Brief Report

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Empty-Headed Dynamical Model of Infant Visual Foraging

ABSTRACT: *Visual foraging is one important way that very young infants explore and learn about their environment. We recently showed that a simple stochastic dynamical model acts quantitatively like free-looking 1-month-old infants, even though it does not include any components that directly represent the perceptual-cognitive processes that operate on the input from visual foraging. This suggested that early in development, generic low-level processes like noise and hysteresis in the mechanisms controlling gaze may drive visual foraging behavior and therefore regulate the input to higher-level perceptual-cognitive processes that later come to have more influence on free looking. Here we evaluate the model's ability to behave like 3-month-olds studied under the same experimental conditions as 1-month-olds. The results show that the empty-headed model can also behave like 3-month-old infants, although not as well as 1-month-olds. Its partial success at 3 months suggests that generic low-level processes controlling gaze remain important in visual foraging. Its pattern of failure suggests that by 3 months time-dependent processes like attention have become especially important.* Dev Psychobiol 56: 1129–1133, 2014.

Keywords: *infant; looking; visual foraging; model; dynamical; stochastic; hysteresis*

INTRODUCTION

Young infants' exploration of their environment is constrained by motor immaturity, but they are aggressive *visual* foragers from birth onward. One way to understand this robust adaptive behavior is to study its intrinsic dynamics. We previously showed that a simple stochastic dynamical system acts very much like 1-month-old infants during free looking (Robertson, Guckenheimer, Bacher, & Masnick, 2004). One intriguing feature of the model is its empty-headedness; it behaves like 1-month-old infants without including any components representing perceptual-cognitive processes. Here we evaluate how well the model acts like 3-month-old infants, for whom such processes would be expected to have more influence on free looking behavior.

The model was originally chosen to have two basic properties (Robertson et al., 2004). First, it is bistable—capable of settling in states corresponding to looking (ON) and not looking (OFF), with potentially different likelihoods (bias). Second, it includes noise, which is ubiquitous in living systems and often has considerable functional significance (Ermentrout, Galán, & Urban, 2008; Faisal, Selen, & Wolpert, 2008; McDonnell & Ward, 2011). The original model was tested on seven different measures of 1-month-olds' free looking behavior. There were values of bias and noise for which the model was able to behave like infants on each of the measures separately, but not together. Based on the details of the original model's behavior, we hypothesized that its failure might be due to the absence of stickiness (hysteresis) in the transitions between the ON and OFF states, a characteristic of infant looking behavior under some conditions (Atkinson, Hood, Wattam-Bell, & Braddick, 1992) and common in

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biological systems more generally (Angeli, Ferrell, & Sontag, 2004; Fröhlich, Bazhenov, Timofeev, Steriade, & Sejnowski, 2006; Kusters et al., 2007). When hysteresis was added to the model, there were parameter values for which the model acted like 1-month-olds on all seven measures of free looking simultaneously.

The success of this simple, three-parameter model had at least two implications. First, the characteristics of infant free looking behavior that the model reproduces are not represented directly in the model's free parameters. Rather, the macroscopic behavior emerges from the elementary (and generic) low-level processes of noise and hysteresis, which operate on a time scale an order of magnitude or more shorter than the transitions between the ON and OFF states corresponding to infant looking behavior. This suggested that similar elementary processes might be important in the dynamics of infant visual foraging in the first weeks after birth. Second, the model does not include components representing the perceptual-cognitive processes that are known to be engaged during looking by young infants (Johnson & Mareschal, 2001; Kellman & Banks, 1998). This suggested that very early in development, the perceptual-cognitive processes that operate on visual input during looking may have less influence on the durations of individual looks than do elementary processes like noise and hysteresis.

The empty-headedness of the simple three-parameter model suggests that it might be less successful acting like older infants, in whom perceptual-cognitive processes engaged during looks are likely to have more influence on their durations. Therefore, the present report evaluates the model's ability to behave like 3-month-olds in the same conditions as 1-month-olds, using the same methods and measures. The model was expected to have more difficulty with the free looking behavior of the older infants, or to fail altogether. In either case, the results were expected to provide useful information about the relevance of the empty-headed model of infant visual foraging during the period of rapid development in the first few months after birth.

METHODS

Model

The stochastic dynamical system with hysteresis described in detail in Robertson et al. (2004) was used,

$$\mathrm{d}u(t) = (u(t)(1 - u^2(t)) + a)\mathrm{d}t + s\,\mathrm{d}W(t). \quad (1)$$

In this system, the transition from not looking at a stimulus (OFF) to looking at a stimulus (ON) occurs when the state variable $u > h/2$, and the transition from ON to OFF occurs when $u \leq -h/2$, where $h \geq 0$ and represents the hysteresis in the system's state-switching behavior. There is a bias toward the ON state when $a > 0$ and a bias toward the OFF state when $a < 0$. The system is bistable when $|a| < 2/(3\sqrt{3}) \approx .385$; for larger magnitudes of bias there is a stable fixed point only for the biased state. The parameter s is the magnitude of Gaussian white noise; W(t) is a standard Weiner process.

Simulations were carried out in LabVIEW (v. 8.5, National Instruments, Austin, TX) using the following update formula,

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

where $\Delta t = 1/60$ s, the sampling interval for infant gaze, and ξ_j was a different sequence of random numbers drawn from $N(0, \Delta t)$ for each simulation. The length of each simulation corresponded to the average length of the infants' data (8 min at 1 month and 11 min at 3 months). The ranges (and increments) of parameter values used were: bias, $0 \leq a \leq 1$ ($\Delta a = .01$); noise, $.3847 \leq s \leq 1.9339$ ($\Delta s = .0077$); and hysteresis, $0 \leq h \leq 1$ ($\Delta h = .025$). The parameter ranges were chosen to include regions in which the model's behavior (defined below) was most similar to that of the 1- and 3-month infants, and the increments were chosen to provide approximately twice the resolution of the simulations reported in Robertson et al. (2004).

Infants

The infant data used to evaluate the model were obtained from 24 1-month-olds (12 males, 12 females; 26–32 days) and 21 3-month-olds (10 males, 11 females; 82–89 days) in a previous study (Robertson, Bacher, & Huntington, 2001a). In that study, infants looked freely at four identical big-bird toys (each subtended 7 horizontal × 9 vertical degrees of visual angle) mounted in a square arrangement (big-bird toys at adjacent corners were separated by 21 deg) on a black screen 100 cm in front of the infants' face. Data collection continued until infants lost interest or became fussy, which occurred after 8 ± 3 min ($M \pm SD$) for the 1-month-olds and 11 ± 3 min for the 3-month-olds. The transitions between looking (ON) and not looking (OFF) at any of the stimuli were determined off-line to the nearest 1/60 s from video-recorded corneal reflections of the stimuli. The beginning of an ON period was defined as the video field at the end of a gaze shift to one of the stimuli when movement of the corneal reflection of the stimulus stopped over the center of the pupil. The ON period continued as long as the reflection of the stimulus stayed centered over the pupil, and ended at the start of the next gaze shift when the reflection began to move away from the center of the pupil. The interval until the next ON (any of the four stimuli) was defined as an OFF period.

Model—Infant Comparisons

Separate sets of simulations were used to compare the model's behavior to the free looking behavior of the 1- and 3-

month-old infants. For the comparison with the 1-month infant data, 24 independent simulations (equal to the number of 1-month-olds) were carried out for each combination of noise, bias, and hysteresis. For the comparison with the 3-month infant data, 21 independent simulations (equal to the number of 3-month-olds) were carried out for each combination of noise, bias, and hysteresis. For each simulation and each infant, the following seven measures were calculated as in Robertson et al. (2004): the transition rate between ON and OFF, the median durations of ONs and OFFs, the percentage of ONs and OFFs shorter than 1 s, and the percentage of ONs and OFFs longer than 10 s. Table 1 contains the infant *M* and *SD* for these measures.

For each simulation with a particular combination of noise, bias, and hysteresis, the model error for each measure was defined as the difference between the outcome of the simulation and the average infant value for the corresponding measure. The *maximum* model error for that combination of parameter values was defined as the largest average (over simulations) model error for the seven measures, expressed in infant *SD* units. Finally, the optimal combination of parameter values at each age was defined as the combination for which the maximum model error was smallest (Robertson et al., 2004). The model's performance at 1 and 3 months was compared using the optimal parameter values at each age.

RESULTS

Figure 1A shows the maximum model error (across the 7 measures) at each age in the noise $\times$ bias plane for selected values of hysteresis. The regions where the maximum model error is less than 1 infant *SD* overlap for the 1- and 3-month infant data, although the regions are larger in all dimensions (noise, bias, and hysteresis) for the 3-month data.

The optimal parameter values (for which the maximum model error is smallest) at 1 month are noise $= .834$, bias $= .25$, and hysteresis $= .275$; the maximum model error for those parameter values is $-.272$ infant *SD* (boxed numerical cursor label in Fig. 1A). At 3 months, the optimal parameter values are noise $= .989$, bias $= .30$, and hysteresis $= .300$; the maximum model error for those parameter values is $-.500$ (boxed numerical cursor label in Fig. 1A).

Model performance at the optimal parameter values differ significantly at 1 and 3 months, as indicated by a multivariate analysis of variance on the 7-measure vector of model errors, Wilks' $\Lambda = .214$, $F(7,37) = 19.5$, $p < .001$. The magnitude of the model error is larger at 3 months than at 1 month for each measure except the duration ON; the median ratio (3 to 1 months) is 2.05, Wilcoxon Signed Rank $T = 2$, $p = .016$. Each measure was therefore examined separately.

For three measures (percent brief and long OFFs, brief ONs), model errors differ significantly at 1 and 3 months, but are in the same direction at both ages (see Fig. 1B). In all cases the errors are larger at 3 months. The model *under*-estimates infants' brief OFFs more at 3 months ($-7.6 \pm 1.0\%$, $M \pm SEM$) than at 1 month ($-3.7 \pm 1.4\%$), $t(43) = 2.28$, $p = .028$. It also under-estimates long OFFs more at 3 months ($-3.6 \pm .2\%$) than at 1 month ($-1.0 \pm .4\%$), $t(43) = 6.04$, $p < .001$. The model *over*-estimates the percentage of infants' brief ONs more at 3 months ($5.7 \pm .8\%$) than at 1 month ($2.3 \pm 1.0\%$), $t(43) = 2.69$, $p = .01$.

For two measures (transition rate, median duration ON), model errors differ significantly at 1 and 3 months, but are in opposite directions (see Fig. 1B). In both cases the errors depart significantly from zero for the 3-month infant data, but not for the 1-month data. The model over-estimates infants' transition rate at 1 month ($.75 \pm .51\ \text{min}^{-1}$) but under-estimates it at 3 months ($-1.41 \pm .43\ \text{min}^{-1}$), $t(43) = 3.22$, $p = .002$. The model error differs from zero at 3 months, $t(20) = 3.27$, $p = .004$, but not at 1 month, $t(23) = 1.46$, $p = .16$. Similarly, the model over-estimates the median duration of infants' ONs at 1 month ($.45 \pm .29$ s) but under-estimates it at 3 months ($-.21 \pm .05$ s), $t(43) = 2.26$, $p = .033$. Again, the model error differs from zero at 3 months, $t(20) = 3.84$, $p = .001$, but not at 1 month, $t(23) = 1.57$, $p = .13$.

For the remaining two measures (median duration OFF, percent long ONs), the model errors do not differ at 1 and 3 months, *p*s > .05 (see Fig. 1B).

Table 1. Measures of Infant Free Looking at 1 and 3 Months

	M (*SD*)	
Measure	1 Month	3 Months
Transition rate (min^{-1})	16.03 (5.57)	25.20 (11.38)
Median duration ON (s)	2.10 (1.84)	1.65 (.96)
Median duration OFF (s)	.74 (.38)	.72 (.90)
ONs < 1 s (%)	38.7 (11.5)	38.8 (12.0)
OFFs < 1 s (%)	64.8 (16.0)	71.7 (15.1)
ONs > 10 s (%)	18.7 (9.8)	8.5 (7.6)
OFFs > 10 s (%)	3.2 (4.1)	4.5 (7.2)

DISCUSSION

A simple stochastic dynamical system, previously shown to behave remarkably like 1-month-old infants during free looking even though it has no components directly representing perceptual-cognitive process that are engaged during looking (Robertson et al., 2004), also

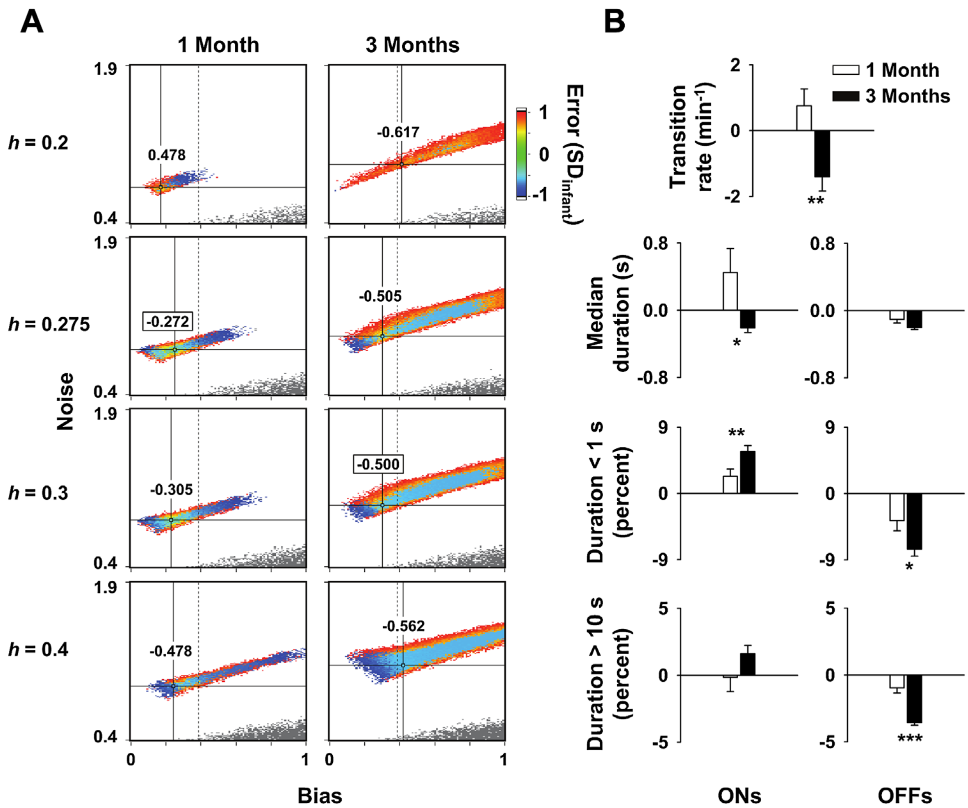

FIGURE 1 Comparisons between the behavior of the model and infants at 1 and 3 months. (A) Maximum model error (the largest difference between model and infant *M* across the set of 7 measures, in infant *SD* units). The results are shown for each combination of noise and bias for selected values of hysteresis, *h*. In each panel, the dashed line indicates the critical value of bias above which only the ON state is stable. The cursors indicate the combination of noise and bias for which the maximum model error was smallest for the indicated hysteresis, and the numerical cursor label indicates the corresponding maximum model error. The boxed cursor labels indicate the maximum model error at the *optimal* parameter values (the values of noise, bias and hysteresis for which the maximum model error is smallest) for each age. (B) Model errors ($M \pm SEM$ difference between model simulations and infant *M*) for each measure for the 1- and 3-month infant data, based on the optimal parameter values for each age. $^{*}p < .05$, $^{**}p < .01$, $^{***}p < .001$, for the 1-month vs. 3-month comparisons.

behaves like 3-month-olds. Its success suggests that the basic properties of the model—bias, noise, and hysteresis in the transitions between looking and not looking—may represent fundamental processes that influence infant free looking across the first 3 postnatal months, a time of rapid perceptual-cognitive development. Furthermore, the parameter values which yield model behavior most like that of infants at each age are roughly similar, suggesting no dramatic changes in the processes they may represent. However, the range of parameter values that yield model behavior within a standard deviation of infant behavior is larger at 3 months, which may indicate that those processes have lost relative influence on infant free looking by 3 months.

Although the model succeeds at 3 months, its performance is, in fact, quantitatively worse than at 1 month. For the optimal parameter values at each age, the model's errors (deviations from infant *M*) are significantly larger at 3 months for the set of seven measures of free looking as a whole, and for five of the seven measures individually. The affected measures, and the pattern of their under- and over-estimation, raise the possibility that the model's worse performance at 3 months reflects an increased influence of perceptual-cognitive processes in infants that is not represented in the model.

Specifically, the changes in attention that occur at the beginnings and ends of looks may have more influence on the durations of those looks and the following looks away by 3 months of age. For example, motor and cardiac measures reveal a rapid increase in 3-month-old infants' attention at the beginning of a look (Richards, 1987; Robertson et al., 2001a), and EEG measures show that 3-month-olds' *covert* attention to the next target of fixation during free looking increases just before the current look ends (Robertson, Watamura, & Wilbourn, 2012). The model's difficulty at 3 months may therefore reflect the fact that bias, which is presumed to represent the net effect of factors including attention (Robertson et al., 2004), does not change when the system enters or leaves the states corresponding to looking and not looking. Furthermore, noise in the model is presumed to represent the net effect of factors including irregular fluctuations in spontaneous motor activity (Robertson, Bacher, & Huntington, 2001b; Robertson et al., 2004). But motor activity is suppressed at the beginning of looks and increases just before gaze shifts, and this movement-gaze coupling is tighter at 3 months than at 1 month (Robertson et al., 2001a; Robertson, Johnson, Masnick, & Weiss, 2007). The fact that bias is fixed in the model may be doubly problematic by 3 months because it rules out coupling to noise.

In summary, the simple stochastic dynamical system that can behave like free looking 1-month-olds has substantially more difficulty with 3-month-olds. The fact that the model does not include any components that represent perceptual-cognitive processes seems a likely reason for its poorer performance at 3 months. The specific pattern of difficulties it exhibits suggests that the absence of time-dependent components corresponding to processes like attention in infants may be especially important. On the other hand, the model does not fail altogether with 3-month-olds. Its limited success supports the broader hypothesis that young infants' ability to visually explore and therefore learn about their environment may emerge in both real and developmental time from generic, non-cognitive processes like noise and hysteresis in the neurobehavioral systems controlling gaze.

NOTES

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