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Authors

de Barbaro, Kaya
Chiba, Andrea
DeÅik, Gedeon O

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PAPER

Micro-analysis of infant looking in a naturalistic social setting: insights from biologically based models of attention

Kaya de Barbaro, Andrea Chiba and Gedeon O. Deák

Department of Cognitive Science, University of California, San Diego, USA

Abstract

A current theory of attention posits that several micro-indices of attentional vigilance are dependent on activation of the locus coeruleus, a brainstem nucleus that regulates cortical norepinephrine activity (Aston-Jones et al., 1999). This theory may account for many findings in the infant literature, while highlighting important new areas for research and theory on infant attention. We examined the visual behaviors of $n = 16$ infants (6–7 months) while they attended to multiple spatially distributed targets in a naturalistic environment. We coded four measures of attentional vigilance, adapted from studies of norepinephrine modulation of animal attention: rate of fixations, duration of fixations, latency to reorientation, and target 'hits'. These measures showed a high degree of coherence in individual infants, in parallel with findings from animal studies. Results also suggest that less vigilant infants showed greater habituation to the trial structure and more attentiveness to less salient stimuli during periods of high attentional competition. This pattern of results is predicted by the Aston-Jones model of attention, but could not be explained by the standard information processing model.

Introduction

Measures of infant looking behavior have long been considered an important indicator of attention and processing speed. More recently, developmental science has begun incorporating biological frameworks to better characterize the function and processes of attention-mediating and information-encoding behaviors. For example, concurrent measurement of physiological data such as heart rate has been successfully used to break gaze into component phases of orienting, maintenance, and shift-preparation (Colombo, Richman, Shaddy, Greenhoot & Maikranz, 2001; Richards & Casey, 1991). Current biological literature also posits that the neuromodulatory state of an organism can drive visual attention. Specifically, theoretical advances posit that several behavioral indices of attentional vigilance are paralleled by the activation of the locus coeruleus, a brainstem nucleus that regulates cortical norepinephrine (NE) activity (Aston-Jones & Bloom, 1981a; Aston-Jones, Rajkowski & Cohen, 1999). These indices include several 'micro' behavioral features of looking, including rate and duration of individual saccades. To our knowledge, no study has explicitly assessed the validity of this theory in human infants. However, there are parallels between the Aston-Jones model of attention (AJMA) and a more traditional model in developmental studies that describes some of these measures of attention in terms of

information processing (IP) constructs. Thus, research on the coupling between the neuromodulator norepinephrine and animals' attentional states is relevant for (1) refining our understanding of infant attention, and (2) deriving a theoretical framework for measuring and testing novel hypotheses about micro features in infants' looking.

The current work is organized as follows. First, we review the animal literature on NE and behavior, and document its relations to the existing infant literature, specifically the traditional IP model of attention. Although Aston-Jones and colleagues' work clearly shows the role of the LC and NE in attention modulation, it is impossible to measure these effects directly in human infants, and difficult even to measure them indirectly. Thus while we do not measure LC/NE activation in infants, we review the animal research because it lays out the empirical and theoretical basis for the analysis of behavioral measures in the current study. Specifically, we can test the *validity of this theory for explaining infant looking* by examining particular behaviors that should arise in certain circumstances. Some of the relations between these indices are *counterintuitive* under current information processing models. By testing the coherence of these measures of infant looking behaviors, we determined that the Aston-Jones model can account for patterns of visual attention that were heretofore unexplained in human infants.

Address for correspondence: Gedeon O. Deák, Department of Cognitive Science, University of California, San Diego, 9500 Gilman Dr., La Jolla, CA 92093-0515, USA; e-mail: deak@cogsci.ucsd.edu

Aston-Jones model of LC modulation of attention

The activation of NE neurons is widely thought to function in the modulation of a continuum of attentional behaviors (Amaral & Sinnamon, 1977; Aston-Jones, Chiang & Alexinsky, 1991; Berridge, Page, Valentino & Foote, 1993). A nucleus of NE neurons in the LC ascends extensively to limbic and cortical areas that are believed to enact and alter attentional states (Morrison & Foote, 1986; Posner & Petersen, 1990).

At the lowest end of the attentional continuum are activities such as sleeping or resting, as well as automatic or habitual behaviors that require minimal attention to environmental stimuli, such as grooming or drinking (Aston-Jones & Bloom, 1981a). These activities are associated with low frequency oscillatory release of NE, called *phasic* LC activity.

Intermediate levels of NE release are associated with 'selective' or 'focused' attention wherein animals are active, but only moderately responsive to stimuli outside of their immediate focal area (Aston-Jones & Bloom, 1981b; Rajkowski, Kubiak & Aston-Jones, 1994). These states occur in environments in which goals and stimuli stay relatively stable; where environmental processing demands are low but not trivial (Aston-Jones *et al.*, 1999).

At higher frequency oscillations of NE release by LC neurons, called *tonic* firing rates, animals show a higher degree of vigilance or 'anticipatory readiness' to their surroundings (Aston-Jones & Bloom, 1981a). Behaviorally this can be assessed via an increased likelihood of reorienting to novel stimuli, and decreased latency to reorient. For example, Aston Jones and Bloom (1981b) found that LC activity spiked when animals redirected their attention, and blocking NE receptors (thereby extinguishing the effects of NE release) reduced rates of stimulus reorientation. Increased NE is also associated with a high rate of short fixations (Rajkowski *et al.*, 1994). Highly responsive animals have low thresholds for responding to novel visual stimulation and therefore do not maintain gaze to any one location for very long. At extreme levels this results in continuous fast scanning.

This decreased threshold to respond to features of the environment leads to increased and broadened sensory access, allowing animals to more quickly identify and adapt to rapidly changing circumstances (Aston-Jones *et al.*, 1999). This is adaptive in situations of novelty and unpredictability, ranging from minor (e.g. a sound coming from an unknown source) to major (e.g. an attack by a predator). Modeling accounts show that the amount of firing of NE neurons matches the degree of perceived uncertainty (Yu & Dayan, 2005).

However, experimental and observational work shows that states of high vigilance have a reciprocal cost. Specifically, the readiness associated with high vigilance also leads to increased distractibility and difficulties focusing attention to a central location. Rajkowski *et al.* (1994) found that moderate NE release in old-world monkeys

corresponded with steady foveation to a fixed stimulus, and relatively low responses to distractors. By contrast, high NE release was associated with difficulty of central foveation and increased 'scanning' eye movements, and a decreased threshold for response to distractor stimuli (i.e. false alarms).

In sum, LC-dependent levels of cortical NE levels are tightly related to a number of attentional behaviors. These relations have also been observed in adult humans (Skosnik, 2000; Clark, Geffen & Geffen, 1989). To our knowledge, however, no study has documented these relations in human infants. AJMA does make predictions that fit the results of some studies of infants; however, in evaluating these we must also evaluate their fit with models and predictions of information processing theory.

AJMA and current information processing models

Infant information processing efficiency is usually assessed in terms of the duration of the longest look (i.e. 'peak look') to a novel stimulus. Theoretically, the relationship between looking time and processing speed is based on comparator theory (Clifford & Williston, 1993; Solokov, 1963), which states that when infants look at an object they are collecting information to build a mental representation of it, and when they look away they have completed the representation. This is supported by empirical research showing that infants with shorter peak (i.e. longest) fixation durations, or 'short lookers', show similar novelty scores (evidence of learning) as 'long lookers', which is interpreted as evidence that they process the same amounts of information in a shorter time. Thus 'short lookers' are considered fast information processors (Bornstein, 1985; Colombo & Mitchell, 1988; Colombo, Mitchell, Coldren & Freeseaman, 1991; Fagan, Holland & Wheeler, 2007).

A number of predictions are shared by the information processing (IP) model and AJMA. For example, infants identified as fast processors disengage more rapidly to orient to peripherally placed stimuli in a subsequent task (Frick, Colombo & Saxon, 1999). Similarly, during a television viewing task with distractors, Richards and Turner (2001) found that long looks were followed by longer latencies to respond to new distractor stimuli, whereas short looks were followed by shorter response latencies. These studies parallel findings in the animal literature in that increasing vigilance corresponds with increased speed of disengaging and increased probability of reorienting to a new, peripheral event.

Fast looking infants also show a broader spatial distribution of gaze (Colombo & Janowsky, 1998; Jankowski, Rose & Feldman, 2001; Orlian & Rose, 1997) than longer looking peers. Experimentally broadening the spatial distribution of slower looking infants' gaze increased their familiarity with stimuli to levels shown by fast lookers (Jankowski *et al.*, 2001). AJMA suggests that this broadening occurs due to the increased readiness to respond to stimuli associated with vigilant states. AJMA

modeling work has also shown that such 'scanning' patterns are functional for certain types of learning (Yu & Dayan, 2005), as Jankowski *et al.* (2001) identified.

In contrast to findings such as these, there are a number of behavioral elements and relations that are predicted by the AJMA, but are absent from IP theories of infant attention. Studying the differences between the two theories can help to refine models of infant attention.

Two differences between IP theory and AJMA are particularly important. First, IP considers behaviors related to vigilant attentional states (e.g. faster reorientations) as 'better' or more mature. By contrast, AJMA proposes that each end of the continuum of attentional states has reciprocal costs and benefits. That is, the readiness associated with high-tonic activity states (i.e. vigilance) also entails increased distractibility, as the threshold of stimulus salience that will elicit reorientation from a central gaze location is reduced. In other words, attention is more driven by peripheral sensory information. By contrast, at more moderate levels of vigilance, organisms have increased opportunity to self-direct attention and achieve focus, as interference from peripheral events is relatively dampened (Aston-Jones *et al.*, 1999). This is adaptive for tasks that require sustained attention to a centralized location of low perceptual salience, such as studying or waiting for a hard-to-detect cue (Aston-Jones *et al.*, 1999; Rajkowski *et al.*, 1994).

Its basis in comparator theory leads traditional IP to ignore the tradeoff between focused attention and high vigilance, because the outcome of a look is presumed to always be the same: a complete representation of one focal stimulus. However, models of active vision show that we should not conceive of stimulus information as 'out there' in discrete, prepackaged, perceiver-independent 'chunks'. Instead, organisms elaborate features of the environment as a function of prevailing goals and behavioral demands (see reviews by Aloimonos, Weiss & Bandyopadhyay, 1988; Findlay & Gilchrist, 2003; Gibson, 1998; Hayhoe & Ballard, 2005). Under these models, looking away does not signify 'completing a representation', but rather, given the current task, that there is more to be gained by looking elsewhere. Conversely, continuing to look can also suggest additional gains from the objects of attention (see also Courage, Reynolds & Richards, 2006, and Ruff & Saltarelli, 1993, for additional evidence from infant studies for these claims). One way to resolve this tension between the two models is by investigating the relationship between vigilance and 'attentional tradeoffs', or time spent looking to high vs. low salience stimuli. Specifically, AJMA predicts that time spent attending to low salience targets in the context of peripheral higher salience 'competitors' will be reduced under states of increased vigilance. This reduction would not be predicted by traditional IP accounts.

Second, AJMA highlights the influence of short timescale factors on attention, or task- and state-specific

adaptation of attention. Both naturalistic observations and experimental manipulations show that changes in the firing rates of LC/NE cells, and their behavioral consequences, shift from moment to moment. These shifts are due to internal and external factors related to stress and uncertainty. For example, an unexpected noise can cause both a spike in NE and a redirecting of gaze, illustrating the potential for novel or unexpected stimuli to affect levels of vigilance (Aston-Jones & Bloom, 1981b). This is also evident in activation of LC neurons by a variety of physical and psychological stressors (Abercrombie & Jacobs, 1987; Morilak, Fornal & Jacobs, 1987a, 1987b). Again, this is unsurprising as increasing vigilance has the effect of decreasing uncertainty about the surroundings (Yu & Dayan, 2005). The typical pattern of LC/NE activation is one of dynamic adaptation in response to stability or change in the environment: as uncertainty is reduced, so is activation of LC/NE (Aston-Jones & Cohen, 2005).

By contrast, the traditional IP model does not incorporate such factors, but hypothesizes that looking times reflect stable individual trait(s) of information processing. For example, the traditional IP model interprets 'fast' shifting of attention as an indicator of intelligence (Frick *et al.*, 1999). Although AJMA does not preclude stable individual differences in cognitive efficiency, it would allow that this behavior might be a sign of a temporary state, such as a response to novelty or acute stress. This contrast between models suggests that it is important to control for or measure environmental factors such as acute stress or novelty to test for their relationships with looking behaviors. For example, it is predicted that upon initial exposure to a novel environment, an animal should show more vigilant behaviors, but with increasing exposure and exploration, attention should become less vigilant, and the animal can deliberately focus attention and action on specific environmental features.

The current study

The goal of the current study was to establish the relations between infant analogs of the behavioral indices of vigilance that have shown high coherence in the animal literature. For this purpose we created an observational paradigm to capture multiple measures of infants' attention to surrounding stimuli. Specifically, we measured vigilance using four measures. Two measures captured degree of responsivity of the infant to peripherally presented target stimuli: reorientation latencies and reorientation likelihoods. For these, increased vigilance corresponds to shorter latencies of reorientation and increased likelihood of reorientation. Two additional measures captured specific features of fixations related to vigilance. These were the duration and rate of fixations during the time of stimulus presentation, where vigilance entails a high rate of short fixations. These four micro features of attention allowed us to assess the vigilance of

individual infants. By examining the within-subjects coherence of these multiple independent measures of vigilance, we tested whether infant attentional behaviors were consistent with the AJMA model. Additionally, we wanted to assess the relations between these micro measures of vigilance and the two counterintuitive claims of AJMA: the individual differences in attentional tradeoffs and the adaptation of attention over time.

Capturing these four features of looking required a number of specific changes from the typical experimental paradigms used to study infant attention. Typical paradigms keep adults out of the infant's line of gaze (but see Benasich & Tallal, 1996) and artificially constrain the infant's direction of attention by selective lighting of a single central stimulus. Instead, our experiment was performed in a well-lit room with six monitors placed around the infant. The video monitors were situated all around the infant, so they were not all visible from any given viewing angle. The monitors would turn on and off in a quasi-randomized sequence to play a colorful video-clip with music. Such stimuli are known to be highly salient to infants (Phillips-Silver & Trainor, 2005; Teller, Civan & Bronson-Castain, 2005). In order to localize the sound and fixate on the video, the infant would have to redirect attention to the current target monitor. An experimenter was seated facing the infant. This contributed to ecological validity in that an infant would seldom be left alone in an unfamiliar setting. Otherwise, the room was empty and painted with neutral colors. This setup allowed us to observe infants as they attended to a naturalistic scene where sources of salience were spatially distributed and multimodal, as well as dynamically changing.

As the monitors turned on, infant responses to the target stimuli provided our measures of responsivity. The design included six trials, which allowed us to study adaptation of infant looking over time: as different monitors played, infants could vary in their persistence of vigilance. AJMA suggests acute regulation of the LC/NE system; thus we hypothesized decreasing vigilance to the decreasing novelty across trials. Additionally, we measured percent of time spent looking to low salience stimuli (such as floor or walls) during target monitor presentation, as an additional potential correlate of low vigilance states.

Methods

Participants

Sixteen 6- to 7-month-old infants (11 boys, 5 girls; mean age in days = 205, range 174–223 days) were recruited to participate. Most of the infants ($N = 12$) had participated in an experiment in our lab one month earlier. Infants were recruited from local mother-infant social groups such as playgroups and exercise classes. Average age of parents was 35.5 years (range 26–43) and average

education was 4.7 years post high school (range 2–7). Three additional infants could not be coded due to equipment error. Infants were recruited and tested using procedures approved by the Human Research Participants Protection committee (UCSD).

Materials and setting

The testing room was fitted with five unobtrusive cameras (one in each corner and a fisheye lens overhead) and a microphone for auditory data collection. It was also outfitted with six 30 cm flat-screen video monitors, each with stereo speakers, placed in specific locations around the room: three to the left of the infant (to his/her front, periphery and back) and three to his/her right, in similar locations. Infants sat facing an experimenter on their caregiver's lap in a seat designed to allow a full range of torso rotation. Caregivers wore shaded glasses and sound-isolating headphones to ensure that they could not systematically influence their infant's responses.

All clips were drawn from the series 'Baby Einstein'. Each depicted colorful moving toys or animals that were found in a pilot study to be highly and approximately equally interesting to infants. Synthesized classical music clips from the videos were edited to play at a uniform volume, and were synchronized with the onset of the video. The six video-and-sound stimuli were identical across subjects. Prior to participating in the task, infants were familiarized with the lab setting for approximately 10 minutes, and then completed another brief social-interaction task.

Procedure

At each trial, one of the six monitors (i.e. 'target') began playing an 8 second musical video clip. The five remaining monitors displayed a static image the color of the surrounding walls meant to neutralize their effects. For reasons unrelated to our questions, 2 seconds after the video onset the experimenter pointed and looked to the target monitor and said '[Infant's name], look!' The pointing was held until the end of the clip, after which her arms returned to the center, and she looked back to the infant. Following the offset of each clip was a 2 second inter-trial interval, followed by the next trial, for a total of six trials. Between clips the experimenter smiled at the infant and said 'Hi baby!' but otherwise did not physically or verbally engage the infant. Clip order was quasi-randomized (with the constraint that neither side nor latitude was repeated across successive trials). Every infant received the same order.

Coding

Coding was completed by a single coder who was unaware of the hypotheses. For calculating reliability statistics, the first author additionally coded 20% of the videos.

Sound coding

An audio spectral analysis of video was performed using Audacity sound editing software (<http://audacity.sourceforge.net/>) to find the onset of each video clip and the experimenter's verbal prompt.

Behavioral coding

The coder coded frame-by-frame (30 Hz) for each trial, for the duration of each video clip (i.e. 8 seconds per trial over six trials for 48 seconds total per infant). The following behavioral variables were coded:

- Reorientation onset* (RO) was the first frame of the infant's saccade or head turn in the direction of the target monitor, in response to the music or video. This did not require that the next fixation was to the target, but merely an initiation of a reactive shift in the correct direction. Motions in another direction or plane (e.g. vertical shifts) were not counted. Cohen's Kappa (κ) = .77.
- Looking region* was a continuous, mutually exhaustive index of the area of the room where the infant was looking. Location categories were the *experimenter's head/torso*, *experimenter's arm/hand* (if extended; e.g. pointing), *down* (floor; area beneath the seats; wall below monitors), *non-target monitors* (regions around any of the five monitors not playing the video in any given trial) and *target monitor*. Thus, the areas designated *target monitor* and *non-target monitor* changed in every trial. κ = .81.
- Fine-grained fixations*. When infants' eyes were visible in the camera angles, fixations were recorded. Fixations were defined as an infant's eyes remaining static for at least 230 ms (seven frames at 30 fps). Our four-camera system provided appropriate views of the infant's eyes from the four facings. Through observing the quad view of these four cameras, we were able to determine when the infant was making rapid small saccades versus remaining fixed on a location. Due to the dynamic quality of the videos, it was difficult to determine whether fine-grained saccades on a target monitor were examining image details, or tracking moving objects in the video. Thus, this variable was not coded when the looking region was the target monitor. Across trials, the two coders were correlated at $r = .85$ for number of fixations, and $r = .82$ for average duration of fixations.

Measures of vigilance

From these coded behaviors we derived several variables that parallel those in the animal literature described above.

- Latency to Reorientation Onset (LRO)* was the latency of the infant's first saccade or head turn in the direction of the target monitor. LRO was calcu-

Table 1 Average (and SD) of four independent theoretical measures of vigilance

Descriptive statistics	LRO	Target Hits	Fixation Duration	Fixation Rate
Average (SD)	1.27 sec (.77)	5.18 trials (1.10)	0.86 sec (.20)	0.72/sec
Range	0.46–3.5	3–6 (out of 6)	0.51–1.34	0.24–1.13/sec

Note: LRO = Latency to Reorientation Onset.

- lated by subtracting the RO from the onset of the target video, via the onset of sound. For analyses, we used the median LRO over the six trials.¹
- Target Hits (TH)* was the percentage of trials in which an infant fixated upon the target monitor.
- Fixation Duration* was the average duration of all fixations to regions other than the target monitor, coded over all six trials.²
- Fixation Rate* was the ratio of the count of coded fixations in regions other than the target monitor to the total amount of time spent looking at all of these areas. This normalizes the count across infants such that it is independent of looking durations.

The four measures of vigilance are independent. However, there are potential dependencies between the looking time measures. Looking times are analyzed as a percentage of the trials, and thus at extreme levels could become dependent. Importantly though, unless proportion looks to any one location approach ceiling or floor, there can be a great deal of independence between them. For example, an infant who has a short LRO or high THs can spend a lot of time looking at the experimenter if upon gazing to monitor, she quickly returns to gaze to the experimenter. We therefore examined individual infants as well as sample means for ceiling/floor effects. None were found, indicating that all measures vary independently.

Results

Descriptive statistics for the four measures of vigilance showed considerable variability among infants (Table 1),

¹ During analyses we examined distributions for average LRO scores and discovered that for many of the subjects a single trial was at least 1.5 SD above the average. To minimize this skewing effect of these trials we used the median latency to initial motion scores for this and all following analyses.

² Note that our definition of fixation follows that of the animal literature rather than the infant literature. Infant literature often uses the words 'look' and 'fixation' interchangeably to refer to uninterrupted gaze towards a large on-screen stimulus. However, such 'looks' are actually composed of many individual fixations joined by saccades. This distinction is relevant because, as noted above, it is the duration and rate of these finer-grained fixations that have been identified as indices of vigilance in animal samples.

Table 2 Correlation coefficients among four theoretical measures of vigilance

	LRO	Target Hits	RC Fix Duration	Fixation Rate
Target Hits	0.79**	1.00		
Fixation Duration	0.43 [†]	0.81**	1.00	
Fixation Rate	0.58*	0.36	0.26	1.00
Vigilance Index	0.87**	0.91**	0.77**	0.68**

Note: LRO = Latency to Reorientation Onset; RC = Reverse-coded; Fix = Fixation.
[†] $p \leq .10$; * $p \leq .05$; ** $p \leq .01$.

thus allowing for the examination of coherence among measures of vigilance.

Primary analysis: relations among ‘measures of vigilance’

To investigate whether individual infants would show coherent patterns of behavioral vigilance we calculated correlations between the four proposed measures (Fixation Duration and LRO scores were reverse-coded so that higher scores indicated higher vigilance). All correlations were in the expected direction, and there were positive correlations between all pairings of measures (see Table 2).

Vigilance Index

Given the high correlations among the four predicted measures of attentional vigilance, we created a summary Vigilance Index. For this we averaged the four standardized values (using Z-scores reverse-coded where appropriate). The relatively high degree of correlation between this index and each measure (Table 2) validates that a summary index is appropriate; likewise, the fact that each pair of measures is not perfectly correlated suggests that there is added value in creating such an index. This table also shows that the correlation between each of the individual measures and the Vigilance Index was high. Figure 1 shows standardized scores for each of the four measures of vigilance and the summary index for each infant.

Additional measures: looking distribution; attention to experimenter; adaptation across multiple trials

We found interesting correlations between the Vigilance Index and our continuous and mutually exhaustive measures of looking time (Table 3). These measures were summed over all trials (i.e. 48 seconds total) and then calculated as a percentage of total time. To summarize, vigilance was strongly negatively correlated with time spent looking at the experimenter, looking down, and moderately negatively correlated with responding to verbalizations. A large positive correlation was found between the Vigilance Index and Target Monitor Look-

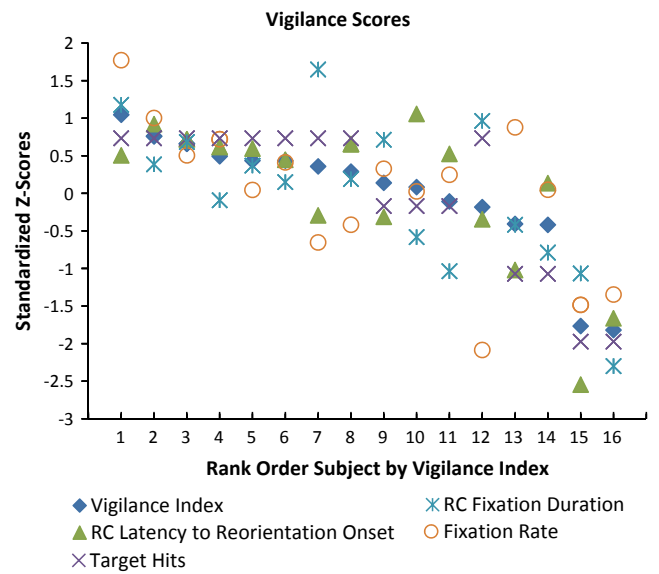


Figure 1 Subjects are arranged along the x-axis in rank order of vigilance index, from left to right. For each subject, the ‘column’ includes the vigilance summary index, and each specific vigilance measure.

Table 3 Correlation results: Vigilance Index and proportions of looking time to different regions of the room, and responses to experimenter’s verbalizations

Variable controlled (%)	Vigilance Index
% Experimenter Looking Time	-0.76**
% Non-target Monitor Looking Time	0.45 [†]
% Down Looking Time	-0.64**
% Target Monitor Looking Time	0.86**
% Response to verbalization	-0.44 [†]

[†] $p \leq .10$; * $p \leq .05$; ** $p \leq .01$.

ing time. Non-target monitor looking (i.e. time looking around the room at other monitors) was moderately correlated with the Vigilance Index.

We also investigated vigilance to the experimenter’s cue as an index of sensitivity to social events; specifically verbal and gestural cues. As described above, 2 seconds into the trial, the experimenter extended her arm towards the target monitor and said ‘[Infant’s name], look!’ If infants reoriented to the experimenter’s hand or face within 2 seconds of the onset of the verbal cue they were coded as ‘responding to verbalization’. The percentage of trials in which this occurred was negatively correlated with the Vigilance Index ($r = -.44$). Thus, more vigilant infants were less likely to attend to social cues.

In order to test for group differences in changes in vigilance measures over time (i.e. adaptation of the vigilant attentional profile) we divided the infants into Low and High Vigilance groups, using a median split of the summary index scores. This method provides a less sensitive analysis than correlations shown above; however, previous studies have used this technique to identify meaningful subgroups for individual difference analyses (Frick *et al.*, 1999).

On average, across trials less-vigilant infants showed a greater decline in attentiveness to targets, or faster habituation, to the trial structure itself. We compared early trials (1–2) to late trials (5–6).³ Though high vigilance infants spent more time looking to target monitors than their low vigilance peers, all but two infants (in the baseline group) spent the majority of their early trials looking to the target monitors (majority was considered greater than 50%⁴). By contrast, during late trials, only one of eight low vigilance infants met this criterion, while six of eight high vigilance infants did. A *t*-test shows that this pattern of change is highly significant ($p < .01$). Thus while high vigilance infants maintained high target attentiveness consistently through the end of the session, low vigilance infants reduced their target looking as the trial progressed.

Discussion

There have been calls in the literature to broaden our metrics of looking behavior beyond the standard measure of duration (Aslin, 2007; Kagan, 2008). Our study is the first to code fine-grained measures of gaze distribution to multiple targets that are distributed broadly around a room. Multiple synchronized cameras were used to capture video of individual gaze fixations within longer periods of shifting attention to dynamic ecological events. Trained human coders took standard (NTSC, 30 fps) video recordings and, using commercially available coding software, achieved high reliability in capturing some elements of individual fixations. This is notable because current eye-tracking systems cannot readily capture fixations from infants who are broadly scanning natural environments.

We were able to characterize infants in our sample on a continuum of vigilance, based on a set of heterogeneous measures derived from the non-human animal and adult human attention literature. The work of Aston-Jones and colleagues shows coherence among features of visual attention, specifically a high rate of fixations, short duration fixations, frequent reorientation to peripheral stimuli, and short latencies to respond to peripheral stimuli. In single cell recording studies as well as pharmacological and behavioral experiments, these behaviors have been shown to tightly correspond to the release of norepinephrine from the locus coeruleus (Aston-Jones *et al.*, 1999; Skosnik, 2000).

We know of only one study that has used a fine-grained measure of fixation as it might relate to other

indices of looking behavior in an infant sample. Bronson (1991) found that shorter fixation duration of 3-month-olds was related to broader scanning of a photograph. This is consistent with AJMA, but as with the studies reviewed above, it documents a relation between only two of the indices of vigilance. We analyzed both rate and duration of fixations, as well as two measures that had already been used in the infant literature, reorientation latency and likelihood. Overall, we found correlations between a higher rate and shorter duration of fixations, short response latencies, and high number of reorientations to peripheral targets. Most previous research on infant attention has shown relations between summed or maximum looking time and a single index of vigilance. By showing the within-subjects coherence of multiple independent measures of vigilance, our work extends the support to the validity of AJMA framework for an infant sample.

Although there was overall high coherence among measures of vigilance, one measure, rate of fixations, was slightly less (though still reliably) correlated with the others. A more careful examination of the data suggests that this indicates a complex relation between fixation rate and overall vigilance, at least in this paradigm. Specifically, there was greater coherence in infants with higher overall vigilance than those with lower overall vigilance. One explanation is that at low levels of vigilance, other endogenous factors (e.g. the infant's interests) dominate rates of fixation, but at high levels of vigilance, fixation rates are increasingly determined by a more centralized factor that modulates several behavioral manifestations of vigilance. This hypothesis bears future study.

Additionally, when we investigated the relationships between micro-behavioral measures of vigilance and looking time behaviors that captured attentional tradeoffs and adaptation in looking behavior over the course of the session, we found many strong relationships in the directions predicted by AJMA. These are particularly interesting as they are not predicted by traditional IP models of attention. We discuss these findings in more detail below.

Additional relationships to vigilance

Attentional tradeoffs

AJMA predicts that infants who are more responsive to their surroundings will spend proportionally less time looking at less salient elements of their environments, and more time looking to salient but peripheral locations. To test this prediction, we compared the amount of time spent looking to elements of the room with varying levels of salience.

We designed our paradigm to create a situation of maximal attentional tradeoffs between video clips (high salience stimuli) and other more neutral stimuli in the room. Specifically, the category 'looking down'

³ The use of a fixed order of target locations across trials means that there is a confound between target location and early and late trials (specifically, the two 'early' trials were the 'Left Back' and 'Left Periphery' monitors, and the two late trials were 'Right Back' and 'Right Front' monitors). However, as there is no reason to believe that infants would look left more than right, we report these findings here.

⁴ During our analyses we used a number of different values for this criterion and found that the same pattern of significance held.

comprised visually accessible but low salience areas (e.g. floors, walls, chair, experimenter's lap, or infants' own toes). The contrast between these areas was confirmed in the current data: in early trials, when novelty and uncertainty were highest, infants spent 70% of trial time (but not inter-trial time) looking at target monitors. By contrast, infants spent only 7% of total trial time looking down. Consistent with AJMA, individual proportion of time spent looking to available but low salience areas was tightly linked with overall vigilance: the correlation between the vigilance index and looking down was $r = -.64$. In other words, infants who were less vigilant were less driven by unpredictable peripheral stimuli, and thus could direct their attention to less salient stimuli.

This potential to 'self-regulate' attention, or the ability to systematically focus on more or less salient events in a top-down manner, is critical for cognitive and affective control in a dynamic environment. For example, although we did not specify it in our coding scheme, focused or exploratory toe-looking was common in 'down' looking. Such exploratory activity is a potential benefit of focused, less reactive attention. An increase in such 'willful elaboration' is thought to contribute to the increase in looking times to complex stimuli (such as video or objects that can be manipulated by the infant) shown by older infants (e.g. see Courage *et al.*, 2006; Ruff & Saltarelli, 1993).

Gaze to experimenter

We also found that less vigilant infants spent relatively more time looking towards the experimenter and were more likely to look at the experimenter within 2 seconds of the social 'pointing' cue. At first glance this seems to suggest an alternative explanation of our data: perhaps infants whom we described as 'more vigilant' were in fact less sociable, and this trait (Buss & Plomin, 1984), rather than vigilance, affected the individual differences in looking time. That is, infants who are less interested in the experimenter might instead look around the environment.

However, there are reasons to question this alternative. First, it is not independent. Decreased sociability may co-occur with LC/NE-mediated vigilance as a behavioral manifestation of a mildly stressed infant. Activation of the LC/NE pathway is a major aspect of the sympathetic nervous system response, and gaze aversion co-occurs with sympathetic activation in distressed infants (Gunnar, Larson, Hertsgaard, Harris & Brodersen, 1992; Haley & Stansbury, 2003). Potentially stressful aspects of our paradigm could have been the experimenter's non-response to the infant (akin to the 'still-face' paradigm; Tronick, Als, Adamson, Wise & Brazelton, 1978) or the sudden onset of videos. Because reactive infants would show both gaze aversion (Stansbury & Gunnar, 1994) and vigilance, sociability differences are not an independent alternative explanation. In

ongoing research we are testing this hypothesis using physiological indices of sympathetic activation related to stress and attention.

Another reason why looking pattern results cannot be explained by individual differences in sociability is that our measures are not interdependent (see methods section above). Thus, the construct of vigilance explains our results more comprehensively and parsimoniously than the construct of sociability.

Nonetheless, as explained, we expect sociability to be altered by vigilance. A potential implication is that highly responsive, stimulus-driven infants may miss perceptually subtle – but important – social cues such as gestures and gaze direction. However, in more naturalistic circumstances, adults might overcome this inattentiveness by increasing the salience of their bids for an infant's attention (e.g. Brand, Baldwin & Ashburn, 2002). Another implication is that while highly vigilant children might attend to and learn more from unpredictable, perceptually salient events, they will have difficulty maintaining focused attention to less salient events (e.g. a homework assignment or a teacher's instructions). This implies a neural mechanism that contributes to longitudinal school performance outcomes, not only in individual children but also across ethnic groups and socioeconomic strata (SES). Such outcome differences are also correlated with stress. Many studies show that families of color and/or low SES experience higher levels of stress, and this contributes to infant stress reactivity (Brunner, 1997; Fonagy, 1996; Williams, Yu, Jackson & Anderson, 1997).

Adaptation over session

Vigilance is also adjusted according to changes in uncertainty and stress. We can investigate this by comparing early to later trials of the session, where repetition may decrease the novelty of the target monitor events. We found that less vigilant infants showed a decline in attentiveness to targets across trials, which appears to be a habituation to the trial structure itself. By contrast, most of the vigilant infants continued to spend a high proportion of time looking at the target monitor in later trials. This result directly contradicts the traditional information processing account, which suggests that fast habituating infants should be consistently fast. In addition, the IP account would make the prediction that fast habituators will show other signs of processing speed, such as broad scope of attention and faster reorientation. This prediction was not confirmed; in fact, the opposite pattern was strongly observed.

However, these findings can be explained under AJMA. Specifically, vigilant infants might have been experiencing a mild stress response that caused high responsiveness to exogenous events, and failure to habituate to the occurrence of those events. A stress response entails the activation of the HPA-axis, which can cause prolonged LC/NE-mediated vigilance in

consistently stressful environments (e.g. as a strategy for identifying lurking predators or for reacting to threatening same-species competitors; Arnsten, 1998). By contrast, less vigilant infants showed initial responsiveness to the monitors, but after repeated trials could habituate to periodic video onsets. This is a more typical pattern of response to uncertainty where a pattern can be learned, and uncertainty is thereby reduced (Yu & Dayan, 2003).

Thus, within the typical context of infant habituation studies, where the occurrence of semi-predictable, normally distributed (e.g. peripheral) stimuli has been artificially removed, we ask: Are short lookers *smart*, or are they *stressed out*? In ongoing tests in our lab we are testing the relationships between arousal, HPA-axis activation and attention (Zavala, Overton, Chiba, de Barbaro, Khandrika & Deák, in preparation).

Conclusions

Our analysis of the indices and correlates of vigilance in infants in a semi-naturalistic paradigm supports and generalizes Aston-Jones *et al.*'s (1999) attentional theory. By defining indices of vigilance derived from non-human animal studies, we found that human infants show the same patterns of co-occurring indices. This is one of the first human studies, and the first infant study, to investigate micro-indices of vigilance predicted by AJMA. The relations among vigilance indices cannot be explained by conventional IP accounts of infant looking.

Additionally, the AJMA model provides a framework to integrate universal behaviors ignored in IP theory, including social attentiveness, individual differences in temperament, stress reactivity, and, most generally, distribution of attention in natural (e.g. lit, dynamic, cluttered) environments. We do not argue that speed of processing is a non-factor in infant looking: individual differences are well documented, robust, and relevant to many cognitive skills (Kail & Salthouse, 1994). Generalized processing speed must eventually be integrated with a comprehensive neuro-modulatory model.

However, processing speed cannot itself explain many findings. AJMA theory allows for explanations of: attentional dynamics on both short (e.g. second-to-second) and longer timescales, socio-emotional influences on attention, and the adaptive importance of slow/sustained attention as well as fast looking. Importantly, it may also help to elucidate mechanisms of stress-related social factors not only in infants but in older children's school outcomes (Lee & Burkam, 2002). By demonstrating the viability of AJMA theory to a developmental audience, we hope to encourage a dialogue about how the ecology and neuroscience of infant attention can explain universal patterns of infant cognition and attention.

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