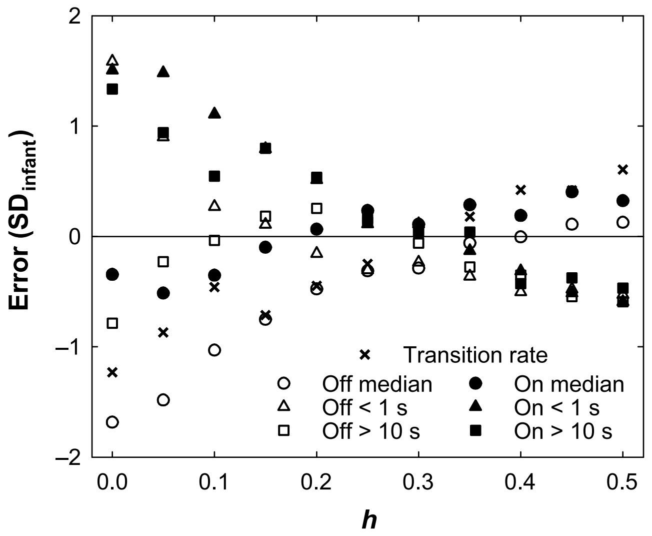

Figure 3 *Model II errors for different amounts of hysteresis,* h*. The model error for each measure is the difference between Model II and infant means at the point in the bias × noise plane where the maximum error for the set of 7 measures is smallest. For* h = *0 and 0.3, this point corresponds to the crosses in Figures 1 and 2, respectively. ON corresponds to looking and OFF corresponds to looking away.*

parameters (bias, noise amplitude). Its failure to behave like 4-week-old infants was resolved by the addition of a single new property (hysteresis), yielding a slightly modified but still simple (three parameters) model system. It is possible that other model systems with different or more complicated properties could also behave like 4-week-old infants. The investigation of such models, if they exist, might yield further insights into the dynamics of infant visual foraging.

The infant visual foraging behavior that we used to evaluate the model is likely to have been simpler than it would be in a more realistic environment populated by numerous physically different objects that vary in attractivness. One approach to modeling visual foraging behavior in such environments would be to allow the bias parameter to depend on the particular object being inspected, as well as the properties and layout of the surrounding objects. In addition, although the variability in each of the infant measures was similar to the variability across repeated model simulations with fixed parameter values (see Figures 1C and 2C), we did not attempt to directly model stable individual differences in infant visual foraging behavior. It is possible that systematic differences in one or more of the model parameters might be able to account for such individual differences. It is also possible that systematic changes in the model parameters might be able to account for some developmental changes in visual foraging behavior in the first few weeks after birth.

The quantitative similarity between the free-looking behavior of 4-week-old infants and the behavior of the dynamical system presented here raises an interesting possibility. The model behaves like infants even though nothing new happens when the model system enters the state that corresponds to an infant looking at a visual stimulus. We know, however, that some perceptual-cognitive activity does occur in young infants when they look at visual stimuli (Haith & Benson, 1998; Johnson & Mareschal, 2001; Kellman & Banks, 1998). Our use of a simple visual environment (although not simple stimuli) for the infants may have reduced some of the potential effects of perceptual-cognitive activity. Nevertheless, our results suggest that 4 weeks after birth the impact of such activity on visual foraging behavior may be relatively small compared to the effects of noise and hysteresis in the mechanisms controlling attention or gaze. Very early in development, stochastic dynamics with hysteresis may drive exploration of the visual environment and thereby regulate opportunities for some of the perceptual-cognitive activity that will soon control such exploration.

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