Understanding the Distribution of Infant Attention: A Dynamical Systems Approach

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Abstract

A process model is presented to account for infant looking patterns in habituation and preferential looking experiments. The model emphasizes the infant's own role in controlling exposure to stimuli. Operating on the level of individual fixations in continuous time, the model ties cumulative looking times to patterns of individual looks. The process described does not make use of a spatial map of stimuli. We explore the behavior of the model using fixed trials, infant-controlled trials, paired presentations, and preferential looking procedures, examining both group and individual measures of cumulative looking times and individual fixations.

Keywords: Attention; Habituation; Visual Paired Comparison; Dynamical Systems Theory; Dynamical Field Model; Infant

Introduction

The principal vehicle of the study of infant cognition is the measurement of visual attention in the laboratory. Countless studies have built on Fantz's (1964) observation that looking times can be used as a signature of recognition and memory. Still, there is little theoretical or experimental work examining infant looking as a process. Although infants spend a significant portion of an experiment looking away, the fine structure of looks and looks away, beyond cumulative measures of looking time, is rarely reported.

We come to this study with the hypothesis that there is more to be learned from patterns of how infants look and look away by examining and accounting for their behavior on multiple scales of measurement. Is there a functional and adaptive purpose to the noisy patterns of looking we observe? Can we understand more about the processes underlying attention and perceptual learning—the processes we hope are indexed by looking time measures—if we more closely account for and understand the fine-scale structure of fixations and gaze shifts? A prerequisite to answering these questions is to understand how perceptual experience depends on, and in turn shapes, patterns of looking.

As a step toward addressing such questions, we have built a process model of infant looking, where the model's own spatially directed looks, controlled in continuous time, are what determine its exposure to stimuli. The model allows us to relate moment-to-moment patterns of looks in space to the more familiar macro-scale measures of cumulative looking times and preferences. It also gives us a useful tool for understanding how looking is affected by differences in experimental procedures. In particular, we compare infant control versus fixed trial lengths, and paired versus single stimulus presentations.

The specific hypothesis formulated with this account is that the patterns of looking observed in infant experiments may be accounted for by a process with the following key features: (a) Targets of gaze shifts are driven by raw salience. (b) Perceptual information is accumulated in time. And (c) release of fixation is modulated by perceptual activation. These assumptions imply a fourth: that the relevant processes driving looking are *not* based on learning what is where in space.

The Model

Background and overview

Dynamical field models provide a general account for the selection and stabilization of a decision from among competing inputs. Reflecting the dynamics of populations of neurons with overlapping receptive fields, a "peak" of highly activated neurons in an otherwise-inhibited field specifies a value along the dimension of the field. Locally cooperative and distally inhibitive interactions within the field assure that only one value (a single peak) is selected. Once a peak is formed, hysteresis makes it is unlikely for the decision or peak location to change. This stability is essential in Dynamical Field Theory in order that the same process by which a decision is made can account for the control of temporally extended, embodied behaviors.[1]

Figure 1 illustrates the overall structure of the model. There are two fields in our model. A peak in the perceptual field specifies a percept of what is currently foveated. A peak in the motor field specifies a plan for the gaze system, either to fixate or to shift the gaze. Both fields receive input from the retina, but the perceptual field gets input only from the currently attended stimulus in the fovea. More intense or complex stimuli are treated in the model as inputs of higher amplitude. An additional input condenses all of the possible

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[1]The general mathematical form for a dynamical field is $\tau \dot{u}_{(x,t)} = g[u] + S_{(x,t)}$, where $g[u] = -u_{(x,t)} + h + \int w(x-x')\sigma(u_{(x',t)})dx'$

$u_{(x,t)}$ is the activation level of the field at location x and time t. $S_{(x,t)}$ is input to the field, h is a negative resting level, and $w(x-x')$ is a homogeneous interaction kernel. The kernel is typically of the form: $w_{\text{excite}} - w_{\text{inhib}} \exp(-1/2((x-x')^2/\sigma^2))$; and $\sigma(u) = 1/(1 + \exp(-\beta \cdot u))$ is a sigmoidal function.
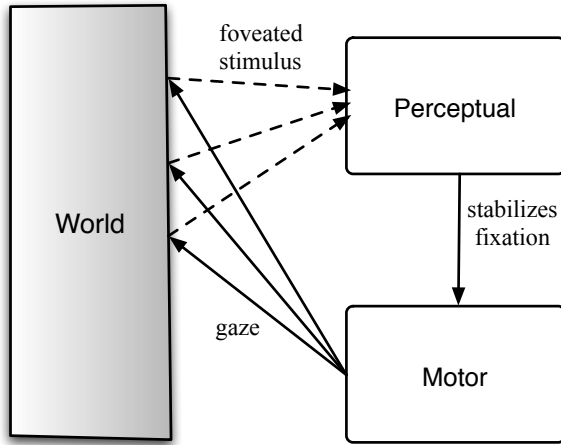
Figure 1: Overview of the field model

other targets of infant attention—lights, experimental equipment, clothing, mom—into one reserved location and percept. This "away" input is weaker than most stimuli and is always presented as part of the stimulus array.

The peak in the perceptual field varies in strength due to stimulus-specific memory effects. This activation level is transmitted as an input to modulate the stability of fixation in the motor field. The essence of our account is that a simple model of accumulation of excitatory and inhibitory perceptual history effects can replicate many features of looking patterns found in a variety of infant looking procedures.

Perceptual field

Figure 2 illustrates the perceptual system.[2] The dimension of the perceptual field spans the space of possible percepts, where neighboring field locations represent similar percepts. The perceptual field receives input represented in this perceptual space from the particular stimulus that is foveated. It generates a peak of activation in the corresponding location in the field.

This field is also coupled to two memory, or preshape, fields, one excitatory and the other inhibitory. The memory fields are defined in the same perceptual dimension. Memory traces build up slowly in both memory fields at the field location where the activation field has a peak. Memory traces in non-activated field-locations decay. The strength of the peak in the activation field in turn varies due to input from these excitatory and inhibitory traces.

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[2]The perceptual activation field $u_{p(f,t)}$, and its excitatory ($p_{p(f,t)}$) and inhibitory ($v_{p(f,t)}$) memory, or preshape, fields are defined as follows:
$$\tau_u \dot{u}_{p(f,t)} = g[u_p] + p_{p(f,t)} - v_{p(f,t)} + C_{p,S} \int v(x) S_{(f,x+\text{gaze}(t),t)} dx$$
$$\tau_p \dot{p}_{p(f,t)} = -p_{p(f,t)} + C_p \sigma(u_{p(f,t)})$$
$$\tau_v \dot{v}_{p(f,t)} = -v_{p(f,t)} + C_v \sigma(u_{p(f,t)})$$
$S_{(f,x,t)}$ is the stimulus description in perceptual and (world-centered) spatial coordinates. $\text{gaze}(t)$ is the position of the eyes as controlled by the motor system. $v(x) = \exp\left(x^2/\sigma_{\text{fovea}}^2\right)$ is a gaussian bump centered at $x = 0$.
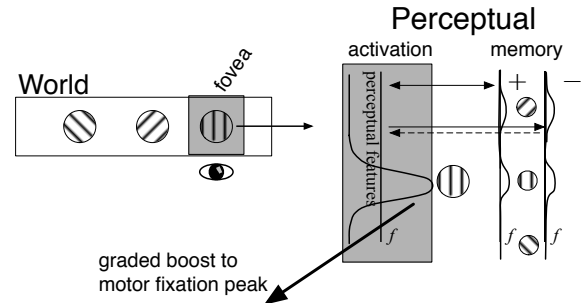

Figure 2: The perceptual system. The activation field generates a peak corresponding to the currently foveated stimulus. Excitatory and inhibitory preshape traces reflect past exposure to different stimuli.

Because the memory traces are localized in feature-space, the perceptual field can respond differently to two different stimuli, depending on the history and timing of past stimulus exposure. Most typically, for example, this means a reduced response to a habituated stimulus relative to a fresh one. Memory traces are built up such that with continued exposure to a particular stimulus, excitation dominates early on, while inhibition dominates later. Since a look away might include a variety of different, uncontrolled visual inputs, we assume that memory traces for those looks do not have a chance to build up coherently. The perceptual peak for the "away" percept stays at a default level of activation.

Motor field and gaze

Figure 3 illustrates the motor and gaze control system.[3] The dimension of the motor field spans the space of possible looking directions, represented in retinal coordinates. A peak at the fovea specifies continued fixation. A peak at an extra-foveal location specifies a shift of the gaze with the corresponding direction and magnitude.

The motor field receives retinotopic input from the array of visible stimuli, including the input for "away" looks. For example, the foveated stimulus provides input at the center of the field, $x = 0$. Inputs are stronger for more salient stimuli but do not distinguish between different, equally salient stimuli. Finally, an additional input corresponding to the total amount of perceptual field activation is provided to the central (foveal) region of the field. This input adds stronger or weaker support to the fixation peak. The duration of each fixation—*when* to shift the gaze—is determined by stochastic competition between the fixation peak and the various potential gaze targets.

Gaze is controlled by the peak in the motor field. It is held steady when a fixation peak is active. When a motor planning

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[3]The motor field is defined as follows:
$$\tau_u \dot{u}_{m(x,t)} = g[u_m] - C_{\text{fix}\Delta} v(x) + C_{m,S} \int S_{(f,x+\text{gaze}(t),t)} df + C_{m,p} v(x) \int \sigma(u_{p(f,t)}) df + \text{reset} \cdot [-C_{\text{killp}} + C_{\text{fixreset}} v(x)] + \text{noise}(x,t)$$
reset is 1 during the final portion of a gaze shift, and 0 otherwise. $\text{noise}(x,t)$ is spatially correlated, gaussian, white noise.
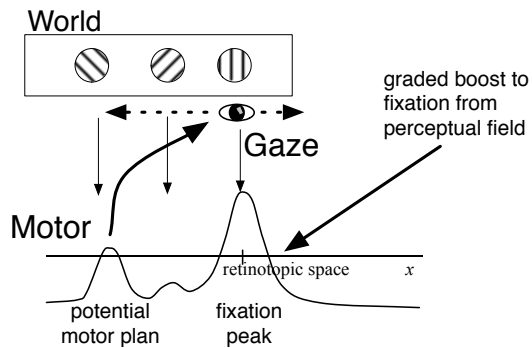
Figure 3: The motor and gaze system. The motor planning field generates either a fixation peak or a peak that determines the magnitude and direction of a gaze shift. These two possibilities compete in the presence of noise. Fixation is more stable when perceptual activation is stronger.

peak arises, a shift of the specified magnitude and direction is generated without feedback over a fixed duration to bring the gaze to the corresponding location. Technically speaking, the motor planning peak is stable, but it is short-lived: At the end of a gaze shift, the motor field is reset to reestablish a fixation peak at its center.

Simulation Results

In this section we illustrate how the model performs in a variety of infant looking paradigms. We look at groups and individuals, using different scales of measurement, including individual fixations as well as cumulative looking times and preference scores.

Habituation with fixed length trials

First we examine the model's behavior in a straightforward habituation paradigm. In this procedure a single stimulus is presented on a fixed schedule of presentations and inter-trial intervals. Fixed-length trials are less common than one might expect, used more in studies of attention for its own sake rather than in broader studies of cognitive development.

Using a fixed trial procedure, Colombo et al. (1997) found a decline in cumulative looking over trials, as well as a decline in mean fixation length over trials. They also reported that more complex stimuli elicited greater looking overall Note that in this procedure, looking decrements are not as dramatic as the steep, exponential shape found in infant-controlled procedures.

Similar to Colombo et al. (1997), we presented the model with 10 trials of 10 seconds each, using 10 second inter-trial intervals. We also added a test phase, where presentations of a novel stimulus (trials 11 and 13) alternate with the familiar stimulus from the earlier phase.

Figure 4 shows cumulative looking time data for simulations using three different stimulus strengths, as well as data for comparison from Colombo et al. (1997). Group data here and throughout the paper are averaged over 16 simulated in-

fants per condition and plotted with standard error bars. After a ramp-up not evident in Colombo et al. (1997), we see a similar subtle decline of looking in all stimulus conditions. Like cumulative looking times, mean look durations (not plotted) also decreased in the model after an initial ramp-up. This illustrates how cumulative looking is tied to fixation length in the model. Stimulus intensity also led to more total looking, similar to the experimental data. In the final trials, the model demonstrates a novelty preference, looking more across trials 11 and 13 than in trials 12 and 14.
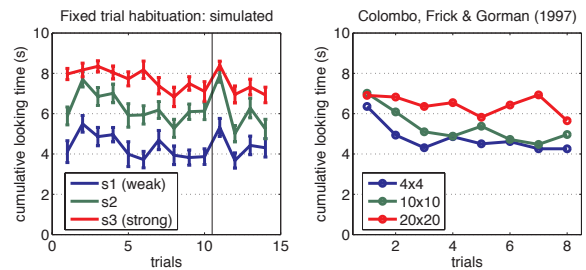

Figure 4: Cumulative looking times by trial for a simulated fixed length habituation procedure with three values of stimulus strength. Data from Colombo et al. (1997) are presented on the right for comparison. In the simulated data, trials 11 and 13 after the black line are presentations of a novel stimulus.

Finally, we can compare the distribution of lengths of individual fixations produced by infants and the model. We are not aware of reports of fixation distributions in a fixed trial procedure, but the general exponential-like shape seems largely independent of procedure. Similar results are reported by Fisher-Thompson & Peterson (2004) for preferential looking and Richards & Gibson (1997) for a single, long stimulus presentation. Figure 5 presents histograms of look lengths to compare this simulation with data from Fisher-Thompson & Peterson (2004). In both the simulations and the data, short looks are common, and long looks occur occasionally. The model generates similar distributions of look lengths in other procedures as well, owing largely to the motor dynamics: Over a short time interval where habituation is not significant, the likelihood of a break of fixation is approximately equiprobable at any moment.

Infant controlled trials

Criteria based on looking are often used to determine the schedule of stimulus presentations, including trial onsets, offsets and number of trials before habituation is presumed. Stimuli may be turned on only when the infant looks at the display; stimulus presentations may continue until the infant looks away for a set amount of time; and trials may continue until the infant's cumulative looking on a number of trials is less than a habituation criterion, usually a percentage of initial looking. In these simulations we examine effects of infant controlled trial offsets and habituation criteria. Note that without a process model that generates looks in time, it is not
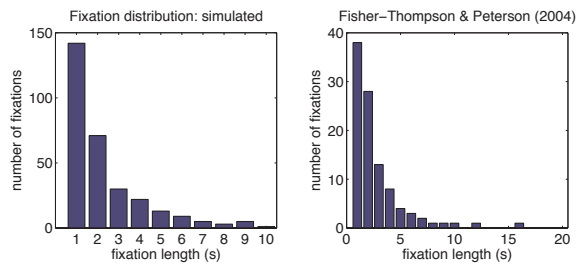
Figure 5: Histogram of fixation times in a simulated habituation experiment (left) and in infant data from Fisher-Thompson & Peterson (2004).

possible to realistically replicate procedures where stimuli are contingent on looking.

Infant controlled procedures also elicit a decline in looking over trials, sometimes much more dramatically than seen with fixed trials. Very long initial looks are not uncommon (Horowitz et al., 1972). Feng et al. (Submitted), also reported that, as with fixed trials, more salient stimuli elicit longer looking.

Figure 6 shows simulated group data with three stimulus strengths for an infant control task design. Any look away was treated as sufficient to end each trial. We found longer initial looking and a more dramatic decline in looking than that found in the fixed habituation simulations.[4] We also show again that overall looking increases with stimulus salience.
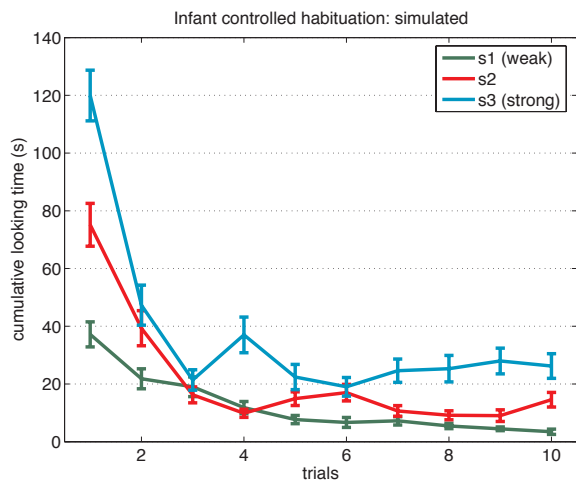

Figure 6: Group data comparing stimuli of varying salience in an infant controlled habituation procedure.

Bornstein & Benasich (1986) suggested three categories of

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[4]We have also verified in the model that backward averaging—where subjects' trial data are aligned backwards from the trial on which each subject reaches criterion—shows the same artifactual peak immediately before criterion that was discussed by Cohen & Menten (1981). For the same reasons they elaborated, the effect here is artifactual as well, not reflecting a pattern found in individual profiles.

individual infants' habituation profiles in their study, which used infant-controlled offset and habituation criteria. The categories are *exponential decrease* for infants whose looking declines steadily from baseline to criterion; *increase-decrease* for those that show an increase in looking, or sensitization, before declining back to criterion; and *fluctuating*, for infants whose looking time curve has multiple peaks and valleys before reaching criterion. Cases of each profile arise in the model. Figure 7 shows comparisons between sample runs of the simulator with infant data from Feng et al. (Submitted). In simulations, these are generated with the same parameter settings. Thus they are not a product of stable individual differences. This illustrates how nonlinear instabilities can amplify early fluctuations in looking, causing distinct patterns to emerge.

Stimulus salience can, however, affect the likelihood of different categories of habituation profile. In simulations of this procedure, a stronger stimulus generated fewer fluctuating profiles and more exponential decreasers. This seems to fit with the overall pattern of the two studies that report counts of such categories. The proportion of exponential-decrease was lowest for Feng et al.'s (Submitted) low intensity condition (a simple animal shape in motion); higher for Feng et al.'s high intensity (the same stimulus with a face) and Bornstein & Benasich's (1986) geometric condition (bulls-eye or grating); and highest for Bornstein and Benasich's social condition (photos of faces). Although Bornstein & Benasich argued the opposite in a footnote, we suspect that the profile which emerges is related to the baseline. A low baseline is harder to reach, so the experiment is likely to continue for more trials, creating more opportunity for fluctuation. For Bornstein & Benasich (1986) and in our simulations, fluctuators took more trials on average to reach criterion than exponential decreasers. Increase-decrease profiles are the rarest of the three, both in the experiments and in our simulations.
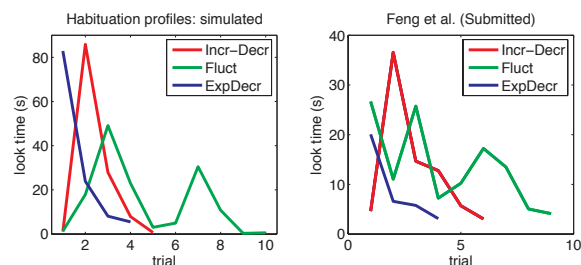

Figure 7: Examples of exponential, fluctuating, and increase-decrease habituation profiles from simulations (left) and Feng et al. (Submitted). Plots stop at the trial where a habituation criterion is met

Paired presentations

Until here, we have discussed the effects of changes to the *temporal* structure of the task: infant control versus fixed trial schedules. The structure of the model also makes it straightforward also to examine the effects of *spatial* structure of ex-

periments. Here we examine the effects of adding a second, simultaneously presented stimulus. First, (not pictured) our model accounts for two observations by Ruff (1975). There is more looking overall when two identical stimuli are presented side-by-side for familiarization, rather than just one. And individual fixations are on average shorter in the identical paired condition. Both effects are straightforward to understand in the model. With paired presentations, gaze shifts compete among two strong looking sites and one weak (away) site. Therefore more shifts result in looks at a true stimulus. Fixations are shorter in the paired condition because there is always a strong extra-foveal target to compete with the fixation peak.

Visual Paired Comparison

Familiarity preference scores provide an additional measure that we can examine in the model. Fantz (1964) presented infants with a series of trials, where one stimulus, called the familiar, was presented repeatedly, but was always paired with a different novel stimulus. We calculate the familiarity preference on each trial, the percentage of total looking at experimental stimuli that was to the familiar. Fantz's infants acquired a preference to look more at the novel stimulus. Figure 8 compares the model's preferences over trials to those from a subset of Fantz's data.
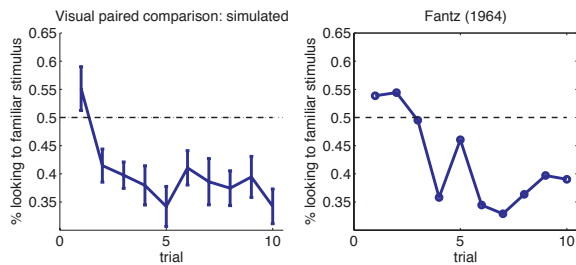

Figure 8: Group preference scores in a Visual Paired Comparison procedure with data for comparison from Fantz (1964).

General discussion

In our account, planning of gaze shifts is based on a retinotopic salience map, with no perceptual information, and there is no memory for locations of prior looks. Thus the motor system does not represent "what," and "where" is only represented in a transient, retinotopic sense. The perceptual system, where stimulus-specific history effects take place, is ignorant of space, generating a response only to the stimulus in the fovea at each moment. Variation in the stability of fixation, rather than search, underlies novelty and familiarity effects. In sum, our account relies on no associations between space and content in memory or in active representation—besides what is given naturally by the structure of the world. The idea that habituation may be governed by fixation is compatible with theory by Cohen (1972) regarding the separation of attention-getting and attention-holding processes.

On the surface, it might seem more straightforward to account for looking preferences with a process using a map of stronger or weaker points of attraction in the visual field. In practice, though, to control gaze in this way requires continual realignment of retinal and body-centered reference frames—a substantial achievement. Here, we suggest that a simpler "myopic" mechanism of modulating release from fixation accounts for observed patterns of looking without the need for keeping track of space.

Our model derives from an earlier dynamical field model (Schöner & Thelen, 2006), which used a similar pattern of accumulation of excitation and inhibition to account for habituation. The earlier model used an activation level to indicate looking or not looking. Because it did not generate looks in space, it could not model experiments with paired stimulus presentations. The lack of space in this model also meant that it had no mechanism for reengagement after a look away without the start of a new trial. Thus that model was silent on the perceptual basis for spatial patterns of looking. Finally, with the current motor system, we have been able to move beyond simplifications used by Schöner & Thelen (2006) and similarly by Gilmore (2001) in modeling infant-control procedures. Here we can realistically implement the contingency of stimulus presentations on looking at the same time as we allow the system to truly control its own stimulation.

An additional difference from the earlier model points beyond the experimental data presented here. In the new model, the perceptual system is centered on an active peak specifying the percept. This allows us to discuss how the system would behave when the gaze settles where there is no visual structure to form a peak. (We would expect gaze not to linger.) Further, the perceptual field enables us to examine how looking and perceptual representations depend on similarity between presented stimuli—the overlap between their perceptual representations. Perone et al. (In press) in this proceedings have used this kind of analysis to examine how overlap between stimuli contributes to categorical effects in infant looking.

We share the same basic conceptual framework, a committment to a process model of habituation based on neuronal dynamics, with another recent model of habituation (Sirois & Mareschal, 2004). Sirois & Mareschal go further than we do in relating their model to neurophysiology. Their model was not aimed to account for looking in detail. It generates cumulative looking times from differences in activation, similar in spirit to Schöner & Thelen (2006). A recent robotic implementation (Sirois, 2005) does has a vision sensor which moves. The visual information provided by the sensor to the model contains the entire scence, translated into the spatial frequency domain so that the effects of retinal shifts are neutralized. In that sense this robotic model does not yet control stimulation through its own actions. An architectural difference between the models is that their primary driver of habituation is the complement of our approach: control over where

to choose to look, rather how long to fixate. Note that assuming that looks are directed to stimuli as a function of how activated their representations are presupposes that the system knows "what is where," that is, has a spatial map of perceptual objects. In contrast, assuming that perceptual activation modulates fixation does not require this to be the case. The two models thus make substantially different assumptions. There is some evidence pointing in the direction of our assumption: Fixation time, but not latencies or probabilities of looks, decreases with stimulus exposure (Cohen et al., 1975; Fisher-Thompson et al., 2004). More work is required, though, to thoroughly tease apart these possibilities.

To gather information safely in an unpredictable world, babies have to find a balance between focused examination of objects and exploration of what is out there to see. Babies (with some exceptions) do not wait until habituation to look away. In order to account for how infants control exposure to stimuli by directing their gaze, our model generates highly variable patterns of looking in many experimental situations. This variability is borne out in experimental data of looking patterns from individual experiments, but we may also consider whether it is a practical necessity for the straightforward control of exploration without global information. Thus the variability we observe in infant looking may be adaptive in achieving a healthy balance between examination and exploration. Our account suggests that this balance is achieved by deciding not where to look, but *when* to look *away*.

Acknowledgements

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