COVARIATION AND SYNCHRONICITY OF SUSTAINED ATTENTION MEASURES IN INFANCY

by

Wei Siong Neo

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THE PURDUE UNIVERSITY GRADUATE SCHOOL
STATEMENT OF COMMITTEE APPROVAL

Dr. Bridgette L. Kelleher, Chair
Department of Psychological Sciences

Dr. Daniel Foti
Department of Psychological Sciences

Dr. Jessica P. Lougheed
Department of Human Development & Family Studies

Approved by:
Dr. Kimberly P. Kinzig

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ABSTRACT

Sustained attention, the ability to direct and maintain attentional focus on tasks and stimuli, emerges during infancy and undergoes rapid development throughout early childhood. Abnormal patterns of sustained attention are implicated in several childhood psychological disorders. Improving our measurement of infant sustained attention may clarify how child psychopathology develops and inform targeted prevention and early intervention efforts. While several behavioral and psychophysiological measures index infant sustained attention, previous studies have employed these measures in isolation, focused on analyses at short timescales of milliseconds to a few seconds, and examined synchronous associations among these measures. Therefore, the associations and temporal relationships across multiple, concurrent behavioral and psychophysiological measures of infant sustained attention remain unclear, particularly at long timescales. The present study assessed sustained attention in 12-month-old infants using behavioral (looking), cardiac (heart rate), and neural (theta and alpha oscillations) measures to investigate two temporal aspects of infant sustained attention. First, we examined whether associations among infant sustained attention measures were similar or different across short (1-second) and long (10-second) timescales. Covariation analyses indicated largely similar association patterns among these measures across the two timescales. Second, we evaluated whether specific infant sustained attention measures temporally preceded other measures. Cross-correlation analyses broadly revealed that short-timescale measures exhibited asynchronous temporal relationships, such that looking behaviors preceded neural oscillations that in turn preceded cardiac responses. Our findings highlight the value of considering the temporal dimension when studying and measuring infant sustained attention. Additional multimodal research may yield greater insights into dynamic biobehavioral processes that underlie infant sustained attention and enhance clinical interventions aimed at promoting optimal outcomes for young children with abnormalities in sustained attention.

INTRODUCTION

Abnormal patterns of sustained attention are implicated in several childhood psychological disorders, including attention-deficit/hyperactivity disorder (ADHD), autism spectrum disorder (ASD), and childhood anxiety and depressive disorders (Lau & Waters, 2017; Rommelse et al., 2011; Visser et al., 2016). Prevention and early intervention efforts that specifically target sustained attention in young children may promote optimal developmental outcomes. Neural and behavioral plasticity in early development may be leveraged to directly alter underlying neurobiological processes and to facilitate skill acquisition across developmental domains (Sonuga-Barke & Halperin, 2010; Wass et al., 2012). Indeed, sustained attention assessed as early as infancy predicts executive and social functioning in early childhood and adolescence (Brandes-Aitken et al., 2019; Pérez-Edgar et al., 2010), compatible with the neuroconstructivist perspective that emphasizes how basic precursors in early development may serve as antecedents to seemingly disparate end-states (Edgin et al., 2015; Karmiloff-Smith et al., 2012). Therefore, improving our measurement and conceptualization of infant sustained attention may clarify how child psychopathology emerges and further enhance clinical prevention and intervention efforts.

According to Richards (2008), infant sustained attention reflects a sustained activation of a general arousal neural system that leads to behavioral and psychophysiological changes. Several behavioral and psychophysiological measures have been used to examine infant sustained attention, with most investigations characterized by three study features. First, most studies have employed these infant sustained attention measures in isolation, that is, using behavioral and/or single psychophysiological measures. Second, most studies have focused on analyses of time-locked, discrete trials at relatively short timescales of milliseconds to a few seconds. Finally, most studies have examined synchronous associations between these measures with limited exploration of differential time lags of individual measures in assessing infant sustained attention. Therefore, the associations and temporal relationships among multiple, concurrent behavioral and psychophysiological measures of infant sustained attention remain unclear, particularly at relatively long timescales. From a developmental psychopathology perspective, relying on single methodologies and measures is unlikely to be sufficient for elucidating the development and maintenance of child psychopathology (Cicchetti & Toth, 2009). Given the involvement of multiple behavioral and physiological systems, individual infant sustained attention measures are unable to definitively capture the multimodal construct of infant sustained attention, necessitating the use of multiple measures (Fox et al., 2007). In other words, individual measures may provide both shared and unique information about infant sustained attention, based on relative strengths of different methodologies (De Los Reyes & Aldao, 2015). In fact, a multiple-levels-of-analysis approach has been specifically highlighted as critical for advancing our understanding of childhood psychological disorders (e.g., ADHD) and for maximizing the impact of clinical prevention and intervention efforts (Hinshaw, 2018).

Extending our understanding of how infant sustained attention operates beyond relatively short timescales is valuable for both theoretical and practical reasons. The duration of infant sustained attention is variable and can last a few tens of seconds (Richards & Casey, 1992), warranting investigation at longer timescales to enable a better characterization across the temporal dimension. Additionally, the concepts of physiology and timescale are intertwined, such that physiological activity can be conceptualized as occurring along a phasic-to-tonic continuum (Aston-Jones & Cohen, 2005). Broadly, phasic activity refers to transient fluctuations in physiological activity, either spontaneously or in response to an event, that occur on a relatively short timescale (e.g., sub-second to seconds); tonic activity refers to slow shifts in baseline physiological activity that occur on a relatively long timescale (e.g., sub-minute to minutes; Huang et al., 2008; Wass et al., 2015). Therefore, measuring infant sustained attention across different timescales may reveal commonalities and distinct aspects of phasic and tonic attention that may map onto shared and unique attentional abnormalities in child psychopathology. From a translational perspective, gaining a better appreciation on the temporal dimension of infant sustained attention may inform how we assess it in more naturalistic settings and guide adaptations of existing paradigms that use a more trial-based, short-timescale approach. As a first step toward an integrated, temporally-informed account of infant sustained attention, we adopted a multimodal measurement approach that spanned behavioral, cardiac, and neural levels to examine infant sustained attention at both short and long timescales.

Infant Sustained Attention Measures

Infant sustained attention has been primarily indexed across three levels: behavioral, cardiac, and neural. We briefly review key infant sustained attention measures and prior work on how they relate to one another in various experimental and observational contexts.

Behavioral Measures

Looking is one of the most common ways to measure infant attention, with methods ranging from manual coding of looking behaviors to eye tracking of gaze patterns. Since Fantz's (1958) seminal work on looking behaviors in infants, dozens of fixation paradigms and hundreds of studies have been devoted to how infants attend to various static and dynamic visual stimuli, covering topics as diverse as detection, discrimination, preference, categorization, and expectations (Aslin, 2007; Gredebäck et al., 2009). Similarly, with relatively recent technological advances, eye tracking has become a popular research tool to extend behavioral studies from broad measures of infants' looking behaviors to nuanced details of fixation patterns (Aslin, 2012; Gredebäck et al., 2009). Regardless of the specific methodology, the direction of a look is generally interpreted as the locus of visual attention (Holmqvist et al., 2011). Therefore, when infants look longer at stimuli and are slower in orienting toward peripheral distractors, they are behaviorally assessed to be exhibiting sustained or focused attention (Colombo & Cheatham, 2006).

Despite their ease of implementation, studies that rely on behavioral indices of attention have three major shortcomings. First, infants' looking behaviors do not always index attention. For example, during the heart rate (HR)-defined attention termination phase where HR has returned to baseline levels, infants often continue to look at stimuli but are no longer actively attending to and processing them (Reynolds & Richards, 2008; Richards, 1985). Second, measuring infants' looking behaviors reliably may be challenging in some contexts. For example, when manually coding gaze location, accuracy may be complicated by the complexity of visual scenes with multiple stimuli in close proximity to one another. Additionally, eye tracking data quality is lower for young children, where about 20% of participants are excluded for not having valid fixations and data accuracy and precision are below advertised specifications (Dalrymple et al., 2018; Wass et al., 2014). Finally, looking behaviors need to be interpreted and may not always index the same attentional process. For example, infants' looking preferences for familiar stimuli shift to preferences for novel stimuli across the first year of life within the same looking paradigm (Perone & Spencer, 2013; Roder et al., 2000). Thus, interpreting infants' looking behaviors may require the consideration of developmental and contextual factors that may not be readily available and straightforward.

Cardiac Measures

Given these limitations of looking behaviors, researchers have increasingly leveraged complementary measures of infant attention that are more sensitive and objective than traditional behavioral measures (Gredebäck et al., 2009). The most widely employed physiological measure for assessing infant sustained attention is derived from electrocardiography (ECG) signals. Over five decades of research have consistently demonstrated that infants and young children exhibit lower HR during attentive states (Kagan & Lewis, 1965; Lewis et al., 1966). Specifically, greater HR deceleration was associated with longer duration of attending to visual or auditory stimuli. Additionally, Richards and colleagues (Reynolds & Richards, 2008; Richards & Casey, 1992) have advanced a HR-defined attention model that integrates looking behaviors and HR, where three distinct phases (i.e., stimulus orienting, sustained attention, and attention termination) are posited to reflect different levels of attention and information processing. The sustained attention phase involves active, infant-controlled cognitive processing and is indexed by looking accompanied by a sustained deceleration of HR, relative to baseline cardiac activity. These HR-defined attention phases have received considerable support through experimental paradigms involving behavioral and HR measures of infant sustained attention (Lansink & Richards, 1997; Reynolds & Richards, 2008; Richards, 1994; Richards & Casey, 1992). Translational work have also applied these HR-defined attention phases in clinical trials, such as investigating whether docosahexaenoic acid supplementation would enhance HR-defined sustained attention in infants during lab-based tasks (Colombo et al., 2004, 2011, 2016). Furthermore, a growing literature has examined resting state HR and HR deceleration in children and adolescents diagnosed with ADHD and ASD to inform sustained attention abnormalities in these psychological disorders (Bellato et al., 2020; Klusek et al., 2015). Methodological differences across studies, such as the nature of tasks and stimuli (e.g., social vs. nonsocial activities and stimuli) and how HR deceleration was quantified (e.g., change in mean HR vs. amplitude of HR deceleration), likely contributed to current mixed findings in these clinical populations. Therefore, there remains a need for more systematic investigation of basic factors that potentially influence our measurement and understanding of HR-defined sustained attention.

Neural Measures

Neural measures, such as cortical oscillations and event-related potentials (ERPs), have also been used to measure infant sustained attention. Briefly, neural oscillations reflect synchronized, rhythmic activity of large populations of neurons and are typically classified into several frequency bands, each of which possesses distinct functional characteristics (Clayton et al., 2015; Saby & Marshall, 2012). Developmental cognitive neuroscientists have focused on theta (3–6 Hz), alpha (6–9 Hz), and gamma (20–60 Hz) oscillations. In fact, early infant electroencephalography (EEG) studies focused on alpha oscillations and demonstrated the classic adult EEG finding that visual stimulation decreases the amplitude of alpha oscillations (Lindsley, 1938). While less attention has been devoted to theta oscillations than alpha oscillations in early development, initial studies have explored the functional role of theta oscillations in affective and cognitive processing (Saby & Marshall, 2012). Notably, for the domain of visual attention, laboratory-based EEG studies have documented that variations in attention are associated with amplitude and power changes in cortical oscillations across different frequency bands (Clayton et al., 2015). Infant theta oscillations increase during situations involving a high degree of attention, such as active exploration of toys and social exchanges, and are posited to reflect the engagement of neural networks involved in cognitive control and monitoring (Orekhova et al., 1999; Orekhova et al., 2006; Stroganova et al., 1998; Xie et al., 2018). In contrast, infant alpha oscillations are attenuated over cortical areas involved in attentional processes during HR-defined sustained attention, likely indicating the releasing of task-relevant neural regions from inhibition (Xie et al., 2018). These neural measures have excellent temporal resolution but usually require sophisticated and expensive equipment, though there is an emerging trend to develop more portable and cost-effective systems that are suited for field studies.

Broadly, several behavioral, cardiac, and neural measures have been used to assess infant sustained attention. Looking is the most common behavioral measure and eye tracking techniques have enabled us to better interpret infants' looking behaviors. Nevertheless, the utility of eye tracking for measuring infant sustained attention in naturalistic settings remains relatively unknown. A decelerated HR indexes infant sustained attention and is the most widely used physiological measure to complement looking behaviors. While HR-defined sustained attention has been successfully used as a clinical outcome measure, these translational applications continue to be based on lab-based tasks and more work is needed to extend such efforts to better measure infant sustained attention in naturalistic settings. Relative to ERPs, EEG oscillations are relatively novel neural measures of infant sustained attention; compared to behavioral and cardiac measures, they offer the advantage of enhanced temporal resolution. Similar to behavioral and cardiac measures, recent technological advances have increased the potential of using EEG oscillations to measure infant sustained attention in naturalistic settings but much remains unexplored.

Multimodal Measurements of Infant Sustained Attention

Despite the availability of several infant sustained attention measures, only a few recent studies have simultaneously employed behavioral and multiple psychophysiological measures of infant sustained attention. Importantly, a multimodal approach allows researchers to narrow the range of possible valid interpretations and advance plausible scientific accounts (Aslin, 2007). In a study that incorporated looking, HR, and EEG oscillations to assess sustained attention in 6- to 12-month-old infants, Xie and colleagues (2018) examined the relationships between HR-defined attention phases, theta oscillations, and alpha oscillations. At six to eight months of age, infants exhibited similar theta power and alpha power across all three HR-defined attention phases. In contrast, 10- and 12-month-old infants showed greater theta power and reduced alpha power during sustained attention than attention termination. Critically, this study was one of the first to examine infant sustained attention using HR and EEG oscillations, which extended a more established literature involving HR and ERPs (Richards, 2011). However, it is important to note that Xie and colleagues (2018) analyzed infant sustained attention measures using relatively short one-second segments, leaving questions unanswered about the associations among these measures at relatively long timescales.

Phasic and Tonic Physiological Activity across Short and Long Timescales

As highlighted earlier, the concepts of physiology and timescale are intertwined. Physiological activity changes in response to internal and external events as well as spontaneously over time, with these changes reflective of a phasic-to-tonic continuum (Aston-Jones & Cohen, 2005). While there are no well-defined boundaries, phasic and tonic activities occur on relatively short (e.g., sub-second to seconds) and long (e.g., sub-minute to minutes) timescales, respectively (Huang et al., 2008; Wass et al., 2015). As an illustration, infant attention waxes and wanes over both short and long timescales; the rapid gain in infant attention in response to preferred toys and novel events is more phasic in nature, whereas the gradual reduction in infant arousal level within a wake–sleep cycle reflects a more tonic change. Furthermore, attentional difficulties in different childhood psychological disorders may stem from differential abnormal patterns of phasic and tonic activity. For example, a child with ASD who visually inspects objects in an atypical manner may exhibit aberrant phasic increases in attention after seeing those objects, while a child with ADHD with inattentive symptoms may show atypically low tonic activity in attention for prolonged periods of time.

Given that different psychophysiological measures are unlikely to have simple one-to-one correspondences due to distinct underlying phasic and tonic activity, integrative research that examines and compares multiple measures is valuable. To that end, a recent study on arousal, which is related to sustained attention, examined the covariation of several peripheral measures (i.e., electrodermal activity, head movement velocity, HR, peripheral accelerometry, and pupil size) in 12-month-old infants across timescales ranging from 1 to 60 seconds (Wass et al., 2015). Head movement velocity, HR, and peripheral accelerometry consistently exhibited positive associations across the entire range of timescales, whereas electrodermal activity and pupil size were associated with some of the other peripheral measures only at relatively long timescales of at least 30 seconds. Following up on their work, Wass and colleagues (2016) used cross-correlation analyses to determine whether and to what degree specific arousal measures temporally precede other measures, by probing temporal dynamics among electrodermal activity, head movement velocity, and HR. Changes in head movement velocity consistently preceded changes in HR that in turn preceded changes in electrodermal activity, further clarifying the temporal specificity of the associations between peripheral measures first identified in Wass and colleagues (2015). However, Wass and colleagues (2015, 2016) did not specifically examine infant sustained attention nor use neural measures, thus the associations among looking, HR, and EEG oscillations—well established infant sustained attention measures—at short and long timescales remain unknown. Similarly, the temporal relationships among these infant sustained attention measures have not been investigated.

Clarifying similarities and differences across timescales is an important first step toward determining optimal timescales for measuring infant sustained attention, especially for naturalistic settings. It is conceivable that associations at longer timescales may be stronger given that psychophysiological data tend to be relatively noisy and unstable at shorter timescales. Alternatively, associations at longer timescales may be weaker due to the inclusion of multiple psychophysiological processes and responses in a given time window. If infant sustained attention operates similarly across timescales, naturalistic assessments of infant sustained attention may expand from current short-timescale paradigms to include long-timescale measurements. On the other hand, if there are substantial differences between infant sustained attention at short and long timescales, assessments of infant sustained attention may need to more explicitly consider the temporal dimension and establish best practices to integrate short- and long-timescale measurements. Additionally, investigating the temporal relationships among infant sustained attention measures will enhance our understanding of potential cascading patterns. Such knowledge may in turn advance prevention and intervention efforts by identifying candidate behavioral and psychophysiological systems and processes to target, especially those that occur temporally early in attentional processing.

The Present Study

To begin addressing current gaps on the associations among behavioral, cardiac, and neural measures of infant sustained attention at long timescales and their temporal relationships, the present study had two primary objectives. Our first aim was to determine whether previously identified associations among infant sustained attention measures at the short timescale (operationalized as 1-second segments) would extend to a longer timescale (operationalized as 10-second segments), thus providing us with preliminary insights on how infant sustained attention might be consistent or vary across the phasic-to-tonic continuum. Broadly, we expected similar patterns of association among behavioral, cardiac, and neural measures of infant sustained attention across short and long timescales, given prior findings of largely consistent associations among arousal measures across timescales (Wass et al., 2015). Specifically, we predicted that (a) looking proportion and theta power, and (b) HR and alpha power would be positively related, while (c) looking proportion and HR, (d) looking proportion and alpha power, (e) HR and theta power, and (f) theta power and alpha power would be negatively related, based on previous findings that greater sustained attention is indexed by longer looking duration/larger looking proportion, lower HR, increased theta power, and decreased alpha power (Xie et al., 2018). Our second aim was to examine and quantify temporal relationships among behavioral, cardiac, and neural measures of infant sustained attention, potentially advancing our understanding of how underlying behavioral and biological systems operate in tandem to support infant sustained attention. We expected looking behaviors to temporally precede psychophysiological measures that reflect detailed processing of visual stimuli. We also predicted that theta power and alpha power would precede HR, given that EEG and HR signals are relatively fast- and slow-changing, respectively.

METHOD

Participants

Participants included 36 infants (52.8% male) between 10.49 and 13.97 months of age (*M* = 12.28, *SD* = 0.92) from an ongoing longitudinal study of early development at Purdue University. We recruited families locally through social media, study flyers, and web-based advertisements. Study entry criteria included: (a) chronological age between 10 and 14 months; (b) full-term birth, defined as gestational age of at least 37 weeks; (c) no known developmental concerns; and (d) no first-degree familial history of ASD or intellectual disability. The institutional review board at Purdue University approved all study procedures. Mothers provided informed consent for their child's participation. We compensated families for their time at $10 per hour.

Task

The present study focused on a passive, free-viewing task, modeled after prior infant studies (e.g., Guy et al., 2018). Specifically, four static face and toy images (i.e., infant's mother's face, stranger's face, infant's favorite toy, and rattle toy) were presented across three blocks of 50 trials for a total of 150 trials. Each trial either showed a single image for one second or two side-by-side images of the same category for four seconds. Intertrial interval was approximately one second. Task duration was approximately 6 minutes and 30 seconds, excluding breaks between blocks. Infants sat on their mother's lap and viewed these images on a desktop monitor approximately 60 cm directly in front of them.

Data Acquisition and Processing

We collected concurrent behavioral, ECG, and EEG data from infants throughout the task. Briefly, for each infant, we pre-processed, time-synchronized, and standardized these three parallel data streams to yield four time series of behavioral (i.e., looking proportion), cardiac (i.e., HR), and neural (i.e., theta power and alpha power) measures of infant sustained attention in 1-second epochs and four corresponding time series in 10-second epochs. Full data acquisition and processing details for each data stream are described below.

Behavioral Recording and Processing

We video recorded infant behaviors throughout the task at 30 frames per second and coded looking behaviors offline using ELAN (Max Planck Institute for Psycholinguistics, 2020). Two behavioral coders independently assessed whether infants were looking (coded as 1) or not looking (coded as 0) at the computer screen for each 100-ms time bin of the task.[1] To assess interrater reliability, we used Gwet's AC_1, an interrater reliability statistic that is more robust to marginal probabilities than Cohen's kappa (Gwet, 2008). Interrater reliability for looking codes was excellent (M = .94, SD = .03, range: .88–.98). Based on looking codes by the primary behavioral coder, we calculated the proportion of time that an infant looked at the computer screen for each 1-second and 10-second epoch before standardizing these two looking proportion time series independently for each infant. Within-infant, standardized looking proportion values were outliers (i.e., standardized values below or above three) for 0.07% (n = 8) of 1-second epochs; no within-infant, standardized looking proportion values were outliers across all 10-second epochs. To minimize effects of outliers, we winsorized them by setting their values to ±3.

ECG Recording and Processing

We recorded infant cardiac activity throughout the task using the Actiwave Cardio HR monitor (CamNtech, 2019).[2] The HR monitor recorded a single channel of ECG signals at a sampling frequency of 1,024 Hz through two standard ECG chest electrodes. Offline processing of ECG signals included the following steps. First, we visually inspected the presence and quality of raw ECG signals in EDFbrowser (van Beelen, 2020). Second, two physiological coders independently marked one of the fiducial points (e.g., R-waves) for each ECG waveform in QRSTool (Allen et al., 2007). To assess interrater reliability, we used Gwet's AC_1 after determining the number of marked fiducial points in each 250-ms time bin of the ECG signals. Interrater reliability was excellent (M = 1.00, SD = .01, range: .97–1.00). Third, based on the fiducial points marked by the primary physiological coder, we obtained interbeat interval (i.e.,

[1] Behavioral coders could not assess looking behaviors for 5.3% of time bins across all infants because infants' eyes were beyond the field of view of the video camera. To be conservative and given that infants were typically disengaged from the task during such occurrences, infants were considered to be not looking at the computer screen for these time bins.

[2] Due to equipment malfunction, we used the Faros 180 HR monitor (Bittium, 2018) to record two infants' cardiac activity at a sampling frequency of 1,000 Hz.

duration between two successive heart beats) data in milliseconds. Fourth, a coder, certified to be research-reliable on processing pediatric ECG signals by the Brain-Body Center for Psychophysiology and Bioengineering, examined and edited the interbeat interval data for artifacts (e.g., missed R-waves). No artifacts were identified for 25 (71.4%) infants; for the remaining infants, a minimal percentage of ECG signals required artifact correction (M = 0.76%, SD = 1.17, range: 0.10–3.02). Fifth, we converted interbeat interval to HR for each 1-second and 10-second epoch before standardizing these two HR time series independently for each infant. Finally, we winsorized within-infant, standardized HR values that were outliers by setting their values to ±3. Standardized HR values were outliers for 1.18% (n = 132) and 0.09% (n = 1) of 1-second and 10-second epochs, respectively.

EEG Recording and Processing

We recorded infant neural activity throughout the task using the BrainVision actiCHamp 24-bit amplifier and 32 actiCAP active Ag/AgCl electrodes (Brain Products, 2020). We sampled EEG signals at a frequency of 500 Hz through BrainVision PyCorder (Brain Products, 2015) without applying any online filter. Offline processing of EEG signals included the following steps, which primarily occurred in BrainVision Analyzer (Brain Products, 2020). First, we bandpass filtered raw EEG signals from 1 to 20 Hz using a non-causal Butterworth infinite impulse response filter with roll-off slope of 48 dB/octave, which minimized distortions of infant theta and alpha frequency bands between 3 and 9 Hz (Saby & Marshall, 2012) while eliminating the influence of skin potentials and muscle activity. Second, we visually determined channels with excessive noise or no signals and conducted topographic interpolation for these channels using quartic spherical splines (Perrin et al., 1989). Across all infants, the mean number of interpolated channels was 3.97 (SD = 2.59, range: 0–9). Third, we re-referenced EEG signals to the average of the left and right mastoid electrodes and retained four electrode clusters that spanned frontal, central, parietal, and occipital regions.[3] Fourth, we performed segmentation to yield 2-second segments with 50% overlap between segments to account for the subsequent application of the Hamming window described below. Fifth, we conducted artifact rejection using an automated procedure on individual channels and segments. Specifically, we determined artifact rejection parameters such that EEG

[3] The frontal cluster consisted of F3, Fz, and F4 electrodes. The central cluster consisted of C3, Cz, and C4 electrodes. The parietal cluster consisted of P3, Pz, and P4 electrodes. The occipital cluster consisted of O1, Oz, and O2 electrodes.

data spanning 50 ms before and after the occurrence of either of the following criteria were regarded as artifacts: (a) rate of change in voltage between two consecutive data points was greater than 50 μV/ms; or (b) difference between minimum and maximum voltages within any 200-ms period was smaller than 0.5 μV or larger than an infant-specific voltage, which ranged from 150 to 275 μV (*M* = 188.97, *SD* = 38.03). This infant-specific voltage was determined such that at least 70% of resultant 1-second and 10-second epochs were free of artifacts for at least two of the three electrodes in each electrode cluster, thereby allowing us to balance between rejecting too many segments that would limit available segments for statistical analyses and including too many segments with noisy signals that would negatively impact signal-to-noise ratios. Sixth, to decompose EEG data into their constituent frequencies at a resolution of 0.5 Hz, we applied the fast Fourier transform on individual channels and segments with a 50% Hamming window to yield EEG power spectra of 1-second epochs. Seventh, we calculated mean theta power (3–6 Hz) and mean alpha power (6–9 Hz; Saby & Marshall, 2012) for each electrode cluster and 1-second epoch; we then averaged across 10 consecutive 1-second epochs to obtain mean theta power and mean alpha power for each electrode cluster and 10-second epoch. Preliminary analyses revealed that both mean theta power and mean alpha power were moderately associated across electrode clusters for both 1-second and 10-second epochs (1-second theta power: r_s = .54; 10-second theta power: r_s = .60; 1-second alpha power: r_s = .42; 10-second alpha power: r_s = .47). Therefore, we calculated overall mean theta power and overall mean alpha power by collapsing across electrode clusters for both 1-second and 10-second epochs before standardizing these four EEG power time series independently for each infant. Finally, we winsorized within-infant, standardized theta and alpha power values that were outliers by setting their values to ±3. Standardized theta power values were outliers for 1.49% (*n* = 157) and 0.80% (*n* = 8) of 1-second and 10-second epochs, respectively; standardized alpha power values were outliers for 1.49% (*n* = 156) and 0.50% (*n* = 5) of 1-second and 10-second epochs, respectively.

Data Analytic Plan

First, we computed descriptive statistics of looking proportion, HR, theta power, and alpha power at both short (i.e., 1-second epochs) and long (i.e., 10-second epochs) timescales to characterize these infant sustained attention measures. We also assessed split-half reliability of these measures by calculating the Pearson's correlation between odd and even epochs before applying the Spearman–Brown correction. Split-half reliability was considered to be poor for values at or below .50, moderate for values between .50 and .75, good for values between .75 and .90, and excellent for values above .90 (Portney, 2020).

Second, we determined associations between pairs of infant sustained attention measures at both short and long timescales to examine similarities and differences in covariation patterns across the two timescales. For each possible pair of short-timescale measures (i.e., looking proportion–HR, looking proportion–theta power, looking proportion–alpha power, HR–theta power, HR–alpha power, and theta power–alpha power), we calculated the Spearman's correlation between their standardized values across all epochs; this calculation was performed independently for each infant, yielding six Spearman's correlations per infant. We then used six separate one-sample *t*-tests to evaluate whether the mean Spearman's correlation across infants for each pair of measures was statistically different from zero. Significant *t*-tests indicated that the pair of measures was significantly associated across infants. Holm-Bonferroni correction was applied to account for multiple comparisons. We conducted parallel analyses for long-timescale measures. Additionally, we used the Wilcoxon signed rank test to compare the six mean Spearman's correlations of short-timescale measures with those of corresponding long-timescale measures.

Finally, we performed cross-correlation analyses to investigate temporal relationships among infant sustained attention measures at both short and long timescales. Briefly, cross-correlation techniques involve quantifying associations between two time series across a range of time lags between them. Specifically, the association between two original time series without the introduction of any time lag is determined; relative to the other time series, one time series is temporally displaced backward and forward in systematic increments of time lag (i.e., ± 1, ± 2, …, $\pm k$) and the association between the original and displaced time series is determined for each increment of time lag (e.g., original time series at time t and displaced time series at time $t - k$, …, original time series at time t and displaced time series at time $t - 1$, original time series at time t and displaced time series at time $t + 1$, …, original time series at time t and displaced time series at time $t + k$). Following the approach by Schlotz and colleagues (2008), we selected the maximum increment of time lag (i.e., value of k) such that the number of overlapping epochs between the original and displaced time series would be at least as great as the number of non-overlapping epochs across all time lags. Preliminary analyses indicated that, on average, infants participated in

2.74 blocks of trials (*SD* = 0.61, range: 1–3), resulting in a total of 96 blocks across all infants. Of these 96 blocks, 89 (92.7%) blocks contained at least 100 one-second epochs and 10 ten-second epochs. Therefore, for each possible pair of short-timescale measures and each infant, we calculated the Pearson's correlation between the standardized time series at time lags from −50 to +50 one-second epochs. We conducted parallel cross-correlation analyses for long-timescale measures at time lags from −5 to +5 ten-second epochs. These cross-correlation analyses yielded 101 short-timescale and 11 long-timescale cross-correlations for each pair of measures and each infant. For each pair of measures, we then computed average cross-correlations across infants at both short and long timescales before determining the time lag at which peak cross-correlations occurred. Peak cross-correlations at a time lag of zero indicated that the pair of measures was synchronous, whereas peak cross-correlations at a non-zero time lag indicated that the pair of measures was asynchronous, with one measure temporally preceding the other measure. Additionally, to examine how asynchronous a pair of measures was (i.e., asymmetry of cross-correlations around the time lag of zero), we used the Wilcoxon signed rank test to sequentially compare the cross-correlations at corresponding positive and negative time lags (i.e., ±1, ±2, …) until a statistically non-significant result was obtained. In other words, we determined the maximum time window in which cross-correlations were asymmetric around the time lag of zero, which represented the time window where one measure reliably preceded the other measure. We performed all statistical analyses in SAS 9.4.

RESULTS

Descriptive Statistics and Split-half Reliabilities

Complete behavioral, ECG, and EEG data were available for 32 (88.9%) infants; we included available data from three other infants.[4] On average, infants' time series data contained 338.11 one-second epochs (*SD* = 93.03, range: 79–393) and 32.40 ten-second epochs (*SD* = 9.06, range: 7–39). Table 1 details descriptive statistics and split-half reliabilities for infant sustained attention measures at short and long timescales. Broadly, means and variabilities of corresponding short- and long-timescale measures were similar. Split-half reliabilities were good or excellent for all measures at both short (range: .83–.87) and long (range: .82–.91) timescales, except that looking proportion had a moderate split-half reliability of .68 at the long timescale.

Covariation of Infant Sustained Attention Measures

Table 2 summarizes mean Spearman's correlations across infants for each pair of infant sustained attention measures, with short- and long-timescale measures presented below and above the diagonal, respectively. Consistent with our prediction, covariation patterns across short- and long-timescale measures were similar, as evidenced by comparable mean Spearman's correlations for corresponding short- and long-timescale measures (i.e., difference in short- and long-timescale correlation coefficients ≤ .10). Nevertheless, as a whole, mean Spearman's correlations across long-timescale measures were greater than those across short-timescale measures (Wilcoxon signed rank $S = 10.5$, $p = .031$), indicating larger associations for long-timescale measures.

[4] We excluded one infant from analyses due to limited data (i.e., 17 one-second epochs and 1 ten-second epoch); this infant's EEG data also contained excessive artifacts identified during the artifact rejection processing step. Behavioral data was unavailable for one infant due to technical issues with the video recording. One infant's ECG data was excluded due to missing metadata needed for time-synchronizing ECG signals. One infant's EEG data was excluded due to excessive artifacts identified during the artifact rejection processing step.

Table 1. Descriptive Statistics and Split-half Reliabilities of Infant Sustained Attention Measures at Short and Long Timescales

	Short Timescale (1-second Epochs)				Long Timescale (10-second Epochs)			
Measure	*M*	*SD*	Range	Split-half Reliability[a]	*M*	*SD*	Range	Split-half Reliability[a]
Mean looking proportion	.50	.20	.04–.87	.87	.50	.20	.05–.87	.68
Mean heart rate (beats/min)	134.40	10.17	110.90–164.54	.87	134.64	9.61	115.93–164.54	.89
Mean theta power (μV^2)	13.91	5.34	5.89–29.55	.83	13.48	5.11	5.54–28.26	.82
Mean alpha power (μV^2)	4.72	2.11	1.79–12.56	.84	4.63	2.09	1.70–12.30	.91

Note. [a]Split-half reliability was assessed by correlating odd and even epochs and applying the Spearman-Brown correction.

Table 2. Correlations Between Infant Sustained Attention Measures at Short and Long Timescales

Measure	1	2	3	4
1. Looking proportion	—	−.27***	.07	.17**
		[−.37, −.16]	[−.08, .21]	[.07, .28]
2. Heart rate	−.18***	—	.14*	.06
	[−.25, −.11]		[.02, .26]	[−.03, .14]
3. Theta power	.05	.10**	—	.47***
	[−.04, .14]	[.04, .16]		[.41, .54]
4. Alpha power	.08**	.05	.40***	—
	[.03, .13]	[−.00, .09]	[.36, .44]	

Note. Mean Spearman's correlations between infant sustained attention measures at short (1-second epochs) and long (10-second epochs) timescales are shown below and above the diagonal, respectively. Values in square brackets indicate 95% confidence intervals. The underlined correlation is not statistically significant after correcting for multiple comparisons using the Holm-Bonferroni correction.

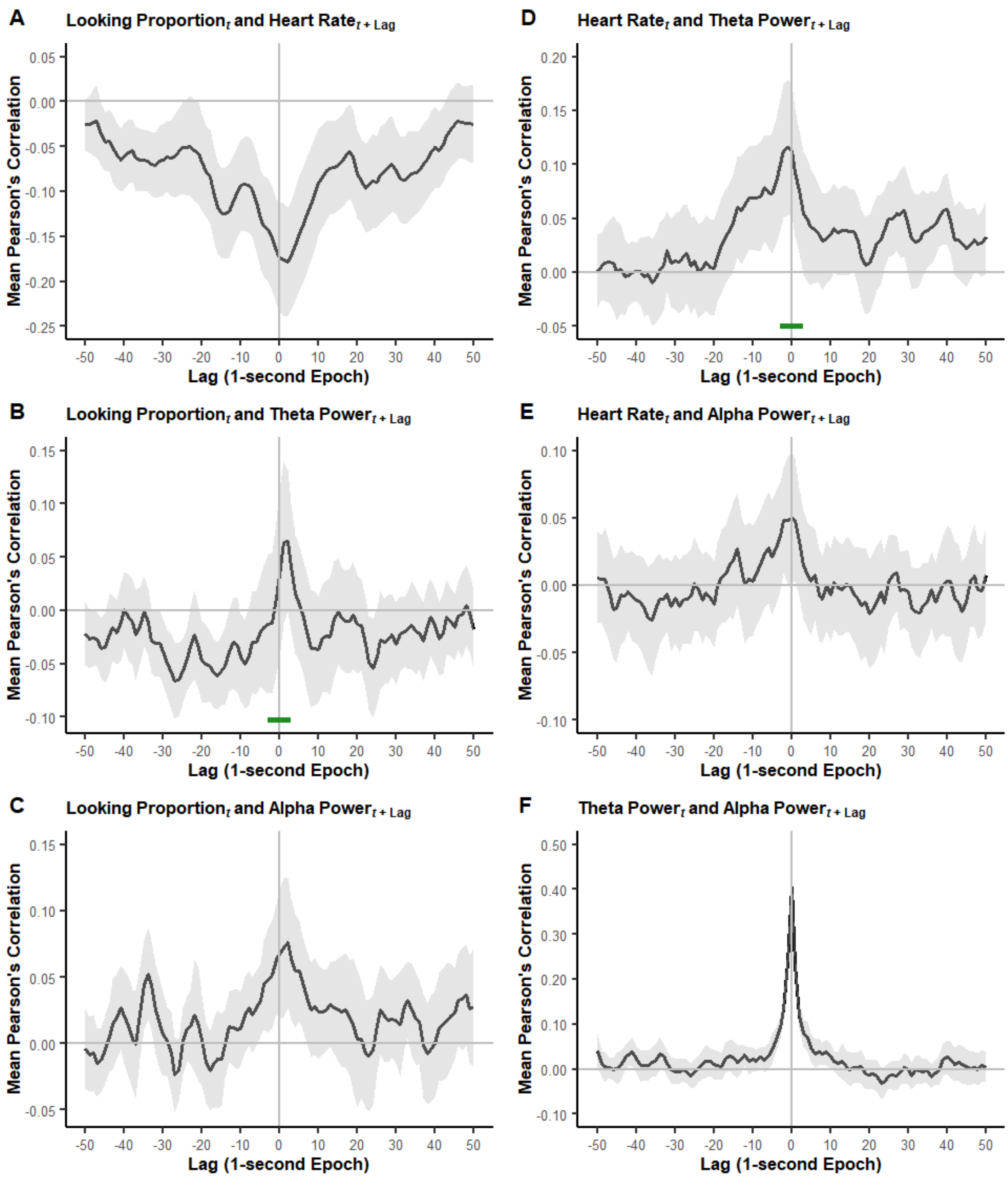
*p < .05. **p < .01. ***p < .001.

We observed three patterns of findings for the associations between specific pairs of short-timescale measures. First, as expected, looking proportion was negatively related to HR, even after correcting for multiple comparisons (Holm-Bonferroni p < .001). Second, while in the predicted direction, looking proportion and theta power (Holm-Bonferroni p = .268) as well as HR and alpha power (Holm-Bonferroni p = .111) were not statistically related. Third, contrary to predictions of negative associations, we found positive associations between looking proportion and alpha power (Holm-Bonferroni p = .011), HR and theta power (Holm-Bonferroni p = .011), and theta power and alpha power (Holm-Bonferroni p < .001). Similar results were obtained for long-timescale measures, except that the positive association between HR and theta power was no longer statistically significant after correcting for multiple comparisons (Holm-Bonferroni p = .060).

The above covariation analyses included all epochs where looking proportion in individual epochs ranged from .00 to 1.00. This heterogeneity in looking proportion might have potentially moderated associations between infant sustained attention measures and contributed to some of the unexpected findings; for example, predicted associations might only emerge when infants were reasonably attentive. Therefore, we conducted supplemental analyses where behavioral and psychophysiological data were restricted to epochs where infants spent a substantial proportion of time looking at the computer screen (i.e., looking proportion ≥ .75). These supplemental analyses yielded largely similar results (see Appendix), suggesting that the observed associations between infant sustained attention measures, including the unexpected ones, are likely robust across the entire continuum of non-looking to looking behaviors.

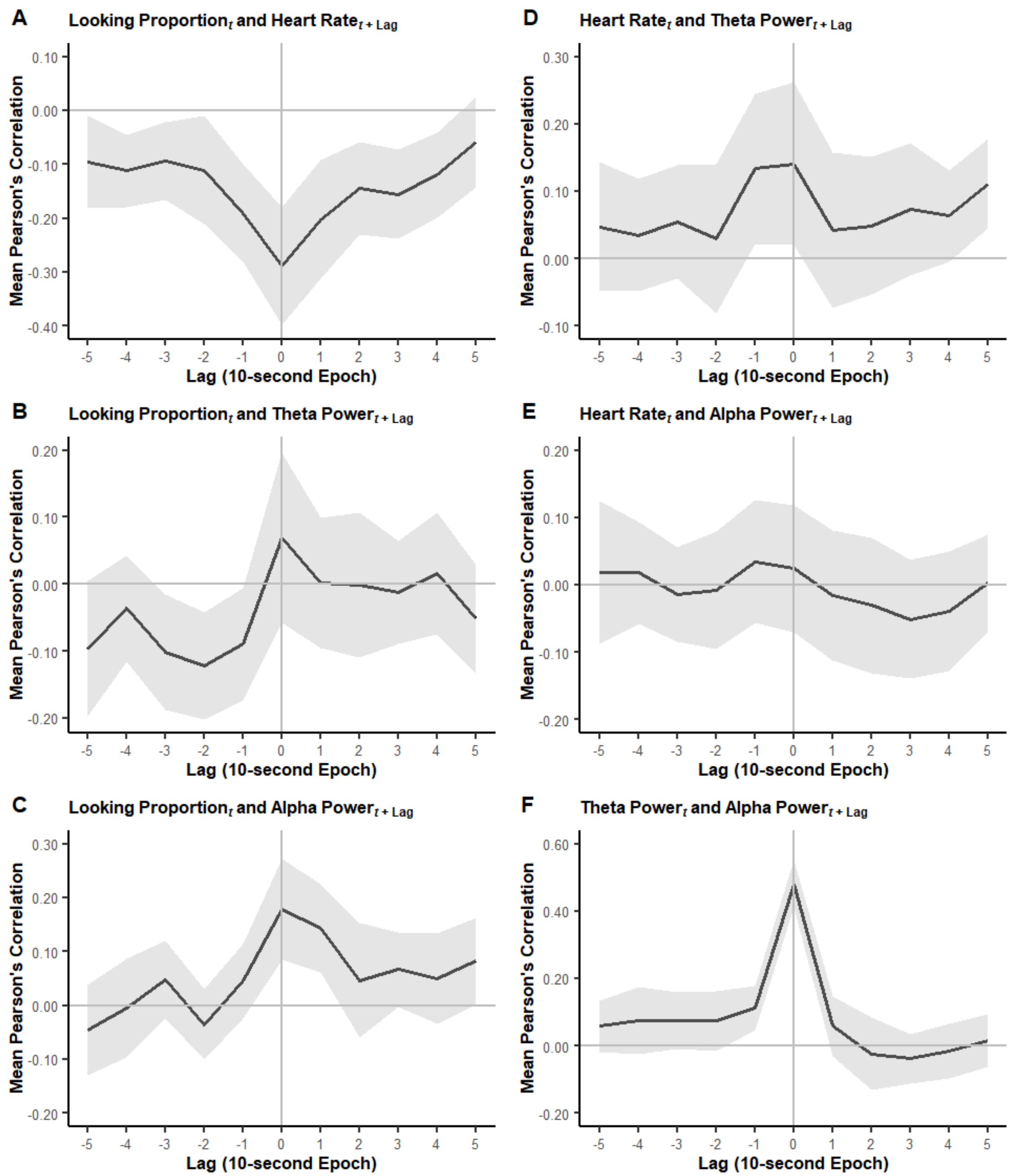
Synchronicity of Infant Sustained Attention Measures

Figures 1 and 2 depict cross-correlations for each pair of infant sustained attention measures at the short and long timescales, respectively. Several asynchronous temporal relationships were present for short-timescale measures. Looking proportion exhibited asynchronous relationships with HR, theta power, and alpha power, as indicated by peak cross-correlations occurring at a non-zero time lag of +2 (HR: peak $r = -.18$, 95% CI = [−.24, −.12]; theta power: peak $r = .07$, 95% CI = [−.00, .13]; alpha power: peak $r = .08$, 95% CI = [.03, .13]). In other words, looking proportion preceded each of these psychophysiological infant sustained attention measures by two seconds. The significant asymmetry around the time lag of zero further supported the asynchronous relationship between looking proportion and theta power. Specifically, cross-correlations at positive time lags between +1 and +3 were significantly greater than those at corresponding negative time lags (Wilcoxon signed rank *S*s > 142, *p*s < .006), suggesting that looking proportion reliably preceded theta power by up to three seconds. However, for the asynchronous relationships between looking proportion and HR as well as between looking proportion and alpha power, the asymmetry around the time lag of zero was already not statistically significant at the time lag of ±1 (HR: Wilcoxon signed rank $S = 46$, $p = .398$; alpha power: Wilcoxon signed rank $S = 22$, $p = .688$).



Note. Within each panel, the black line represents cross-correlations between the two short-timescale infant sustained attention measures as a function of time lag (i.e., Pearson's correlations between the standardized time series of the two measures, with the time series of the second measure systematically displaced backward and forward in increments of one-second epochs relative to the time series of the first measure). The gray shaded region represents 95% confidence intervals. A peak cross-correlation that occurs at a non-zero time lag indicates that the two measures are asynchronous; the first measure temporally precedes the second measure if the peak cross-correlation occurs at a positive time lag; the second measure temporally precedes the first measure if the peak cross-correlation occurs at a negative time lag. Green lines in panels B and D indicate time windows of significant asymmetry around the time lag of zero, as assessed by Wilcoxon signed rank tests on cross-correlations at corresponding negative and positive time lags (i.e., ±1, ±2, …).

Figure 1. Cross-correlations between Infant Sustained Attention Measures at Short Timescale.



Note. Within each panel, the black line represents cross-correlations between the two long-timescale infant sustained attention measures as a function of time lag (i.e., Pearson's correlations between the standardized time series of the two measures, with the time series of the second measure systematically displaced backward and forward in increments of 10-second epochs relative to the time series of the first measure). The gray shaded region represents 95% confidence intervals. A peak cross-correlation that occurs at a non-zero time lag indicates that the two measures are asynchronous; the first measure temporally precedes the second measure if the peak cross-correlation occurs at a positive time lag; the second measure temporally precedes the first measure if the peak cross-correlation occurs at a negative time lag.

Figure 2. Cross-correlations between Infant Sustained Attention Measures at Long Timescale.

Additionally, the temporal relationship between HR and theta power was asynchronous, such that its peak cross-correlation (peak r = .12, 95% CI = [.05, .18]) occurred at the time lag of −1, indicating that theta power preceded HR by a second. In fact, cross-correlations at negative time lags between −1 and −3 were significantly greater than those at corresponding positive time lags (Wilcoxon signed rank Ss > 118, ps < .025), offering support that theta power reliably preceded HR by up to three seconds. On the contrary, HR and alpha power were synchronous with its peak cross-correlation (peak r = .05, 95% CI = [.00, .10]) occurring at the time lag of zero; similarly, theta power and alpha power were synchronous (peak r = .40, 95% CI = [.36, .45]). Collectively, these synchronicity analyses of short-timescale measures highlight a plausible cascading pattern of infant sustained attention across behavioral and physiological systems, with looking behaviors leading to neural activity (i.e., theta oscillations) followed by cardiac responses (i.e., HR deceleration).

At the long timescale, infant sustained attention measures largely exhibited synchronous temporal relationships. As an exception, HR and alpha power were asynchronous with its peak cross-correlation (peak r = .03, 95% CI = [−.06, .13]) occurring at the time lag of −1; nevertheless, the asymmetry around the time lag of zero was not statistically significant (Wilcoxon signed rank S = 43, p = .430).

DISCUSSION

Sustained attention is multifaceted and undergoes rapid development during infancy (Colombo, 2001; Courage & Richards, 2020; Ruff, 1990). A multimodal measurement approach, which incorporates several behavioral and psychophysiological measures of infant sustained attention, may clarify how abnormal patterns of sustained attention emerge in early development. Researchers and practitioners may leverage such knowledge to improve prevention and early intervention efforts aimed at ameliorating attentional difficulties in childhood psychological disorders. Understanding the temporal dimension of infant sustained attention is critical for enhancing the way we measure and conceptualize it. The present study investigated two temporal aspects of infant sustained attention: (1) whether associations among infant sustained attention measures are similar or different across short and long timescales; and (2) whether specific infant sustained attention measures temporally precede other measures. To our knowledge, this study is the first to examine the covariation and synchronicity of behavioral, cardiac, and neural measures of infant sustained attention at short and long timescales, informing the biobehavioral processes underlying sustained attention during a critical developmental period. Our results indicated that association patterns among infant sustained attention measures were largely similar across short and long timescales. Additionally, short-timescale infant sustained attention measures exhibited asynchronous temporal relationships, such that looking behaviors preceded neural oscillations that in turn preceded cardiac responses. These findings underscore the importance of considering the temporal dimension when measuring infant sustained attention. Further investigation and validation of our preliminary findings may potentially optimize the identification of treatment targets for sustained attention abnormalities in young children.

Similar Associations of Infant Sustained Attention Measures at Short and Long Timescales

Our first major finding was that associations between corresponding pairs of infant sustained attention measures at short and long timescales were similar in both direction and magnitude. This finding suggests that infant sustained attention measures at both timescales of 1- and 10-second epochs are probably assessing relatively phasic processes. Yet, it is also possible that infant sustained attention may operate similarly across the phasic-to-tonic continuum

(Aston-Jones & Cohen, 2005), if the timescale of 10-second epochs represents relatively tonic processes. Additional research that extends this initial investigation by examining a broader range of timescales will likely clarify details of phasic and tonic activity of infant sustained attention. Critically, the similar associations across short and long timescales raise the possibility of using long-timescale infant sustained attention measures instead of short-timescale measures that have been more widely employed thus far. In other words, researchers and practitioners may flexibly use short- and long-timescale measures, which may be especially practical when assessing infant sustained attention in naturalistic contexts. Indeed, this potential of leveraging long-timescale measures of infant sustained attention is further supported by our finding of larger associations among long-timescale measures than those among corresponding short-timescale measures.

Nevertheless, it is important to recognize that looking proportion had a lower but moderate split-half reliability at the long timescale, which may reflect the nature of infants' looking behaviors and the approach used to quantify them in the present study. The duration of an infant looking episode typically ranges from a few to tens of seconds (Richards & Casey, 1992). Given that split-half reliability was assessed using odd and even epochs, relatively frequent changes between looking and non-looking episodes in the order of a few seconds may have contributed to the lower split-half reliability of looking proportion for 10-second epochs. Additionally, infant's looking behaviors were originally coded in a dichotomized manner (i.e., looking or not looking at the computer screen). Therefore, future work may benefit from a more nuanced quantification of looking behaviors, including using more sensitive metrics from eye tracking and pupillometry such as dwell time in specific areas of interest, fixation duration, and pupil diameter (Eckstein et al., 2017; Hepach & Westermann, 2016; Holmqvist et al., 2011). Notably, some of these looking measures may even better differentiate between phasic and tonic changes that will likely further inform the temporal dimension of infant sustained attention (Granholm & Steinhauer, 2004; Hepach & Westermann, 2016).

Notably, consistent with an extensive literature documenting that HR is decelerated during infant sustained attention (Reynolds & Richards, 2008; Richards, 2008), we found that greater looking proportion corresponded to lower HR at both short and long timescales. This result reinforces the established use of HR as a robust psychophysiological measure of infant sustained attention, offering support for its use in translational applications involving young children. However, we obtained unexpected or non-significant associations between neural measures (i.e., theta power and alpha power) and both looking proportion and HR. Several potential explanations may account for our unexpected findings. First, infant EEG data typically include substantial and heterogeneous artifacts, which may lead to resultant data with relatively poor signal-to-noise ratios (Hoehl & Wahl, 2012). Indeed, when conducting artifact rejection in the present study, we observed a wide range of EEG data quality, which might have negatively affected the associations involving theta power and alpha power. To minimize the impact of these artifacts, future studies may leverage emerging automated processing pipelines for developmental EEG data with substantial artifacts (Gabard-Durnam et al., 2018). Nevertheless, this possibility is unlikely to explain the significant, unexpected associations (e.g., positive associations between theta power and alpha power at both short and long timescales). Second, EEG oscillations may have multiple functional significances. For example, while increased theta power generally indexes greater sustained attention, it has also been linked to attentional fatigue (Clayton et al., 2015). In other words, instead of our original predictions that greater theta power would correspond to lower HR and alpha power, it is plausible that theta power is positively related to both HR and alpha power, which coincides with observed associations. This possibility is further bolstered after considering our study protocol, where the passive, free-viewing task in the present study was typically the last activity that infants participated in at the end of a two- to three-hour session. Finally, while there is general consensus that infant alpha power falls in the 6–9 Hz range, relatively limited work has examined the frequency range of infant theta power (Bell & Cuevas, 2012). Additional work is needed to explore how best to define infant theta frequency band, especially in relation to the functional significance of indexing sustained attention.

Asynchronous Relationships of Infant Sustained Attention Measures at Short Timescale

Our second major finding was that several short-timescale infant sustained attention measures displayed asynchronous temporal relationships, with peak cross-correlations occurring at non-zero time lags. Additionally, based on significant asymmetry around the time lag of zero, looking proportion reliably preceded theta power by up to three seconds and theta power reliably preceded HR by up to three seconds. Collectively, these findings indicate that infant sustained attention may follow a temporal sequence of changes across behavioral, neural, and cardiac systems. Focusing on infant sustained attention, cross-correlational analyses demonstrated that looking behaviors likely initiate the cascading pattern and engage neural and cardiac physiological systems involved in sustained attentional processing. Among psychophysiological measures, the finding that theta power temporally precedes HR is consistent with general physiological principles that neural and cardiac processes are relatively fast and slow, respectively.

From a translational perspective, these findings may inform how we can optimize clinical interventions for young children with abnormalities in sustained attention. For example, inconsistencies in joint attention and deficits in social attention are implicated in ASD and several treatments have been developed to specifically target these attentional challenges (Alvares et al., 2019; Dawson et al., 2012; Jones & Carr, 2004; Murza et al., 2016). Our findings support the central role of directly intervening on looking behaviors as a core step in initiating sustained attention processes. Additionally, such intervention efforts may benefit from the complementary use of psychophysiological measures, which are likely more sensitive than behavioral measures and have thus been increasingly used in clinical trials to monitor treatment progress and to measure clinical outcomes. Specifically, our findings on the temporal relationships among infant sustained attention measures suggest that changes in looking behaviors will be followed by changes in theta power within three seconds, which in turn will be accompanied by HR deceleration within three seconds. Therefore, if a multimodal measurement approach is implemented in clinical settings, the efficacy of behavioral interventions may be directly tracked through online physiological signals (i.e., corresponding changes in theta power and HR after changes in looking behaviors), enabling rapid, personalized enhancements of clinical interventions.

On the other hand, long-timescale infant sustained attention measures largely exhibited synchronous temporal relationships, with peak cross-correlations occurring at time lags of zero. These synchronous temporal relationships at the long timescale likely reflect that looking behaviors, HR, theta power, and alpha power are all relatively fast-changing processes and generally do not have time lags in the order of tens of seconds between any two measures. More broadly, our analyses of temporal relationships highlight the importance of understanding typical timecourses as well as phasic and tonic activity of individual infant sustained attention measures, which will critically inform the design of research studies and intervention programs.

Limitations and Future Directions

Further research is needed to address the present study's limitations. Our sample of infants was relatively small and of limited sociodemographic diversity; most infants were from White, educated, and well-resourced families. Replicating our findings in larger and more diverse samples will be instrumental for future validation and translational efforts of using multiple measures to assess and intervene on infant sustained attention. Additionally, the present study used a passive, free-viewing task that was of moderate duration (i.e., 6 minutes and 30 seconds), which limited the range of short to long timescales that we could examine; as a contrast, Wass and colleagues (2015) investigated timescales ranging from 1 to 60 seconds with a task battery that lasted 20 minutes. Future work incorporating multiple measures of infant sustained attention should design specific tasks and stimuli that will optimize the measurement of infant sustained attention across a broad range of timescales. Ideally, the selection of these timescales should be informed by systems neuroscience in order to better capture the full phasic-to-tonic continuum of individual measures.

More advanced methodological approaches may further extend our initial findings. The covariation analyses in the present study focused on bivariate associations; similarly, although examining temporal relationships yielded some additional insights into the temporal dynamics of infant sustained attention measures, the current synchronicity investigations were limited to bivariate analyses. Multivariate statistical models may be considered in future work, especially given that infant sustained attention could be conceptualized as a multimodal, coordinated system with multidirectional influences across behavioral and physiological components (Richards, 2008). Notably, there is an emerging literature that employs a dynamic systems approach to model affective and cognitive processes over developmental periods from early childhood to adolescence (Thelen & Smith, 1994; Yang et al., 2019). With a dynamic systems approach, moment-to-moment changes across behavioral, cardiac, and neural measures as well as biologically-informed feedback processes (e.g., cardiac–neural communication loops) may better characterize the fluctuations of infant sustained attention across time. Relatedly, our covariation and synchronicity analyses emphasized mean associations and cross-correlations across infants. In other words, we did not explicitly model the observed variability in associations and cross-correlations between pairs of infant sustained attention measures. Additional research on these substantial interindividual differences may potentially reveal subsets of underlying patterns and dynamics of infant sustained attention, including plausible variations in processes that precede and follow sustained attention episodes. Furthermore, such individual differences may partially account for the heterogeneity of symptoms within individual childhood psychological disorders, which may in turn facilitate more personalized clinical interventions.

Given the potential translational impact of this line of research, it will be valuable to critically consider the differential impact of lab-based and naturalistic paradigms on the measurement of infant sustained attention. Lab-based tasks are typically structured and specifically programmed to elicit sustained attention in a relatively controlled manner. In contrast, sustained attention processes in real-world contexts are largely spontaneous and guided by relatively unstructured activities (e.g., free play and parent-child interactions; Brandes-Aitken, 2019). These methodological distinctions highlight the need for investigating infant sustained attention in more naturalistic contexts, which may yield different temporal associations and relationships among measures. Relatedly, it will be vital to extend our preliminary work to pediatric clinical populations with abnormalities in sustained attention. Given that different childhood psychological disorders may have distinct profiles of attentional difficulties, it is plausible that covariation and synchronicity of sustained attention measures may differ across child psychopathology. Therefore, it will be critical to characterize the temporal aspects of sustained attention for individual childhood psychological disorders. This work underscores the importance of studying the temporal dimension of infant sustained attention, which will enhance how we measure and conceptualize it from a multimodal biobehavioral perspective. Ultimately, this work may enhance prevention and early intervention efforts aimed at promoting optimal outcomes for young children with abnormalities in sustained attention.

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APPENDIX

Correlations Between Infant Sustained Attention Measures at Short and Long Timescales for Looking Epochs

Measure	1	2	3	4
1. Looking proportion	—	−.26***	−.06	.10
		[−.37, −.16]	[−.23, .12]	[−.06, .25]
2. Heart rate	−.11**	—	.21*	−.00
	[−.20, −.03]		[.03, .40]	[−.17, .17]
3. Theta power	−.07*	.11**	—	.39***
	[−.13, −.01]	[.04, .19]		[.23, .54]
4. Alpha power	.00	.01	.35***	—
	[−.05, .05]	[−.05, .07]	[.31, .39]	

Note. Behavioral, ECG, and EEG data were restricted to looking epochs (i.e., infants were assessed to be looking at the computer screen). Mean Spearman's correlations between infant sustained attention measures at short (1-second epochs) and long (10-second epochs) timescales are shown below and above the diagonal, respectively. Values in square brackets indicate 95% confidence intervals. Underlined correlations are not statistically significant after correcting for multiple comparisons using the Holm-Bonferroni correction.

*p < .05. **p < .01. ***p < .001.