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Infant sustained attention differs by context and social content in the first 2 years of life

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Abstract

Sustained attention (SA) is an endogenous form of attention that emerges in infancy and reflects cognitive engagement and processing. SA is critical for learning and has been measured using different methods during screen-based and interactive contexts involving social and nonsocial stimuli. How SA differs by measurement method, context, and stimuli across development in infancy is not fully understood. This 2-year longitudinal study examines attention using one measure of overall looking behavior and three measures of SA—mean look duration, percent time in heart rate-defined SA, and heart rate change during SA—in $N = 53$ infants from 1 to 24 months across four unique task conditions: social videos, nonsocial videos, social interactions (face-to-face play), and nonsocial interactions (toy engagement). Results suggest that developmental changes in attention differ by measurement method, task context (screen or interaction), and task stimulus (social or nonsocial). During social interactions, overall looking and look durations declined after age 3–4 months, whereas heart rate-defined attention measures remained stable. All SA measures were greater for videos than for live interaction conditions throughout the first 6 months, but SA to social and nonsocial stimuli within each task context were equivalent. In the second year of life, SA measured with look durations was greater for social videos compared to other conditions, heart rate-defined SA was greater for social videos compared to nonsocial interactions, and heart rate change during SA was similar across conditions. Together, these results suggest that different measures of attention to social and nonsocial stimuli may reflect unique developmental processes and are important to compare and consider together, particularly when using infant attention as a marker of typical or atypical development.

KEYWORDS
autonomic regulation, focused attention, heart rate, social attention, sustained attention

Research Highlights

- Attention measure, context, and social content uniquely differentiate developmental trajectories of attention in the first 2 years of life.

- Overall looking to caregivers during dyadic social interactions declines significantly from 4 to 6 months of age while sustained attention (SA) to caregivers remains stable.
- Heart rate-defined SA generally differentiates stimulus context where infants show greater SA while watching videos than while engaging with toys.

1 | INTRODUCTION

Sustained attention (SA) is an early-emerging, endogenous form of attention that reflects cognitive processing and active engagement with the environment (Hendry et al., 2019). Behavioral and physiological measures of attention have been used to distinguish looking behavior that reflects active information processing and stimulus engagement (i.e., sustained attention) from other forms of looking that reflect, for example, attention orienting or termination. That is, attention can be defined and quantified using fixation measures, such as look duration, or heart rate measures, such as heart rate decelerations. Look duration is commonly used to study visual learning and reflects stimulus encoding, particularly during screen-based tasks (Aslin, 2007; Colombo, 2002). Heart rate-defined measures of attention use heart rate changes within individual looks to parse a single look into three phases of attention, with each phase reflecting unique cognitive processes: attention orienting, SA, and attention termination (Reynolds & Richards, 2008). Attention orienting refers to the initial shift of attention to a particular stimulus and is denoted by a significant decrease in heart rate. SA is characterized by a sustained lowering of the heart rate that is driven by the parasympathetic nervous system. During this heart rate-defined phase of SA, infants show increased brain arousal and alertness, longer look times, lower responsivity to peripheral stimuli, and reduced distractibility (Richards & Turner, 2001; Xie et al., 2018; Xie & Richards, 2016). The third phase of attention, attention termination, is marked by an increase in heart rate back to pre-look levels and is often followed by a look away from the stimulus. Heart rate-defined SA has been suggested as a direct and precise attentional index of information processing depth and learning (Bahrick et al., 2016; Colombo, 2001; Reynolds et al., 2011; Xie & Richards, 2016).

Infant looking behavior and attention undergo significant developmental change across the first year of life, in part due to the maturation of posterior and anterior attention systems. The attention orienting network involves posterior and frontal brain regions, supports attention shifting and disengagement, and emerges between 3 and 6 months (Colombo, 2001; Petersen & Posner, 2012). The executive attention network involves anterior brain regions, supports top-down control of attention, and begins to emerge after 6 months (Colombo, 2001; Petersen & Posner, 2012). Accordingly, developmental increases in both heart rate deceleration during SA and the amount of time spent in heart-defined SA are observed between 3 and 12 months, suggesting that heart rate-defined SA reflects anterior attention driven by endogenous goals (Courage et al., 2006; Richards & Casey, 1992). In contrast, studies of fixation measures of attention indicate a nonlinear, triphasic developmental trajectory of look duration. For example, look duration increases from 0 to 2 months, drops between 3 and 6 months, and increases again from 6 to 24 months (Colombo, 2001; Richards & Anderson, 2004). These data point to discrepant age-related changes in attention when measured with heart rate versus look duration, particularly between 3 and 6 months when anterior attention mechanisms are emerging, and highlight the need for direct comparison of these attention measures over time.

Stimulus content and the context in which stimuli are presented can modulate infant SA throughout development. For example, simple social stimuli (e.g., faces) and complex, dynamic social stimuli (e.g., video scenes of social interactions) have been found to be superior in eliciting and sustaining heart rate-defined SA compared to nonsocial stimuli (Courage et al., 2006; Richards & Anderson, 2004). This pattern is particularly salient in the second half of the first year of life when increases in heart rate- and fixation measures of attention to dynamic social stimuli (e.g., faces, voices), but not nonsocial stimuli, are observed (Bahrick et al., 2016; Courage et al., 2006; Curtindale et al., 2019). Beyond the first year of life, 18- and 24-month-olds show longer looks and a higher proportion of time spent looking at comprehensible, complex, social videos compared to distorted videos (Pempek et al., 2010; Richards, 2010; Richards & Cronise, 2000).

Developmental increases in SA, particularly for social stimuli, reflect the role of SA in supporting critical cognitive functions and shaping infant learning (Brandes-Aitken et al., 2023; Colombo, 2001; Frick & Richards, 2001; Richards, 1997; Xie et al., 2018). Infant SA has been linked to the emergence of behavioral skills in early childhood, including self-regulation and social communication, as well as neurodevelopmental differences like symptoms of autism spectrum disorder (ASD) and attention deficit hyperactivity disorder (ADHD) (Bradshaw & Abney, 2021; Brandes-Aitken et al., 2019; Johansson et al., 2015; Jones et al., 2016; Miller et al., 2016; Pérez-Edgar et al., 2010; Roberts et al., 2012; Tonnsen et al., 2018). Infants later diagnosed with ADHD show blunted trajectories of fixation-defined SA from 3 to 24 months of age (Miller et al., 2016). Infants with fragile X syndrome show shallower heart rate decelerations during looks and those with longer fixation durations show more ASD symptoms (Roberts et al., 2012). Heart rate-defined SA is associated with social-communication skills and genetic liability for ASD (Bradshaw & Abney, 2021; Tonnsen et al., 2018). Critically, the association between SA and ASD may be developmentally specific. Jones et al. (2016) noted that infants later diagnosed with ASD show disrupted SA to social stimuli at 6 months of age, but not at

12 months. These studies suggest that SA may be an important early marker of atypical neurodevelopment and highlight the importance of developmental and context specificity in identifying such markers.

Whereas a significant amount of work has been done on heart rate-defined measures of social and nonsocial attention during screen-based tasks in infancy (for reviews see Conte & Richards, 2021; Hendry et al., 2019), fewer studies have documented the development of social and nonsocial attention during dynamic, real-life interaction contexts. Examining infant SA in-situ accounts for the dramatic changes in motor, cognitive, and communication skills that occur in the first 2 years of life. For example, motor constraints of the neonate restrict visual input to ceilings, walls, and caregiver faces within the first 2 months of life (Jayaraman et al., 2013). Beyond the first 2 months, as new motor and cognitive skills emerge, infants become more active agents in exploring their environment and altering their own visual input. By 6 months, infants can move their head and eyes to events of interest and reach for and bring toys closer in their field of view. Limited research suggests that these developmental gains occur along with increases in heart rate-defined SA and focused attention (i.e., changes in motor activity and facial expressions during a look) during live interaction tasks from 6 months to 4 years (Lansink et al., 2000; Oakes et al., 2002; Ruff & Capozzoli, 2003).

To date, studies on infant SA represent a mix of measures (fixation- and heart rate- defined SA) and contexts (interactive and screen-based tasks; social and nonsocial stimuli). Direct comparison of developmental changes in fixation and heart rate measures of SA across multiple contexts throughout the first 2 years of life has yet to be done. Studies have documented the value in evaluating both fixation- and heart rate-defined measures of attention wherein divergent and convergent patterns across measures may illuminate novel developmental processes (e.g., Brez & Colombo, 2012; Curtindale et al., 2019; Richards & Cronise, 2000). Similarly, studies highlight marked differences in fixation measures of SA during interactive versus screen-based tasks (Wass, 2014; Yurkovic et al., 2021). Given the importance of SA for infant learning and its translational potential as a marker of later atypical development, documenting whether and how different attention metrics translate across contexts is vital. The overarching goal of this study is to examine context-specific trajectories of fixation- and heart rate-defined SA across the first 2 years of life. Unique patterns of attention across contexts could define developmental shifts in SA, refine theories of infant attention and learning, serve as a foundation from which to understand individual variability and atypical development, and further guide the use of SA as a marker of ongoing neurodevelopmental processes and a predictor of developmental outcomes (e.g., Bradshaw & Abney, 2021; Brandes-Aitken et al., 2023).

The current study characterizes and compares trajectories of four attention measures from 1 to 24 months of age across four conditions that vary by task context (live-interactive vs. screen-based) and stimulus content (social vs. nonsocial). The screen-based tasks consisted of social and nonsocial videos. The live-interactive tasks consisted of face-to-face play (social interaction) and toy engagement (nonsocial interaction). For each of these four conditions (social videos, nonsocial videos, social interaction, toy engagement), we compute four attention measures, including one measure of overall looking behavior and three measures of SA. These four measures are as follows: percent time looking (overall looking behavior), mean look duration (fixation measure of SA), percent time in heart rate defined-SA (heart rate measure of SA), and mean heart rate change within bouts of heart rate-defined SA (heart rate measure of SA). To align with developmental shifts in cognition, motor skills, and interactive context, the dyadic social interaction condition was only administered until 6 months of age. Attention measures during all four conditions were compared from 1 to 6 months and attention during three conditions (social videos, nonsocial videos, and toy engagement) were compared from 9 to 24 months. Stimulus comprehensibility is linked to SA in infancy and, as young infants have limited cognitive skills, significant experience with caregivers, and minimal experience with screens, we anticipate that live-interaction conditions will initially elicit more attention from 1 to 6 months of age compared to screen-based stimuli, and that social interactions will elicit the most attention. Between 9 and 24 months, we hypothesize that screens (social and nonsocial videos) will elicit increasing attention compared to toys, consistent with that observed in previous studies (Courage, 2017; Pempek et al., 2010; Richards, 2010), and that attention to social videos will be especially high as communication and language skills are in a period of rapid growth during this time.

2 | METHOD

2.1 | Participants

Participants included 53 infants ($n = 26$ female, $n = 27$ male) between 1 and 24 months of age who were part of a longitudinal study on social development. Demographic characteristics for all participants, including sex, race/ethnicity, primary caregiver education, and income are displayed in Table 1. Eligibility criteria for all participants included: enrollment into the study prior to 4.5 months of age, full-term birth (> 37 weeks gestation), no congenital vision or hearing abnormalities, and no known genetic syndromes (e.g., Down Syndrome, Fragile-X Syndrome). Although infants were required to enroll in the study prior to 4 months, recruitment efforts were geared toward newborns and the study team attempted to enroll infants at the youngest age possible. The average age of enrollment was 2.32 months (SD = 1.27; see distribution of age at enrollment in Supplementary Information, Figure S1). All procedures were approved by the University Institutional Review Board and families completed informed consent prior to study procedures.

2.2 | Procedure

Infants and caregivers were invited to the lab at ages: 1, 2, 3, 4, 6, 9, 12, 15, 18, and 24 months. To be flexible in response to individual family needs and circumstances, missed visits were tolerated. Our statistical methods, described below, are well-suited for a longitudinal dataset with missing data and missing data was accounted for in all analyses.

TABLE 1 Participant demographics.

	N (%)
Sex	
Female	26 (49%)
Male	27 (51%)
Race/Ethnicity	
African American or Black	15 (28%)
Asian	2 (4%)
Hispanic/Latino	1 (2%)
Mixed	4 (8%)
White	26 (49%)
Not reported	5 (9%)
Total household income	
< $60,000	12 (23%)
$60,000–$100,000	19 (36%)
> $100,000	20 (37%)
Not reported	2 (4%)
Primary caregiver education	
High school/GED or less	4 (7%)
Some college	12 (23%)
Bachelor's degree	12 (23%)
Postgraduate degree	23 (43%)
Not reported	2 (4%)
Sample size by study timepoint	
1 month	16 (30%)
2 months	31 (58%)
3 months	37 (70%)
4 months	38 (72%)
6 months	45 (85%)
9 months	35 (66%)
12 months	25 (47%)
15 months	22 (42%)
18 months	19 (36%)
24 months	13 (25%)

Participants had up to 10 opportunities to complete study visits and those who were unable to complete a study visit at their specified time point were invited back at the following time point. Attempts to see every participant at every time point were made unless a participant requested to withdraw; no participants requested to withdraw from this study. All enrolled participants who completed at least one study visit were included in the study. The proportion of participants who completed study visits at each time point ranged from 85% to 25% of the full sample, with the greatest drop-off occurring at 24 months (see Table 1). Due to missingness, results are reported and interpreted with caution at the later time points (age 18 and 24 months).

At each visit, participants completed four attention tasks. Two were screen-based tasks and two were interaction tasks. Interaction tasks always occurred before screen-based tasks, but social and nonsocial content within each context (screen vs. interaction) were randomized for each participant and visit. At the beginning of each visit, a wireless electrocardiogram (ECG) recorder (Actiwave, CamNtech Inc, Boerne, TX), was then placed on the infant's chest. The entire study visit was video recorded using a Noldus Viso system that was synchronized with the start time of the ECG recording. In cases of ECG or video failure, or when automatic syncing was not possible, syncing occurred offline. Figure 1 displays examples of social and nonsocial interactions (face-to-face play and toy engagement tasks, respectively) and social and nonsocial videos (social and nonsocial screen-based tasks). Specific procedures for each task are described below. For the screen-based tasks, infants were shown videos in blocks of social and nonsocial videos with the blocks in a randomized order. Infants were placed in a car seat in a darkened room in front of a computer screen (resolution: 1680 × 1050 pixels; size: 530 × 300 mm). All videos contained sound.

2.2.1 | Face-to-face play

For the social interaction task, the primary caregiver was told to interact with their infant as they normally would at home for 5 min. In 98% of cases, the primary caregiver was the mother. From 1 to 4 months, the infant was placed in a supine position on a soft mat with blankets on a table and the caregiver was standing over them. At 6 months, due to increased mobility, infants were placed either on their back or seated on the floor with their caregiver sitting in front of them (see Figure 1). No toys or toys were available during the interaction. Due to increased mobility and developmental shifts from dyadic (infant-caregiver) to triadic (infant-caregiver-toys) interactions after age 6 months, the social interaction was not administered past 6 months of age. The total interaction period for this task was 5 min.

2.2.2 | Toy engagement

Infants were placed in their caregiver's lap in front of a table and presented with a series of five single toys for 1–2 min each (see Figure 1). All toys were developmentally appropriate, commercially available infant toys that were placed within the infant's reach to provide the opportunity for reaching, grasping, and interacting. The caregiver was told not to touch the toys or talk to/interact with the infant during this time. Each toy had unique interactional affordances and ranged in developmental stage to be appropriate for infants 24 months and younger. While we did not measure interactive behaviors in this study, we use the term "engagement" and "interaction" to indicate the opportunity to interact with the stimuli as opposed to, for example, a puppet show wherein the stimuli are "live" but the context is void of any opportunity for stimulus interaction. The total interaction period for this nonsocial task was 8 min.

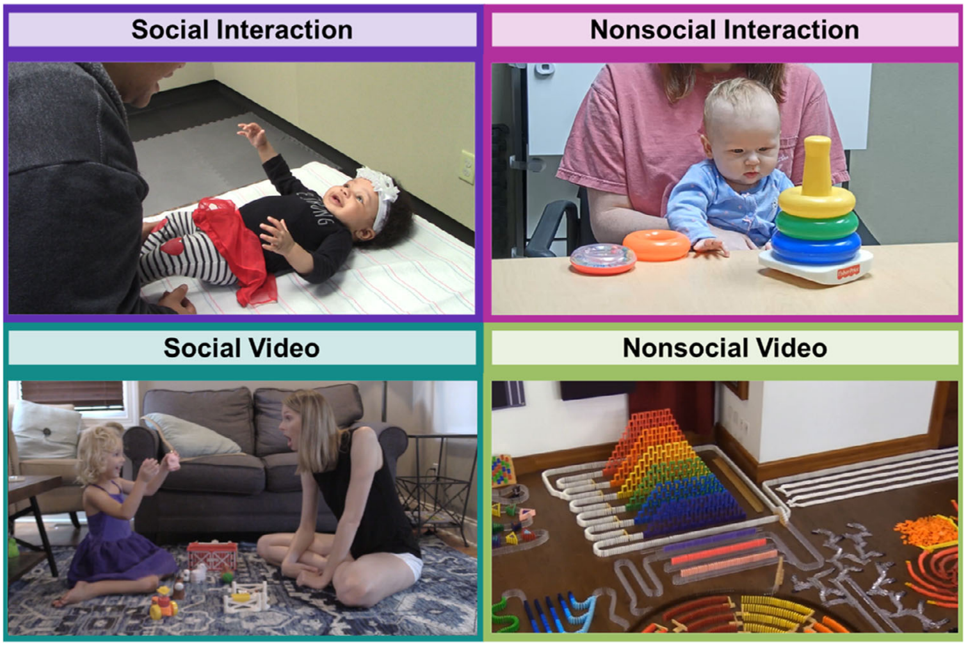

FIGURE 1 Examples of the four attention tasks: Social interaction (face-to-face play) and nonsocial interaction (toy engagement) (top) and social and nonsocial videos (bottom).

2.2.3 | Social videos

A total of five dynamic social videos were presented, each consisting of two animate agents (puppets or people) interacting and communicating with each other. Videos included select scenes from Baby Einstein ($n = 2$) and Sesame Street ($n = 1$; see Figure 1), as well as lab-generated videos of a child and her mother playing with toys and communicating ($n = 2$). The total duration of the social videos was about 5 min.

2.2.4 | Nonsocial videos

A total of 5 dynamic nonsocial videos were presented in the same format as above. These videos were designed to be similar to the social videos in terms of visual (animated and live content) and auditory (with or without music and audio-visual synchrony) components. These contained videos of animated fractals with classical music ($n = 2$) as well as chain reaction/cause-and-effect scenes with toys ($n = 2$) and colorful dominoes ($n = 1$; see Figure 1). None of these scenes contained people, faces, language, or other social or social-like agents (e.g., animals, puppets, hands). The nonsocial videos also lasted about 5 min.

2.3 | Attention measures

Infant attention can be measured in many different ways and parsed into many subcomponents. In this study, we use four different measures to examine attention—one that indexes overall looking behavior and three others that index SA. All four measures are depicted in Table 2 as follows: (1) overall percent time looking (*%look*), (2) mean look duration (*lookDur*), (3) percent time in heart rate-defined SA (*%HRDSA*), and (4) heart rate deceleration during phases of SA (measured using inter-beat-interval changes; *ΔIBI*). Methods for how these measures were extracted are described in detail below.

Videos of each experimental session were reviewed and behaviorally coded for onset and offset of infant looks to the target stimulus for each condition. Target stimuli were as follows: the caregiver's face for the face-to-face play task (social interaction condition), the toy for the toy engagement task (nonsocial interaction), and the screen for both social and nonsocial screen-based tasks (social and nonsocial video conditions). Look onset was defined by infant eyes directed toward the target stimulus. Look offsets were defined by eyes averted away from the target stimulus or eyes closed for > 1 s. Blinks and very brief gaze shifts (< 1 s) that occurred during a bout of looking were ignored and not considered a look offset. Coders were trained to exceed a 0.80 Kappa statistic for inter-rater reliability (McHugh, 2012). Inter-rater reliability was checked periodically for 20% of the coded videos, resulting in an average 0.74 Kappa indicating substantial agreement. From this data, two dependent variables were calculated: Percent Looking (*%Look*) and Mean Look Duration. *Percent Looking* was defined as the summed duration of all looks over the total experiment duration for each condition. *Mean Look Duration* was defined as the average duration of each look across all looks for each experimental condition. Due to the nature of look durations during attention tasks, characterized by a lognormal distribution with a positive skew, lognormal distributions have been shown to be the best fit for looking time data across development (Csibra et al., 2016; Pempek et al., 2010; Richards, 2010; Richards & Anderson, 2004; Wass, 2014). Accordingly, a lognormal transformation was applied to mean look durations in this study.

TABLE 2 Attention measure definitions.

Measure	Definitive metrics		Attention construct	Definition
	Fixations	*Heart rate*		
%look	✓		Looking behavior	Percent time spent looking to the target stimulus
lookDur	✓		Sustained attention	Lognormalized mean duration of all looks to the target stimulus
%HRDSA	✓	✓	Sustained attention	Percent time spent in HRDSA wen looking to the target stimulus
ΔIBI	✓	✓	Sustained attention	Heart rate deceleration (increased IBI) within-HRDSA episodes

Infant ECGs were recorded at a sampling rate that varied across infants between 256 and 1024 KHz. Varied sampling rate was due to hardware updates and differences in hardware capacities. Trained research assistants detected r-peaks and removed artifacts offline using CardioEdit software (Brain Body Center, University of Illinois at Chicago). Artifacts were largely due to movement, but rare heart anomalies, such as ectopic beats and periodic bradycardias were removed if present. Beat-by-beat data was then synchronized with look onsets and offsets from behavioral coding. Changes in inter-beat-interval (IBI) during periods of infant looking were then analyzed, with longer IBI indicating heart rate deceleration. SA was defined by an IBI longer than the pre-look heart period median for five consecutive beats (J. E. Richards & Casey, 1991). Following a deceleration, five successive beats with an IBI shorter than the median pre-look IBI marked the end of SA. Two dependent variables were calculated from this data: Percent heart rate-defined SA (*%HRDSA*) and IBI Change in HRDSA (*ΔIBI*). *%HRDSA* was defined as the proportion of overall looking time spent in HRDSA. For *ΔIBI*, corresponding to heart rate deceleration and sustained lowered heart rate, the mean IBI within each episode of HRDSA (as defined above) was subtracted from the pre-HRDSA mean IBI (i.e., mean IBI of the attention orienting phase immediately preceding the SA phase). These values were then averaged within each experimental condition, resulting in a subject- and experiment-level mean IBI change in SA.

2.4 | Data analysis plan

All available data points were included in analyses, regardless of how many study visits each participant completed. Time was defined as continuous age in months. Four statistical models were constructed separately for each of the four attention measures (*%look*, *look duration*, *%HRDSA*, *ΔIBI*) in order to compare how each attention measure varied across age (1–24 months) and condition (social interaction, nonsocial interaction, social videos, nonsocial videos). This allowed us to evaluate condition-specific differences within each of the four attention models while accounting for the complex, nested nature of this dataset where each participant contributed data for multiple time points and conditions (Wu & Zhang, 2006). Models were constructed in three phases: visualization, model parameterization, fit assessment, and between-condition statistical comparison.

First, trajectories of attention over time for all four dependent variables and four conditions were visualized using scatter plots (data not shown) to assess the functional form of change. This initial assessment revealed non-linear relationships between age and attention. In order to model the effect of age on attention in each of the four conditions with flexibility, we applied basis spline functions. A spline function is essentially a piecewise polynomial function in which the individual polynomials have the same degree and connect smoothly at join points whose abscissa values, referred to as knots, are prespecified. The splined effect of age was used in a mixed effects model to compare the effect of age on attention between the four conditions. Subject-specific intercepts were fitted as random effects. For each mixed model, the fixed effects included condition (four levels), the splined effect of age, and the interaction between condition with the splined effect of age. A separate model was fit for each of the four attention measures—*%look*, *look duration*, *%HRDSA*, and *ΔIBI*—as follows, where i = person, j = splined effect of age, k = condition.

$$Y_{ijk} = \beta_{0i} + \beta_{1i}(\text{Age}_{ij}) + \beta_{2ij}(\text{Condition}_{ijk}) + \beta_{3ij}(\text{Age}_{ij} \times \text{Condition}_{ijk}) + e_{ijk}$$

$\beta_{0i} = \Upsilon_{00} + u_{0i}$ (no between-subjects predictor, random intercept)

$$\beta_{ii} = \Upsilon_{10} + u_{1i}$$

$$\beta_{2ij} = \gamma_{20} + u_{2i}$$

$$\beta_{3ij} = \gamma_{30} + u_{3i}$$

The initial visual assessment of the data was used as a starting point for model parameterization, which involved evaluating spline functions of varying degrees (d), number of knots (n), and knot placement (equally

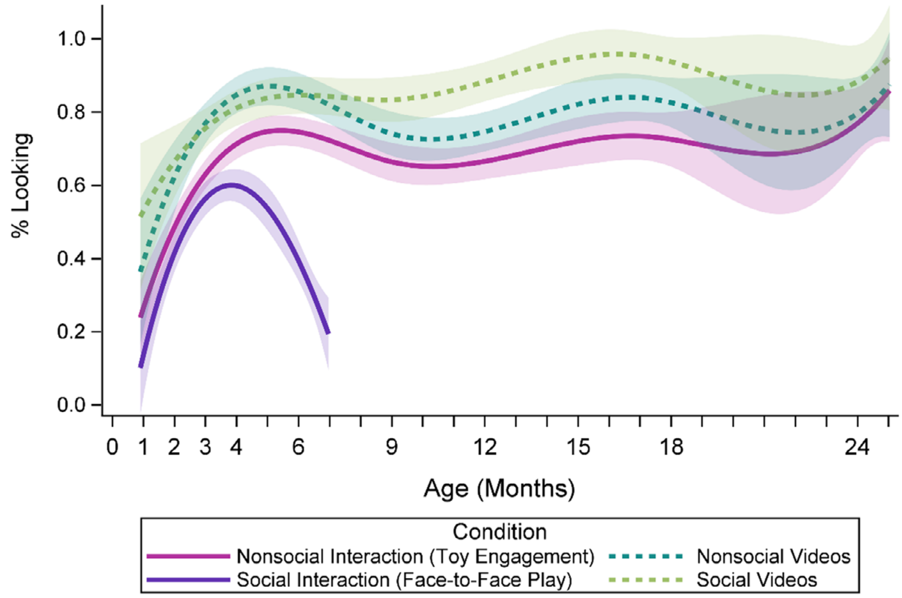

FIGURE 2 Overall looking to the target stimulus represented by the proportion of total looking over total task duration for four attention tasks: Social interaction ("face-to-face play"), nonsocial interaction ("toy engagement"), social videos, and nonsocial videos indexed by percent looking time.

spaced, list). Lower polynomial degrees and *n* knots were tested first to avoid overfitting. Fit assessments were conducted for each model using residual plots and the Akaike information criterion (AIC) to determine the best-fitting polynomial *d* and number of knots *n* for the spline effect. A smaller AIC indicates a better fit, with an AIC change of at least two to be considered a better fit (Symonds & Moussalli, 2011). When the AIC change was < 2, the more parsimonious spline effect (lower *d* and *n*) was selected. Model fit assessments resulted in four models with the following spline effects: (1) *%look*: $d = 3$ polynomial, $n = 2$ equally spaced internal knots; (2) *look duration*: $d = 3$ polynomial, $n = 4$ equally spaced internal knots; (3) *%HRDSA*: $d = 3$ polynomial, $n = 2$ equally spaced internal knots; and (4) *ΔIBI*: $d = 2$ polynomial, $n = 1$ equally spaced internal knot.

Finally, differences between conditions within each measure of attention at each time point are presented as model-based estimates with associated 95% confidence intervals. Model-based estimates that represent linear combinations of model parameters were computed and evaluated statistically using a *t*-test where the null hypothesis is that the difference is equal to zero (H_0: $\mu_{11} = \mu_{12}$) (Cai, 2014). To control for Type I error, a multiplicity correction was used for each model and simulation-based step-down-adjusted *p*-values are reported along with effect sizes (Cohen's *d*). Analyses were conducted using SAS v. 9.4 (Cary, NC) and statistical significance was assessed at the 0.05 level using adjusted *p*-values and are indicated by p_{adj} in the results reported.

3 | RESULTS

Attention trajectories are depicted in Figures 2 and 3 and model summary results for all four models are shown in Table 3. Results are reported by condition and include the following: social screen-based task ("social videos" condition), nonsocial screen-based task ("nonsocial videos" condition), the face-to-face play task ("social interaction" condition) and toy engagement task ("nonsocial interaction" condition). Results illustrate trajectories of each measure of attention to the target stimulus within each condition during which only one stimulus was available. Thus, between-condition comparisons do not reflect stimulus preferences per se. Rather, between-condition comparisons reflect unique looking and attention behaviors when exposed to different classes of stimuli when only one stimulus is available.

3.1 | Overall looking

3.1.1 | Percent looking

Our broad measure of *%looking* encompasses all looking to the target stimulus, regardless of look duration or heart rate changes. In terms of attention phases, this metric encompasses all phases of attention including orienting, SA, and attention termination. Trajectories of infants' looking behavior demonstrated a notable increase in looking during all four experimental conditions from 1 to 4 months of age, especially during interactive tasks (see Figure 2). Comparisons of model-based predicted values at each study time point revealed several notable statistically significant differences between experimental conditions at specific ages, as follows.

By 2 months of age, infants spent significantly more time looking to social videos compared to toys ($t[517] = 3.28$, $p_{adj} = .020$, $d = 0.45$) and caregivers ($t[517] = 4.55$, $p_{adj} < .001$, $d = 0.63$) and by 3 months of age, nonsocial videos elicited significantly more looking compared to toys and caregivers ($t[517] = 4.25$, $p_{adj} < .001$, $d = 0.54$; $t[517] = 5.87$,

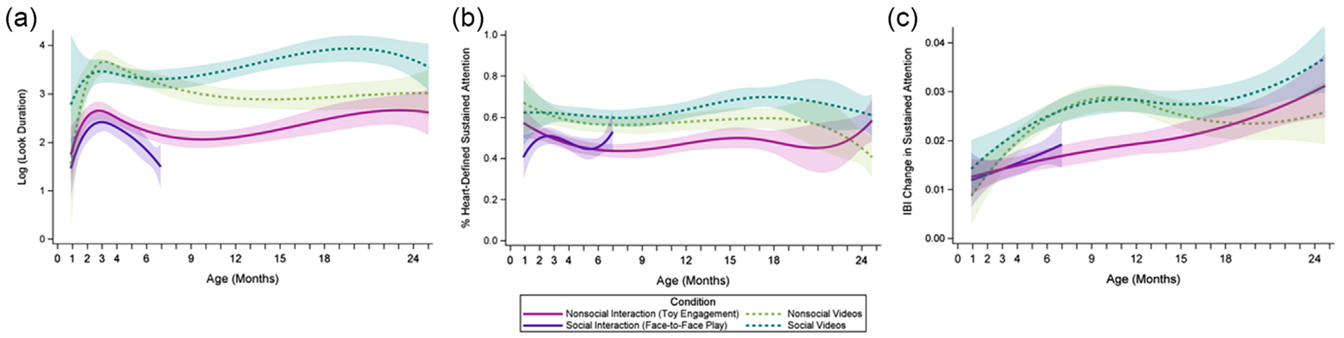

FIGURE 3 Trajectories of sustained attention during four tasks indexed by: (a) lognormal look duration, (b) %HRDSA represented by the proportion of time in HRDSA over each look duration, and (c) mean change in IBI during episodes of sustained attention. HRDSA, heart rate-defined sustained attention; IBI, inter-beat-interval.

TABLE 3 Model summary results.

Attention measure	Spline effect parameters: Polynomial (degrees)	Spline effect parameters: Knots (*n*)	*F*-Tests of fixed effects: Condition	*F*-Tests of fixed effects: Age	*F*-Tests of fixed effects: Condition * Age
%look	cubic	2	F(3,143) = 2.92, *p* = 0.036	F(5,217) = 24.23, *p* < 0.0001	F(13,517) = 7.42, *p* < 0.0001
lookDur	cubic	4	F(3,143) = 17.21, *p* < 0.0001	F(4,193) = 10.86, *p* < 0.0001	F(12,491) = 3.18, *p* < 0.001
%HRDSA	cubic	2	F(3,133) = 1.07, *p* = 0.365	F(5,208) = 2.08, *p* = 0.070	F(13,475) = 2.11, *p* = 0.013
ΔIBI	quadratic	1	F(3,132) = 2.63, *p* = 0.053	F(3,130) = 2.62, *p* = 0.053	F(8,308) = 2.56, *p* = 0.010

p_{adj} < .0001, *d* = 0.52, respectively). By 4 months, infants spent significantly more time looking to toys than caregivers (t[517] = 3.89, p_{adj} = .002, *d* = 0.53). Overall looking during social videos, nonsocial videos, and nonsocial interactions generally followed a similar pattern of change from 1 to 6 months. But looking during social interactions diverged at 4 months. Specifically, *%looking* to the caregiver during a social interaction declined sharply between 4 and 6 months, from about 55% at 4 months to 20% at 6 months. The decrease in looking to caregivers coincides with developmental changes in infants' executive attention, cognition, and motor abilities, which likely shift infants' attention away from faces and toward toys and events in the environment that allow them to exercise their newly emerging problem-solving, fine motor, and gross motor skills.

Between 6 and 12 months, the proportion of time spent looking to videos and to toys remained relatively stable, with *%looking* to social videos becoming increasingly greater than *%looking* to toys (social videos vs. toys: 6 months, t[517] = 3.18, p_{adj} = .026, *d* = 0.44; 9 months, t[517] = 4.30, p_{adj} < 0.001, *d* = 0.59; 12 months, t[517] = 6.18, p_{adj} < 0.0001, *d* = 0.85). At 12 months, infants spent more time looking to social videos compared to nonsocial videos (t[517] = 3.70, p_{adj} = .005, *d* = 0.51). By 24 months, looking time was comparable across all stimuli, however given the increase in missing data at this time point, this trend should be interpreted with caution. In sum, while overall looking was largely stable within each experimental condition from 9 to 24 months, social videos persistently elicited more looking than the other two conditions.

3.2 | Sustained attention

In contrast to overall looking, SA reflects cognitive engagement and is thought to involve distinct, higher-level brain regions. SA has been measured in various ways. Here we report on trajectories of SA, measured using three different methods: mean look duration, *%HRDSA*, and *ΔIBI*. These SA trajectories are depicted in Figure 3.

3.2.1 | Mean look duration

Log-transformed look durations during each condition are presented in Figure 3a. Look durations increased from 1 to 3 months of age for all stimuli. By 2–3 months, look durations during screen-based tasks were significantly longer than interactive and engagement tasks (p_{adj}-values ≤ 0.001, Cohen's *d* range: 0.45–1.07). In contrast, look durations during social and nonsocial interactions were equivalent throughout the entire early infant period, from 1 to 6 months. This trend is different from overall *%looking* (described above) in which high, stable *%looking* during nonsocial interactions was observed from 4 to 6 months, suggesting that infants may be replacing long looks with several short looks when engaging with toys.

Look durations during social videos were largely stable from 3 to 24 months, whereas look durations during nonsocial videos declined gradually from 4 to 12 months and remained stable thereafter.

Social videos elicited significantly longer looks than nonsocial videos from 12 to 18 months (p_{adj}-values < 0.05, Cohen's *d* range: 0.64–0.82). During nonsocial interactions (i.e., toy engagement task), look durations were shorter than those to videos for nearly the entire 2-year period (nonsocial interactions < social videos at months 1–24; nonsocial interactions < nonsocial videos at months 1–18 (all p_{adj}-values < 0.05, Cohen's *d* range: 0.52–1.40). At 24 months, look durations to both nonsocial stimuli became more comparable. Look durations have been used in the literature to measure SA and while both *look duration* and *%looking* measures are defined by infants' looking behavior, they each reveal distinct trajectories by condition. The results reported here show that *look duration* measures of SA show stronger context-specific effects than overall *%looking*, with social videos eliciting longer looks than nonsocial videos, which elicit longer looks than nonsocial interactions, for most of the second year of life.

3.2.2 | Heart-defined SA

SA has also been measured using heart rate changes, specifically heart rate decelerations during periods of looking. *%HRDSA* represents the percent of overall looking time spent in the heart rate-defined phase of SA. *%HRDSA* from 1 to 24 months (see Figure 3b) revealed slightly different trajectories than overall looking time (*%look*; Figure 2) and mean look duration (Figure 3a). In regard to looking at a caregiver during social interactions, infants showed an initial slight increase in *%HRDSA* from 1 to 2 months followed by a slight decline from 3 to 4 months. Videos elicited significantly more *%HRDSA* compared to interactions throughout most of the 1-6-month developmental period. Using statistical tests of model-based predicted values to compare condition effects at study visit time points, *%HRDSA* differences were apparent by 3 months for both social and nonsocial videos (social videos > social interactions, t[475] = 3.95, p_{adj} = 0.002, *d* = 0.54; social videos > nonsocial interactions, t[475] = 4.71, p_{adj} < 0.0001, *d* = 0.65; nonsocial videos > social interactions, t[475] = 3.38, p_{adj} = .015, *d* = 0.46; nonsocial videos > nonsocial interaction, t[475] = 4.08, p_{adj} = 0.001, *d* = 0.56). These results illustrate two important differences from the trends observed in the *%looking* and look duration measures. First, *%HRDSA* did not show the same initial increase in attention from 1 to 3 months that was observed in *%looking* and look durations across all conditions. Second, *%HRDSA* did not show the same decline in attention to social interactions that was observed in the *%looking* and *look duration* measures. These distinctions may highlight unique neurodevelopmental processes underlying looking measures of attention and SA and heart rate-defined SA.

Also in contrast to *%looking* and *look durations*, *%HRDSA* for social versus nonsocial videos did not differ significantly at any time point from 1 to 24 months. However, visual inspection of Figure 3b suggests a subtle divergence that grows larger over the second year of life (18-month social videos vs. nonsocial videos: t[475] = 2.82, p_{adj} = 0.076, *d* = 0.39); 24-month social videos versus nonsocial videos: (t[475] = 2.91, p_{adj} = .062, *d* = 0.40). These time points had more missingness compared to previous time points and a larger sample size at these later study time points is likely to clarify these differences. Still, in the second year of life, *%HRDSA* during nonsocial interactions showed a very similar trajectory as *%looking* and *look durations*.

3.2.3 | Heart rate deceleration in sustained attention

In addition to evaluating the proportion of time infants spend in the SA phase of heart rate-defined attention, researchers can also examine the magnitude of heart rate deceleration as an index of SA. Trajectories illustrating the magnitude of heart rate change, reflected as change in inter-beat intervals (*ΔIBI*), during episodes of SA across the first 2 years of life are shown in Figure 3c. In contrast to *%HRDSA*, this SA measure of *ΔIBI* showed an increase for all conditions from 1 to 24 months of age. This finding may indicate an underlying maturational process of the autonomic nervous system wherein parasympathetic influence on attention increases in the infant period.

ΔIBI was statistically comparable for social and nonsocial videos across the entire 2-year developmental window, but context-specific differences were apparent within the first 6 months. By 4 months of age, *ΔIBI* during SA was greater for social videos than for both social and nonsocial interactions (nonsocial interaction: t[308] = 3.76, p_{adj} = 0.005, *d* = 0.52; social interaction: t[308] = 4.73, p_{adj} < 0.001, *d* = 0.65). By 6–12 months of age, both social and nonsocial videos elicited greater heart rate decelerations during SA compared to nonsocial interactions (all p_{adj} < 0.001, Cohen's *d* range: 0.89–1.57). This developmental trend is similar to that observed in look duration and *%HRDSA* measures of SA. This may be an effect of the interactive context whereby early, newly emerging, active interaction with the environment necessitates deployment of the sympathetic nervous system and dispersion of autonomic nervous system resources.

4 | DISCUSSION

Infant SA provides a window into infant experience and learning that helps shape social and cognitive outcomes. Screen-based attention tasks allow researchers to assess basic attention functions with high levels of experimental control, but this experimental setting is largely decontextualized from infants' active interactions with the environment. Interaction-based attention tasks enable examination of how infants flexibly integrate attention and arousal systems into real-world interactions, during which learning actually occurs (Wass, 2014). The overarching goal of this study was to compare overall looking behavior and three distinct measures of SA during four different conditions that vary by content (social vs. nonsocial) and context (videos vs. interactions) across the first 2 years of life. Results illustrate unique developmental trajectories that differ by attention measure, task context, and stimulus content, with the greatest amount of change and between-measure and between-task divergence occurring in the 1–6-month developmental window.

4.1 | The first 6 months

From 1 to 3 months of age, a large, nonspecific increase in overall looking (*%look*) to the target stimulus during all four conditions was observed. During this time, videos elicited more looking than toy engagement and face-to-face play. In contrast to our hypotheses, social interactions did not elicit the greatest amount of overall looking and, in fact, elicited the *least* amount of infant looking by 4 months compared to toys and videos. After 4 months of age, a marked decline in looking during social interactions was observed. Six-month-olds spent less than 20% of the social interaction looking to the caregiver, compared to 60%–80% of time spent looking to the toy during the toy engagement and to the screen during social and nonsocial videos. This decline in looking between 4 and 6 months was only observed in the social interaction condition and is important to consider in light of results from SA measures, described below.

Whereas *%looking* provides useful information about overall looking behavior and stimulus saliency, SA metrics, such as *look duration*, *%HRDSA*, and *ΔIBI*, can provide insight into active engagement and information processing (Colombo, 2002; Reynolds & Richards, 2008; Xie & Richards, 2016). In contrast to the large increase in overall *%looking* observed during all conditions from 1 to 4 months, as described above, SA measures (*look duration*, *%HRDSA*, *ΔIBI*) showed an attenuated developmental trend with more subtle increases, or no increase, in SA from 1 to 6 months. It is notable here that the significant decline in caregiver face looking (*%looking*) observed between 4 and 6 months was not observed in the heart rate-defined SA measures (*%HRDSA*, *ΔIBI*). These data suggest that while 6-month-olds spend less time looking to the caregiver's face during a social interaction (compared to social interactions at 4 months and compared to other conditions at 6 months), these looks reflect the same amount of SA measured with heart rate (*%HRDSA*) and the same amount of within-look stimulus engagement and information processing measured with heart rate (*ΔIBI*), across the first 6 months.

This finding highlights a developmental shift in the attentional importance of the face in infant-caregiver interactions after 4–6 months and adds to a growing body of evidence that collectively points to a developmental decline in face-looking in infancy (Deák et al., 2014; Fausey et al., 2016; Frank et al., 2012; Jayaraman & Smith, 2019; Kaye & Fogel, 1980; Yu & Smith, 2016). Lower frequencies of caregiver face-looking during triadic (infant-caregiver-toy) interactions have been observed in infants 6 months and older (Deák et al., 2014; Yu & Smith, 2016). Screen-based eye-tracking studies also evidence developmental increases in distributed attention to complex social scenes characterized by decreased face-looking and increased hand-looking (Frank et al., 2012). Naturalistic studies of infants' daily visual experience in the home show a significant decrease in the frequency of faces available in the infant's visual field between 3 and 7 months (Jayaraman & Smith, 2019). By comparing developmental trajectories of overall looking to those of SA in this study, we add to this existing evidence in three important ways. First, we extend this finding to infants as young as 6 months of age and to dyadic (infant-caregiver) interaction contexts. Second, we document that the decline in face-looking occurs between 4 and 6 months of age. Third, we show that decreased face-looking does not necessarily reflect decreased SA or stimulus encoding, and accordingly does not indicate decreased value of attending to the face during caregiver interactions.

The timing of this sharp decline in face-looking aligns with an important developmental shift associated with emergence of endogenous, or executive, control of attention at around 6 months (Colombo, 2001; Petersen & Posner, 2012). This developmental window also co-occurs with gains in infant motor control that enable independent mobility and un-supported postures. By 6 months, infants are becoming active agents in their environment. Stimulus engagement becomes embodied as infants not only shift visual attention to novel stimuli, but they alter their proximity to stimuli of interest by reaching, rolling, and crawling (Adolph & Hoch, 2019; Thurman & Corbetta, 2017). The physical context of infant-caregiver interactions shifts from infants in supine or caregivers' arms to face-to-face seated positions. These changes expand the infant's motoric and visual access to the environment, including caregiver hands and body (Fausey et al., 2016; Long et al., 2022; Soska & Adolph, 2014). It is likely that these cross-domain developmental changes contribute to observed changes in overall caregiver face-looking. But critically, the lack of change (*%HRDSA*) and perhaps even slight increase (*ΔIBI*) in heart rate-defined measures of SA from 1 to 6 months during social interactions, relative to the sharp decline in *%looking* and decrease in look duration, suggests that looks to the face continue to shape learning and may even reflect more efficient processing of caregiver faces during interactions. Cognitive accounts of increased face processing efficiency during the first year, including a transition from featural to configural face processing and growing cortical specialization for faces across the first year, support this interpretation (Conte et al., 2020; Schwarzer et al., 2007).

Our novel finding of a developmental decline in face-looking accompanied by relatively stable and increasing trajectories of heart rate-defined SA during face looking has implications for the translation of basic, experimental studies to understanding the development of infant attention in the real world. Decreased attention to faces is often considered a marker of atypical social and/or emotional development, such as ASD or anxiety. Adding to existing work, this study points to a developmental shift in the value of face looking for infant learning and development. It has been suggested that joint attention, an important context for language learning, can be achieved through hand-following rather than gaze-following (Boyer et al., 2020; Yu & Smith, 2017) and a recent study shows that children with ASD and social communication challenges evidence typical rates of face looking (Yurkovic-Harding et al., 2022). Results of this study demonstrate added value of heart rate-defined SA measures in fully understanding developmental changes in face-looking and the importance of faces in infant looking and learning during interactive contexts.

Between 3 and 6 months, infant SA (as measured with look duration, *%HRDSA*, and *ΔIBI*) during social and nonsocial screen-based tasks was greater than that of SA during social and nonsocial interactive tasks. Within this developmental period, we also observed very little change in *%HRDSA* across all conditions and a slight decline in look duration for interactive tasks and nonsocial videos, which has been documented in previous studies (e.g., Courage et al., 2006). However, within each task context (videos and interactions), greater SA to social stimuli compared to nonsocial stimuli was not observed in any of the SA measures in the first 6 months of life. This finding contrasts with our hypothesis that social conditions (social videos and social interactions) would elicit more SA in early infancy. Some studies show increased looking behavior for social videos beginning at 3 months of age (Bahrick et al., 2016; Courage et al., 2006), while others have not found increased heart rate-defined SA for social videos during this period (Curtindale et al., 2019). Methodological differences may help explain this inconsistency. Our nonsocial videos consisted of animated, dynamic fractals and live-action films of complex cause-and-effect sequences with several objects and synchronized audio. These may have been more cognitively engaging than nonsocial stimuli used in previous studies (e.g., a single object hitting a surface and computer-generated moving shapes). Perhaps enhanced attention to social stimuli observed in previous studies may be partially explained by enhanced attention to complexity or cause-and-effect dynamics, rather than the social content per se. Future studies that tightly control stimulus dynamics and contingency will help disentangle these mixed findings.

4.2 | The second year of life

Trajectories of attention were much more stable from 9 to 24 months of age compared to the first 6 months. Both social and nonsocial videos elicited more looking and SA than toy engagement through about 18 months. This finding may be driven by the confluence of low-level and high-level features, such as perceptual saliency and cognitively engaging content, that are more prominent in videos compared to toys, leading to increased attention getting and attention holding (see Courage & Setliff, 2010 for review). In contrast to videos, attention to real-world features of the environment is usually dependent on the infant's active engagement and interaction. SA to toys is likely not domain-specific, as it relies on, and is modified by, cognition and motor abilities.

Interestingly, despite the marked developmental gains in cognition and motor skills experienced by infants between 6 and 24 months, *%look*, *look duration*, and *%HRDSA* measures remained largely stable within each of the three tasks (social videos, nonsocial videos, and toy engagement). Each experiment contained identical videos and toys at each visit and even with the significant brain maturation and developmental advancements that take place across the first 2 years, general looking and SA to these stimuli remained largely stable. This may reflect a highly stable attention system integrated with a flexible cognitive system wherein infants adaptively integrate new skills and cognitive representations to continue attending to and learning from repeated experiences and similar environments.

Although a general trend suggested greater looking (*%look*) to social compared to nonsocial videos, this was only statistically significant at 12 months. Similarly, neither of the heart rate-defined SA measures (*%HRDSA*, *ΔIBI*) differentiated social and nonsocial attention to videos at any time point. The look duration measure of SA most robustly differentiated social and nonsocial attention from 12 to 24 months. This was characterized by relatively stable, smaller look durations during nonsocial videos and toy engagement along with increasingly longer look durations during social videos. This developmental period is marked by significant gains in social-communication skills, including receptive language, which likely contributes to increased look duration to social videos beginning between 9 and 12 months (Richards, 2010). Indeed, longer look durations during complex tasks may reflect enhanced processing (Kannass & Oakes, 2010).

4.3 | Limitations

There are some limitations to consider in drawing conclusions from this study. Our social interaction condition was limited to dyadic, face-to-face interactions from 1 to 6 months. Future research should incorporate triadic interactions at older ages to further understand developmental shifts in SA to other features, including hands, body, toys, and face. In addition, studies that include a social interaction condition with an unfamiliar social partner will allow us to evaluate the impact of familiarity and predictability on looking and SA. The impact of motor behavior on attention measures, particularly during the interaction tasks, was not examined in this study. Characterizing motor skills and behavior may be an important component of infant attention during live interactions, especially for atypically developing populations. Despite the strengths of this study in terms of its longitudinal design and dense sampling, missing data, particularly at 1–2 months and 18–24 months limit the study's interpretations. The statistical models used are tolerant of missing data, but findings drawn from the earlier and later time points should be interpreted with caution.

4.4 | Conclusions

This study describes trajectories of looking and SA to two different classes of stimuli (social and nonsocial) across two different contexts (videos and interactions) in infants from 1 to 24 months of age. Our findings suggest that each metric of attention reflects unique developmental processes. Social interactions with caregivers, a highly specialized and developmentally critical context, did not elicit the greatest amount of attention using any attention measure at any timepoint. In fact, looking to caregivers (%look and look duration) decreased after 3–4 months of age, while measures of SA to caregivers remained stable or increased slightly. These results demonstrate that a decrease in looking to the caregiver in this context does not necessarily equate to a decrease in SA and may instead reflect increased efficiency of face processing. We also speculate that decreased looking to caregiver's face is related to developmental gains in attention shifting and motor control as well as a re-allocation of attentional value to other environmental and caregiver features (e.g., hands and body).

Both live-interactive tasks (face-to-face play and toy engagement) generally elicited less SA compared to social and nonsocial videos throughout the first 2 years. Sustaining attention requires a whole-body response supported by the parasympathetic nervous system. The developmental resources required to attend to and engage with the real-world environment may be greater than that of attending to a video, resulting in fewer resources to sustain attention, particularly in early infancy. Thus, effective and efficient learning from the environment in early infancy may be better characterized by a balance between parasympathetic and sympathetic influences that may be best captured with multiple measures of SA rather than single measures of *look duration*, *%HRDSA*, and *ΔIBI*. Overall, these results highlight the importance of a context-specific, multimethod approach that incorporates both looking and heart rate measures of attention to further refine attentional mechanisms of infant learning and identify markers of atypical development.

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CONFLICT OF INTEREST STATEMENT

The authors have no conflicts of interest to disclose.

DATA AVAILABILITY STATEMENT

Data are available upon request.

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SUPPORTING INFORMATION

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