Received: 26 October 2018 | Revised: 15 April 2019 | Accepted: 16 April 2019

DOI: 10.1002/dev.21867

RESEARCH ARTICLE

Developmental Psychobiology WILEY

Mapping cortical rhythms to infant behavioral tendencies via baseline EEG and parent-report

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Abstract

An important goal of developmental science is to understand how the early organization of the brain and behavioral tendencies are interconnected. A foundational step in pursuit of this goal is to identify brain-behavior relations. Much progress has been made identifying such relations during infancy by linking baseline electroencephalography (EEG) activity to infants' performance in lab-based measures of socio-emotional and cognitive development. Parent-report represents another resource in expanding our understanding to infants' behavioral tendencies in their natural environment. The current study explored how parent-report of 6- to 12-month-old (N = 53) infants' attention and regulatory abilities relates to cortical activity. The results confirmed one key hypothesis that lower levels of theta and higher levels of beta and gamma over the frontal region would be related to infants' attentional abilities. These results are consistent with the extant baseline EEG literature. Cuddliness was robustly related to higher levels of theta and lower levels of beta over the posterior, likely reflecting infants' tendency to use another person to self-regulate. Our results indicate links between these cortical rhythms and attention and regulatory processes have infant origins. Our results indicate furture research investigating brain-behavior relations using parent-report is warranted.

KEYWORDS

infant baseline EEG, infant cognitive development, infant temperament

1 | INTRODUCTION

Identifying connections between the emerging organization of the brain and behavioral tendencies is an important endeavor in developmental science. This knowledge will advance our understanding of human development and may be leveraged to promote specific patterns of neuronal organization associated with positive developmental outcomes. Electroencephalography (EEG) has provided valuable insight into how cortical rhythms are related to socio-emotional and cognitive development during infancy. However, the practical constraints of collecting EEG data from infants across a wide array of contexts has limited our knowledge-base of brain-behavior relations to those captured from a snapshot of infant behavior in laboratory paradigms (e.g., Bell, 2001; Orekhova, Stroganova, Posikera, & Elam, 2006). Parent-report represents a viable resource to broaden our understanding of brain-behavior relations in infancy, as caregivers are able to observe infants in a variety of contexts, including those requiring regulation. Only a few studies have relied on parent-report to study brain-behavior relations, and are limited to a single neural signature derived from one cortical rhythm. The current research was designed to probe the use of parent-report to identify a spectrum of brain-behavior connections. We focused on parent-report of attention and regulatory capacity because these processes have known links to cortical rhythms in childhood and adulthood, likely to have origins in infancy.

Baseline EEG is commonly used to examine brain-behavior relations across the lifespan. Baseline EEG is a recording of the brain's electrocortical rhythms at a time when no assigned task is being performed and provides a window into the organization of the brain, generally thought to be reflective of the individual's trait-like tendencies. Baseline EEG is attained from infants in a calm, alert state while they watch a dynamic display (i.e., a video) or a live actor manipulate an object (e.g., Bell & Fox, 1992; Benasich, Gou, Choudhury, & Harris, 2008; Marshall, Bar-Haim, & Fox, 2002). There is considerable variability in the duration of baseline EEG recorded from infants, ranging from 1–5 min (e.g., Atzaba-Poria, Deckard, & Bell, 2017; Benasich et al., 2008; Brooker, Canen, Davidson, & Goldsmith, 2017; Levin, Varcin, O'Leary, Tager-Flusberg, & Nelson, 2017; MacNeill, Ram, Bell, Fox, & Pérez-Edgar, 2018; Mize & Jones, 2012; St. John, 2016; Tomalski et al., 2013; Wolfe & Bell, 2007). EEG provides a measure of the synchronized firing of neuronal ensembles across a range of frequencies (e.g., 3–50 Hz), referred to as the EEG power spectrum. The power spectrum is normally divided into bands that reflect different cortical rhythms, including theta (4–8 Hz), alpha (8–13 Hz), beta (13–30 Hz), and gamma (30–50 Hz). The speed of cortical rhythms is slower during infancy than childhood and adulthood. For infants, theta is typically defined as 3–6 Hz and alpha as 6–9 Hz. Beta is perhaps the least studied cortical rhythm during infancy and the least consistently defined, but, in adults, it is generally defined as the frequencies between alpha and gamma (for a review, see Anderson & Perone, 2018). Gamma is consistently identified in the 30–50 Hz frequency range across the lifespan.

Much of what is known about brain-behavior relations during infancy is in the 6–9 Hz alpha band (Bell & Fox, 1992; Fox, Henderson, Rubin, Calkins, & Schmidt, 2001; MacNeill et al., 2018; Wolfe & Bell, 2007). Alpha is associated with basic cognitive processes during infancy and predictive of long-term outcomes. For example, alpha is associated with working memory for hiding events in the Piagetian A-not-B task (Bell, 2001; Bell & Fox, 1992; MacNeill et al., 2018) and predicts executive function at 4 years of age and following the kindergarten year (Kraybill & Bell, 2013; see also, Cuevas, Hubble, & Bell, 2012; Kühn-Popp, Kristen, Paulus, Meinhardt, & Sodian, 2016; Wolfe & Bell, 2007).

The few studies that have used parent-report to identify brain-behavior relations have focused on the link between approach and avoidance motivation with frontal alpha asymmetry (e.g., Diaz & Bell, 2012; LoBue, Coan, Thrasher, & DeLoache, 2011; Lusby, Goodman, Yeung, Bell, & Stowe, 2016), which reflects the degree to which alpha is left or right lateralized at homologous frontal sites. Frontal alpha asymmetry has been linked with parent-reported dimensions reflective of approach and avoidance tendencies, such as fearfulness, as well as negative affectivity more broadly (Lusby et al., 2016). Parent-report of attention and regulatory aspects of temperament has been largely neglected in comparison, yet is critical to consider in infancy, as attention-based regulation begins to emerge. Early attentional attributes (e.g., duration of orienting) have important implications for later self-regulation, social competence, and adjustment (Ruff & Rothbart, 1996), and parents have an opportunity to observe these in everyday situations. Infants' attention and regulatory abilities in infancy are associated with later effortful control, dependent on executive functions "coming online" later in childhood (Gartstein, Bridgett, Young, Panksepp, & Power, 2013; Putnam, Rothbart, & Gartstein, 2008), These abilities play a protective role with respect to early behavior problems (in the context of high levels of distress-proneness; Gartstein, Putnam, & Rothbart, 2012), as well as school readiness (Gartstein, Putnam, & Kliewer, 2016). Understanding this emerging regulation in everyday contexts on the neuro-behavioral level requires considering multiple cortical rhythms, addressed in the present investigation.

Infants' attention and regulatory abilities are likely linked to theta and beta activity, similar to relations observed later in life. A number of studies with children and adults have shown that top-down cognitive processes involved in regulating thought and emotion—one broad definition of executive function (Zelazo, 2015; Zelazo & Carlson, 2012)—are related to baseline theta and beta activity. In adults, lower levels of theta and higher levels of beta (sometimes expressed as a ratio) is associated with less risk taking behavior (Massar, Kenemans, & Schutter, 2014; Schutter & Van Honk, 2005) response inhibition to fearful faces in an emotional variant of the Go NoGo response inhibition task (Putman, van Peer, Maimari, & van der Werff, 2010). In children, lower levels of theta and higher levels of beta are associated with better performance on a standardized measures of executive function (Perone, Palanisamy, & Carlson, 2018). High levels of theta and lower levels of beta have also been observed in children with Attention Deficit Disorder with Hyperactivity (ADHD; Lubar, 1991; for a review, see Arns, Conners, & Kraemer, 2013) and young orphans (Marshall, Fox, & the BEIP Core Group, 2004), who are more likely to develop into children described as hyperactive and inattentive (Audet & Le Mare, 2011; Bruce, Tarullo, & Gunnar, 2009).

Infants' attention and regulatory abilities are also likely linked to gamma activity. A growing body of evidence indicates that baseline gamma is associated with attention and executive function in toddlers and pre-school age children (e.g., Gou, Choudhury, & Benasich, 2011; Tomalski et al., 2013; Tarullo et al., 2017). For example, Benasich et al. (2008) found that higher frontal gamma was associated with better performance on standardized measures of attention and inhibitory control at 24 months of age. Attention and regulatory processes during infancy are, of course, different than those studied in children and adults (e.g., rely more on parental intervention, such as soothing efforts and physical proximity, or focusing on an object for extended periods of time). The current study will shed light on whether attention and regulatory processes are also related to theta, beta, and gamma during infancy.

Information about infants' attention and regulatory abilities can be gleaned from the Infant Behavior Questionnaire-Revised (IBQ-R; Gartstein & Rothbart, 2003). The IBQ-R is a parent-report instrument based on Rothbart's psychobiological model of temperament. In Rothbart's model, individual differences in early reactivity and regulation are viewed as serving a critical role in shaping the child's foundational experiences with their environment, including interactions with parents, that go on to have cascading effects across the lifespan (Rothbart, 2011). Parents respond to questions about their infant's behaviors in everyday reactivity and regulation eliciting contexts in the recent past. Responses to items are grouped into 14 fine-grained subscales, which have been factor-analyzed to produce three overarching factors, one of which, labeled as orienting/regulatory capacity, reflects emerging attentional and regulatory abilities (Gartstein & Rothbart, 2003). The orienting/regulatory capacity factor is made up of four subscales, including duration of orienting (e.g., attention to an object for extended periods of time), low intensity pleasure (e.g., amount of pleasure related to low levels of intensity), soothability (e.g., reduction in distress by parental intervention), and cuddliness (e.g., expression of enjoyment while being held by a caregiver). The latter two reflect the fact that regulation in infancy is often externally driven, to a large extent depending on parental interventions (Kopp, 1989). Duration of orienting represents the early appearing attentional skill anchoring emerging self-regulation, and its parallel form prominent later in childhood—attentional focusing serves the same function for the effortful control factor (Rothbart, Ahadi, Hershey, & Fisher, 2001) widely defined as the ability to suppress a prepotent response in favor of a more adaptive novel one (Kochanska, Murray, & Harlan, 2000), reflecting self-regulation starting in the toddler period. Low intensity pleasure complements these three scales in comprising orienting/regulatory capacity, similar to the effortful control factor, which also includes this fine-grained dimension (Rothbart et al., 2001). It is thought that the ability to enjoy calm activities with subtle stimulation reflects effective regulation on the part of the infant or child. Although factor scores from the IBQ-R have been used in many studies, the fine-grained IBQ-R subscales are uniquely predictive (e.g., Lengua, 2006; Oldehinkel, Hartman, De Winter, Veenstra, & Ormel, 2004; Willoughby, Waschbusch, Moore, & Propper, 2011), contribute to temperament types (Gartstein et al., 2017), and exhibit their own growth patterns (Gartstein, Hancock, & Iverson, 2018). Thus, we focused on the fine-grained subscales here.

1.1 | The current study

The goal of the current study was to probe the use of parent-report to identify brain-behavior relations during infancy. We recorded baseline EEG from 6- to 12-month-old infants and acquired parent-report of their infant's emerging attention and regulatory abilities via the IBQ-R. We chose this age range because the IBQ-R is well-suited for infants in this range and orienting/regulatory capacity at the end of the first year predicts executive control processes in toddlerhood (Gartstein et al., 2013). We hypothesized parent-report of infants' attention in their natural environment (i.e., duration of orienting) to be related to lower levels of theta and higher levels of beta and gamma over the frontal region. This expectation is based on prior studies showing that attention and executive control processes are linked to cortical rhythms in this fashion in children and adults (e.g., Perone, Palanisamy, et al., 2018; Schutter & Van Honk, 2005). Furthermore, prior studies have shown lab-based measures of looking during infancy predict executive function in early childhood (Cuevas & Bell, 2014). Thus, duration of orienting might reflect the origins of basic higher level processes linked to these cortical rhythms. Our examination of soothability, low intensity pleasure, and cuddliness were largely exploratory, yet all of these dimensions are regulatory in nature, contributing to infants' ability to manage their level of arousal and modulate reactivity, and thus were expected to be linked to theta, beta, and gamma. This research represents an important step toward integrating parent-report in the study of brain-behavior relations during infancy and will expand our understanding of links between cortical rhythms and regulatory processes in different development periods.

2 | METHOD

2.1 | Participants

Fifty-three 6- to 12-month-old infants participated in this study (M = 8.43 months, SD = 1.51 months, 31 girls). Twenty-six additional infants participated but were excluded because parents did not complete the IBQ-R (n = 6), equipment malfunction (n = 2), fussiness (n = 1), uninterpretable EEG (n = 2), or missing data due to experimenter/computer error (n = 15). Mothers with infants were recruited via social media advertisements, local birth centers/parent-infant programs, and pamphlets distributed in locations frequented by families with infants in the Pullman, WA and Moscow, ID communities. Families with children with significant medical or birth complications, including infants identified as born preterm (<37 weeks of gestation) and/or developmentally delayed/disabled, were excluded, as these conditions are expected to result in altered patterns of temperament development and EEG recordings. Non-English speaking caregivers were also excluded, as instruments utilized for a larger project families participated in are not available in languages other than English. All families received an infant T-shirt (about $10 value) incentive at the end of their laboratory visit as a thank-you for participation in the study. Participating families were largely Caucasian (90.1%). Mothers were primarily married (90.9%), and educated (M = 16.01 years, SD = 2.04 years), with family income above $30,001 (81.1%).

2.2 | Procedure

Mothers were asked to complete the IBQ-R within 2 weeks of their laboratory visit. The IBQ-R consists of 191 items resulting in 14 subscales. Individual items are rated on a 7-point scale reflecting the frequency of occurrence of different manifestations of temperament in the past week. In developing the IBQ-R, an emphasis was placed on maximizing validity of parent-report. Although questions have been raised about parents' ability to report regarding their children's attributes, careful construction of questions, a short-term time frame, and avoiding items that compare children, mitigate these concerns. IBQ-R subscales have been consistently demonstrated as reliable and valid (Gartstein, Bridgett, & Low, 2012). Reliability of the IBQ-R has been supported for mothers and fathers, as well as samples from different cultures, with Cronbach's alphas ranging from 0.77 to 0.96 (Gartstein, Knyazev, & Slobodskaya, 2005; Gartstein & Rothbart, 2003) with support for predictive and construct validity of this instrument (Gartstein & Bateman, 2008; Gartstein et al., 2010; Gartstein & Marmion, 2008). Internal consistency was also demonstrated for the present sample: subscale $\alpha = 0.73–0.90$, mean $\alpha = 0.82$.

We examined relations between the four orienting/regulatory capacity subscales identified by Gartstein and Rothbart (2003). Duration of orienting refers to attention to and/or interaction with a single object for extended periods of time and is measured from questions such as, "How often during the last week did the baby stare at a mobile, crib bumper or picture for 5 min or longer?" Low intensity pleasure is defined as the amount of pleasure or enjoyment related to low stimulus intensity, rate, complexity, novelty and incongruity and is measured from questions such as, "When playing quietly with one of his/her favorite toys, how often did the baby show pleasure?" Cuddliness refers to expression of enjoyment and molding of the body to being held by a caregiver and is measured from questions such as, "When rocked or hugged, during the last week, how often did the baby seem to enjoy him/herself?" Soothability reflects the reduction of fussing, crying, or distress when soothing techniques are used by the caregiver. Soothability is measured from questions such as, "When patting or gently rubbing some part of the baby's body, how often did s/he soothe immediately?"

2.3 | EEG Recording

Infants were seated in a high-chair and an EEG cap (Cortech Solutions, Inc.; Wilmington, NC) was placed on their head. Figure 1 shows the 32 electrode sites EEG was recorded from. After the cap's placement, small amounts of electro-conductive gel were placed in each site. Individual "pin-type" electrodes (BioSemi - Cortech Solutions, Inc.; Wilmington, NC) were then "snapped" into each corresponding site. All of the EEG data were collected via the BioSemi Active Two amplifiers and initial screening via the BioSemi acquisition software at a sampling rate of 1,024 Hz. The EEG was referenced to Cz online. Baseline EEG was recorded for 1 min while infants watched a segment of *Baby Einstein*, *Baby Mozart* video, which depicts a number of colorful objects displayed as classical music is played through the duration of the video. The choice of 1 min duration of baseline EEG recording and the stimuli is consistent with many existing infant baseline EEG studies (Bell, 2001; Bell & Fox, 1992; Marshall et al., 2002; Morasch & Bell, 2011). An important advantage of a short recording duration is that a larger proportion of infants can provide useful data during most of it. However, longer durations could be useful in identifying infants who might be less attentive or restless during the recording. Mothers were instructed to limit their interaction with the infant to directing their infants' attention to the screen.

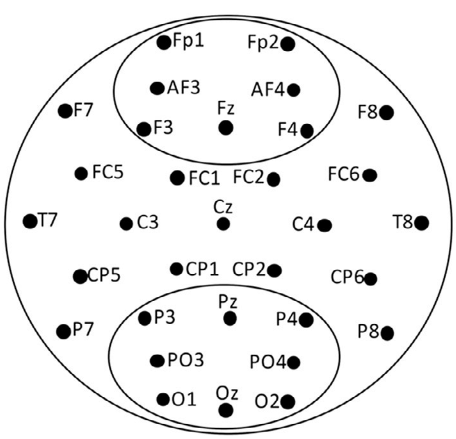

FIGURE 1 The 32 electrode sites with labels that the EEG was recorded from is shown. Circled electrodes show sites included in the frontal and posterior regions of interest

2.4 | EEG Processing

The EEG was processed in EEGLAB with ERPLAB and FieldTrip plugins. The continuous EEG was down-sampled to 256 Hz and a high-pass filter at 1 Hz and a 60 Hz notch filter was applied. Excessively noisy electrodes were removed and interpolated, and the EEG was then re-referenced to the average. The continuous EEG was divided into 1 s epochs with 75% overlap. Epochs were rejected if the absolute voltage of any electrode exceeded 100 microvolts for more than 100 ms. Time-frequency decomposition was performed on the remaining epochs using Fast Fourier Transformation (FFT) with a 1 s Hanning window for 3 to 50 Hz. The average proportion of epochs used for time-frequency decomposition was 88.62% (SD = 11.56%, *range* = 58.65%–100%). We focused on power at sites over frontal and posterior regions of interest (see Figure 1) which closely align with prior studies with infants and children (Benasich et al., 2008; Perone, Palanisamy, et al., 2018; Tomalski et al., 2013). The frontal region was of interest because prior studies have shown frontal activity during baseline is associated with attention and regulatory processes in children and adults (e.g., Benasich et al., 2008; Guo et al., 2011; Perone, Palanisamy, et al., 2018). We also included the posterior region because activity in frontal and posterior brain regions are associated with executive function across the lifespan (Buss & Spencer, 2017; Ezekiel, Bosma, & Morton, 2013; Hwang, Velanova, & Luna, 2010; for discussion, see Perone, Almy, & Zelazo, 2018) and some baseline EEG studies have reported links to executive function during childhood (Perone, Palanisamy, et al., 2018; Tarullo et al., 2017).

Relative power was calculated in theta (3–6 Hz), alpha (6–9 Hz), beta (9–30 Hz), and gamma (30–50 Hz) bands. In the infant baseline EEG literature, theta, alpha, and gamma have been consistently defined. Beta has been less consistently defined and sometimes involves sampling a select range of frequencies between alpha and gamma. Our choice to define beta as 9–30 Hz is based on its definition in adults which is typically defined as all the frequencies between alpha and gamma (for a review, see Engel & Fries, 2010) and a recent study probing links between baseline theta and beta with children as young as three years of age (Perone, Palanisamy, et al., 2018). Relative power in each band was calculated by dividing power within each band by total power. For example, theta was calculated as 3–6 Hz power divided by 3–50 Hz power. We chose relative power instead of absolute power because previous research suggests that it is more sensitive to age-related changes in EEG bands and normalizes inter-individual differences in skull thickness and other factors that may impact absolute power (Clarke, Barry, McCarthy, & Selikowitz, 2001; for a discussion, see Marshall et al., 2004), which may be particularly problematic given the wide array of ages used in the present study.

2.5 | Analytic strategy

Our analytic strategy involved computing bivariate correlations between electrodes over frontal and posterior regions of interest with the orienting/regulatory capacity IBQ-R subscales for each band. We chose to probe all sites within our regions of interest rather than collapse power across sites so as to not mask patterns that may be relatively anterior, posterior, or lateralized. We evaluated the statistical significance of each observed correlation using nonparametric permutation testing (for detailed review, see Cohen, 2014). A null hypothesis distribution of the *r* statistic—a representation of the *r* statistic if infants' IBQ-R scores and power were unrelated (i.e., if the null hypothesis were true)—was generated from our own data. The advantage of this nonparametric permutation testing is that the probability of the empirically observed test statistic can be determined relative to what would be expected by chance given our data. Generating the null hypothesis distribution for the current study involved randomly swapping infants' IBQ-R scores for a given subscale (e.g., duration of orienting) and computing bivariate correlations between the subscale and power for a given band (e.g., theta) at all electrodes within each region of interest. For each of these permutations, the set of generated *r* statistics was stored, with the process repeated 5,000 times. This technique produced a near Gaussian distribution of the *r* statistic for each subscale and power in the given band. The empirically observed *r* statistic was then evaluated against this distribution, enabling us to derive a p-value. The p-value was obtained by dividing the number of *r* values in the distribution greater than (for positive correlations) or less than (for negative correlations) the observed *r* statistic by the total number of *r* statistics in the distribution. Thus, one-tail p-values are reported. Only correlations that fell in the upper or lower 2.5% (alpha = 0.05) were interpreted as significant.

3 | RESULTS

Age was unrelated to the orienting/regulatory capacity subscales or power at any sites within our regions of interest with the exception of two posterior sites with gamma. These sites were unrelated to any orienting/regulatory capacity subscales and were not considered further. The results are shown graphically in Figure 2. The figure shows positive (solid lines) and negative (dashed lines) correlations between duration of orienting (red circles and lines), low intensity pleasure (green circles and lines), soothability (purple circles and lines), and cuddliness (blue circles and lines) at frontal and posterior sites. Relations for theta (top left), alpha (top right), beta (bottom left), and gamma (bottom right) are shown. As can be seen, lower levels of theta and higher levels of beta and gamma were related to duration of orienting at sites over the frontal region. Higher levels of theta and lower levels of beta were related to cuddliness at sites over the posterior. More specifically, theta was inversely related to duration of orienting at left and right frontal sites Fp1 ($r = -0.30$, $p = 0.015$), Fp2 ($r = -0.34$, $p = 0.006$), AF3 ($r = -0.27$, $p = 0.024$), and AF4 ($r = -0.31$, $p = 0.012$). Beta was positively related to duration of orienting at right frontal sites Fp2 ($r = 0.33$, $p = 0.008$) and AF4 ($r = 0.29$, $p = 0.018$). Gamma was also positively related to duration of orienting at right frontal sites Fp2 ($r = 0.31$, $p = 0.014$) and AF4 ($r = 0.31$, $p = 0.014$). Theta was positively related to cuddliness at left, right, and central posterior sites P3 ($r = 0.33$, $p = 0.008$), Pz ($r = 0.37$, $p = 0.003$), PO3 ($r = 0.32$, $p = 0.010$), PO4 ($r = 0.30$, $p = 0.015$), and O1 ($r = 0.34$, $p = 0.008$). Beta was inversely related to cuddliness at left, right, and central posterior sites P3 ($r = -0.37$, $p = 0.003$), Pz ($r = -0.38$, $p = 0.003$), P4 ($r = -0.31$, $p = 0.013$), PO3 ($r = -0.40$, $p = 0.002$), PO4 ($r = -0.36$, $p = 0.004$), O1 ($r = -0.43$, $p = 0.001$), and Oz ($r = -0.35$, $p = 0.005$). No relations between regulatory subscales and alpha were observed. Two additional significant correlations were noted but removed because these were isolated and not readily interpretable. One relation was between soothability and alpha at Fp2, and the other was between cuddliness and beta at Cz. We turn to a discussion of the implications of these results for understanding

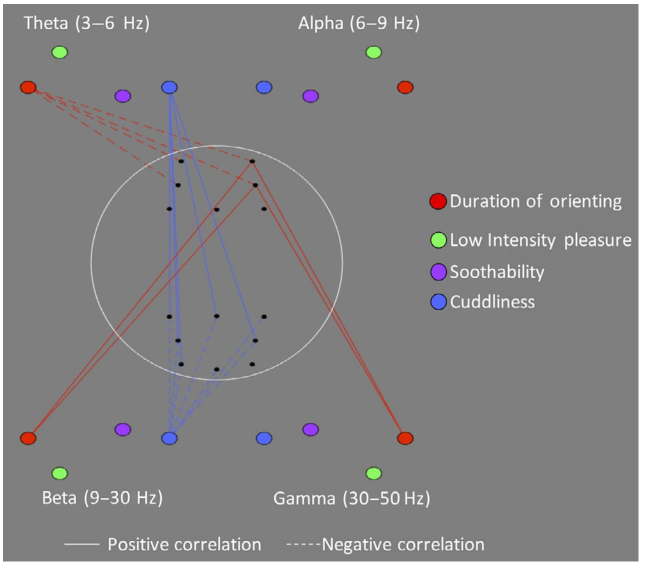

FIGURE 2 The figure shows positive (solid lines) and negative (dashed lines) correlations with duration of orienting (red circles/lines), low intensity pleasure (green circle/lines), soothability (purple circles/lines), and cuddliness (blue circles and lines) at frontal and posterior sites. Relations for theta (top left), alpha (top right), beta (bottom left), and gamma (bottom right) are depicted

brain-behavior relations with respect to attention and regulatory processes as well as the contribution of the current study to the extant literature.

4 | GENERAL DISCUSSION

An important goal of developmental science is to understand how the emerging organization of the brain and infants' behavioral tendencies are interconnected. A critical step involves identifying how infants' behavior in their natural environment is related to brain activity. Parents can provide an unprecedented window into their infant's behavior, and thus parent-report may be a viable resource to elucidate early developing brain-behavior relations. We focused on parent-report of infants' attention and regulatory abilities, in part, because we had specific hypotheses about what cortical rhythms these abilities would be related to and, in part, because these abilities are foundational to healthy developmental outcomes (Moffitt et al., 2011). The primary finding was based on the observation that lower levels of frontal theta and higher levels of frontal beta and gamma were associated with infants' attention abilities (i.e., duration of orienting). This pattern of results is remarkably consistent with existing research conducted with older children and adults (e.g., Benasich et al., 2008; Gou et al., 2011; Massar et al., 2014; Perone, Palanisamy, et al., 2018; Schutter & Van Honk, 2005) and supports parent-report as a valuable resource for the study of brain-behavior relations during infancy. Interestingly, we did not observe any relations with alpha, which is a rhythm often studied in this developmental period. Our observed pattern of results indicates further inquiry into multiple rhythms together can help paint a more complete picture of how the early organization of the brain and infants' behavioral tendencies are connected.

The current study makes two key contributions to the extant literature. First, it sheds new light on the link between attentional processes and cortical activity early in development. Why might duration of orienting in 6- to 12-month-old infants be linked to the theta, beta, and gamma as in later periods of development? One possibility is infants' attentional abilities reflect the origins of basic executive control processes. Indeed, infants' looking behavior in lab-based tasks is predictive of executive function during early childhood (Cuevas & Bell, 2014). Moreover, a series of neural network model simulations have shown a similar set of neurocognitive processes underlie infants' looking behavior and performance in executive function tasks during childhood (Perone, Molitor, Buss, Spencer, & Samuelson, 2015; Perone & Simmering, 2017; Perone & Spencer, 2013). Second, the exploratory aspect of our study revealed cuddliness is related to higher levels of theta and lower levels of beta over the posterior. Cuddliness may represent an important process by which infants use a caregiver to regulate themselves, as has been frequently described (e.g., Kopp, 1982, 1989), reflected in this electrophysiological signature. Why cuddliness is so robustly linked to cortical activity over the posterior region in the baseline EEG context used here is still unclear. Baseline EEG is thought to provide a window into the organization of the brain at the level of the individual, thought to be trait-like in nature. Robust links between baseline activity and behavior in other contexts may be due to baseline providing a marker of the activity of networks that are actively engaged in task-specific contexts (e.g., Bonnard et al., 2016; Deco, Jirsa, & McIntosh, 2013; Elton & Gao, 2015; for discussion, see Anderson & Perone, 2018). Importantly, baseline EEG is not a "pure" measure of the organization of the brain. Baseline EEG is a task, albeit a simple one, and varies widely across studies and developmental periods. How the baseline context influences what brain-behavior relations are observed is poorly understood, and more research is needed.

Although exploration has value for expanding our understanding of brain-behavior relations, it is not without problems. Neuroimaging studies include many variables that can potentially unveil important insights into the brain and often deem some exploration necessary, when the foundation required for a-priori hypotheses is lacking in the existing research. This need for an exploratory approach creates a multiple comparisons problem which does not have a one-size-fits-all solution. In the present investigation, we managed this problem by constraining our analyses to a subset of IBQ-R subscales for which we had some specific hypotheses about where relations would be observed (e.g., lower levels of theta with duration of orienting over frontal regions). However, our study still had an exploratory component as well. How can we be confident our results are not due to chance? We extracted the frequency with which significant correlations occurred by chance from the permutations used to generate our null hypothesis distribution. For each permutation, we counted the number of correlations with $p < 0.025$ (one-tailed) that occurred by chance at any electrode within each region of interest for each IBQ-R subscales and rhythm (e.g., theta with duration of orienting over the frontal region). The results showed one or more significant correlations occurred by chance often, at a rate of 17.96%. However, two or more occurred by chance less often, at a rate of 8.51%, and three or more only occurred at a rate of 4.95%, four or more at a rate of 2.97%, five or more at a rate of 1.74%, six or more at a rate of 0.94%, and seven or more at a rate of 0.37%. These results indicate our empirical observations are unlikely to be due to chance. The most likely empirical pattern to occur by chance are relations between duration of orienting and higher levels of frontal beta and gamma which were limited to two sites over the right frontal region. However, these observations were highly statistically significant, consistent across bands, and fit conceptually with the extant literature, and thus are expected to be reliable.

In conclusion, the present report is an important step toward the use of parent-report to identify brain-behavior relations and, ultimately, how brain and behavior shape each other's development. The pattern of results we observed was quite consistent with lab-based measures of attention and executive function in other developmental periods. We are optimistic that parent-report could be a fruitful resource to advance understanding of the emerging organization of the brain, and larger scale investigations are warranted. One avenue of inquiry would be to examine relations via parent report and direct observation, such as parent-report of duration of orienting and performance in a lab-based attention task. Some prior studies using parent-report and lab-based measures used to probe relations with frontal alpha asymmetry have yielded mixed results (Diaz & Bell, 2012; LoBue et al., 2011). Parent-report and structured laboratory observations are understood to provide complementary, rather than overlapping, information, with recent research suggesting that caregivers provide more trait-like markers of temperament, with laboratory observations speaking primarily to behavioral and emotional state of the infant (Preszler & Gartstein, 2018). A second avenue for future research would be to take advantage of parent-report on a more fine-grained time scale (e.g., Franchak, 2019) to better understand the interconnections between behavior and cortical activity. For example, do changes in the rate with which infants spend time attending to objects in their environment (e.g., frequency each day) as well as changes in the duration with which they attend to objects (e.g., one minute, two minutes, etc.) over weeks and months predict growth in theta activity? Finally, research is required to better understand why parent-report indicators reflecting soothability or low intensity pleasure were not related to the cortical activity measured at baseline here. One possibility is that links between these manifestations of temperament and cortical activity may only surface during lab-based tasks that elicit these processes. Answering these questions is methodologically important and also needed to use our growing knowledge of brain-behavior relations to promote specific patterns of cortical activity facilitating healthy development.

ACKNOWLEDGMENTS

We thank the families that participated in this study and the research assistants who made invaluable contributions to this work, including Natalia Potapova, Elizabeth Youatt, Alana Anderson, and Joshua Underwood.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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REFERENCES

Anderson, A. J., & Perone, S. (2018). Developmental change in the resting state electroencephalogram: Insights into cognition and the brain. *Brain and Cognition*, *126*, 40–52. https://doi.org/10.1016/j.bandc.2018.08.001

Arns, M., Conners, C. K., & Kraemer, H. C. (2013). A decade of EEG theta/beta ratio research in ADHD: A meta-analysis. *Journal of Attention Disorders*, *17*(5), 374–383. https://doi.org/10.1177/1087054712460087

Atzaba-Poria, N., Deater-Deckard, K., & Bell, M. (2017). Mother–child interaction: Links between mother and child frontal electroencephalograph asymmetry and negative behavior. *Child Development*, *88*(2), 544–554. https://doi.org/10.1111/cdev.12583

Audet, K., & Le Mare, L. (2011). Mitigating effects of the adoptive caregiving environment on inattention/overactivity in children adopted from Romanian orphanages. *International Journal of Behavioral Development*, *35*(2), 107–115. https://doi.org/10.1177/0165025410373313

Bell, M. A. (2001). Brain electrical activity associated with cognitive processing during a looking version of the A-Not-B task. *Infancy*, *2*(3), 311–330. https://doi.org/10.1207/S15327078IN0203_2

Bell, M. A., & Fox, N. A. (1992). The relations between frontal brain electrical activity and cognitive development during infancy. *Child Development*, *63*(5), 1142–1163. https://doi.org/10.1111/j.1467-8624.1992.tb01685.x

Benasich, A. A., Gou, Z., Choudhury, N., & Harris, K. D. (2008). Early cognitive and language skills are linked to resting frontal gamma power across the first 3 years. *Behavioural Brain Research*, *195*(2), 215–222. https://doi.org/10.1016/j.bbr.2008.08.049

Bonnard, M., Chen, S., Gaychet, J., Carrere, M., Woodman, M., Giusiano, B., & Jirsa, V. (2016). Resting state brain dynamics and its transients: A combined TMS-EEG study. *Scientific Reports*, *6*(1). https://doi.org/10.1038/srep31220

Brooker, R. J., Canen, M. J., Davidson, R. J., & Goldsmith, H. H. (2017). Short- and long-term stability of alpha asymmetry in infants: Baseline and affective measures. *Psychophysiology*, *54*, 1100–1109. https://doi.org/10.1111/psyp.12866

Bruce, J., Tarullo, A. R., & Gunnar, M. R. (2009). Disinhibited social behavior among internationally adopted children. *Development and Psychopathology*, *21*(01), 157. https://doi.org/10.1017/S0954579409000108

Buss, A. T., & Spencer, J. P. (2017). Changes in frontal-posterior connectivity underlie the early emergence of executive function. *Developmental Science*, https://doi.org/10.1111/desc.12602

Clarke, A. R., Barry, R. J., McCarthy, R., & Selikowitz, M. (2001). Age and sex effects in the EEG: Development of the normal child. *Clinical Neurophysiology*, *112*, 806–814.

Cohen, M. X. (2014). *Analyzing Neural Time Series Data: Theory and Practice*. Cambridge, MA: The MIT Press.

Cuevas, K., & Bell, M. A. (2014). Infant attention and early childhood executive function. *Child Development*, *85*(2), 397–404. https://doi.org/10.1111/cdev.12126

Cuevas, K., Hubble, M., & Bell, M. A. (2012). Early childhood predictors of post-kindergarten executive function: Behavior, parent report, and psychophysiology. *Early Education and Development*, *23*(1), 59–73. https://doi.org/10.1080/10409289.2011.611441

Deco, G., Jirsa, V. K., & McIntosh, A. R. (2013). Resting brains never rest: Computational insights into potential cognitive architectures. *Trends in Neurosciences*, *36*(5), 268–274. https://doi.org/10.1016/j.tins.2013.03.001

Diaz, A., & Bell, M. A. (2012). Frontal EEG asymmetry and fear reactivity in different contexts at 10 months. *Developmental Psychobiology*, *54*(5), 536–545. https://doi.org/10.1002/dev.20612

Elton, A., & Gao, W. (2015). Task-positive functional connectivity of the default mode network transcends task domain. *Journal of Cognitive Neuroscience*, *27*(12), 2369–2381. https://doi.org/10.1162/jocn_a_00859

Engle, A. K., & Fries, P. (2010). Beta-band oscillations—signalling the status quo? *Current Opinion in Neurobiolgoy*, *20*, 156–165.

Ezekiel, F., Bozma, R., & Morton, J. B. (2013). Dimensional change card sort performance associated with age-related differences in functional connectivity of lateral prefrontal cortex. *Developmental Cognitive Neuroscience*, *5*, 40–50. https://doi.org/10.1016/j.dcn.2012.12.001

Fox, N. A., Henderson, H. A., Rubin, K. H., Calkins, S. D., & Schmidt, L. A. (2001). Continuity and discontinuity of behavioral inhibition and exuberance: Psychophysiological and behavioral influences across the first four years of life. *Child Development*, *72*(1), 1–21. https://doi.org/10.1111/1467-8624.00262

Franchak, J. M. (2019). Changing opportunities for learning in everyday life: Infant body position over the first year. *Infancy*, *24*(2), 187–209. https://doi.org/10.1111/infa.12272

Gartstein, M. A., & Bateman, A. E. (2008). Early manifestations of childhood depression: Influences of infant temperament and parental depressive symptoms. *Infant and Child Development*, *17*(3), 223–248. https://doi.org/10.1002/icd.549

Gartstein, M. A., Bridgett, D. J., & Low, C. M. (2012). Self- and other-report measures of temperament. In M. Zentner, & R. Shiner (Eds.), *Handbook of temperament* (pp. 183–208). New York, NY: Guilford Press.

Gartstein, M. A., Bridgett, D. J., Rothbart, M. K., Robertson, C., Iddins, E., Ramsay, K., & Schlect, S. (2010). A latent growth examination of fear development in infancy: Contributions of maternal depression and the risk for toddler anxiety. *Developmental Psychology*, *46*(3), 651–668. https://doi.org/10.1037/a0018898

Gartstein, M. A., Bridgett, D. J., Young, B. N., Panksepp, J., & Power, T. (2013). Origins of effortful control: Infant and parent contributions. *Infancy*, *18*(2), 149–183. https://doi.org/10.1111/j.1532-7078.2012.00119.x

Gartstein, M. A., & Hancock, G. R. (in press). *Temperamental growth in infancy: demographic, maternal symptom, and stress contributions to over-arching and fine-grained dimensions*. Merrill-Palmer Quarterly.

Gartstein, M. A., Hancock, G. R., & Iverson, S. L. (2018). Positive affectivity and fear trajectories in infancy: Contributions of mother-child interaction factors. *Child Development*, *89*(5), 1519–1534. https://doi.org/10.1111/cdev.12843

Gartstein, M. A., Knyazev, G. G., & Slobodskaya, H. R. (2005). Cross-cultural differences in the structure of infant temperament: United States of America (U.S.) and Russia. *Infant Behavior and Development*, *28*(1), 54–61. https://doi.org/10.1016/j.infbeh.2004.09.003

Gartstein, M. A., & Marmion, J. (2008). Fear and positive affectivity in infancy: Convergence/discrepancy between parent-report and laboratory-based indicators. *Infant Behavior and Development*, *31*(2), 227–238. https://doi.org/10.1016/j.infbeh.2007.10.012

Gartstein, M. A., Prokasky, A., Bell, M. A., Calkins, S., Bridgett, D. J., Braungart-Rieker, J., … Seamon, E. (2017). Latent profile and cluster analysis of infant temperament: Comparisons across person-centered approaches. *Developmental Psychology*, *53*, 1811–1825. https://doi.org/10.1037/dev0000382

Gartstein, M. A., Putnam, S. P., & Kliewer, R. (2016). Do infant temperament characteristics predict core academic abilities in preschool-aged children? *Learning and Individual Differences*, *45*, 299–306. https://doi.org/10.1016/j.lindif.2015.12.022

Gartstein, M. A., Putnam, S. P., & Rothbart, M. K. (2012). Etiology of preschool behavior problems: Contributions of temperament attributes in early childhood. *Infant Mental Health Journal*, *33*, 197–211.

Gartstein, M. A., & Rothbart, M. K. (2003). Studying infant temperament via the revised infant behavior questionnaire. *Infant Behavior and Development*, *26*(1), 64–86. https://doi.org/10.1016/S0163-6383(02)00169-8

Gou, Z., Choudhury, N., & Benasich, A. A. (2011). Resting frontal gamma power at 16, 24 and 36 months predicts individual differences in language and cognition at 4 and 5 years. *Behavioural Brain Research*, *220*(2), 263–270. https://doi.org/10.1016/j.bbr.2011.01.048

Hwang, K., Velanova, K., & Luna, B. (2010). Strengthening of top-down frontal cognitive control networks underlying the development of inhibitory control: An fMRI effective connectivity study. *Journal of Neuroscience*, *30*, 15535–15545.

Kochanska, G., Murray, K. T., & Harlan, E. T. (2000). Effortful control in early childhood: Continuity and change, antecedents, and implications for social development. *Developmental Psychology*, *36*(2), 220–232.

Kopp, C. B. (1982). Antecedents of self-regulation: A developmental perspective. *Developmental Psychology*, *18*, 199–214. https://doi.org/10.1037//0012-1649.18.2.199

Kopp, C. B. (1989). Regulation of distress and negative emotions: A developmental view. *Developmental Psychology*, *25*, 343–354. https://doi.org/10.1037//0012-1649.25.3.343

Kraybill, J. H., & Bell, M. A. (2013). Infancy predictors of preschool and post-kindergarten executive function. *Developmental Psychobiology*, *55*(5), 530–538. https://doi.org/10.1002/dev.21057

Kühn-Popp, N., Kristen, S., Paulus, M., Meinhardt, J., & Sodian, B. (2016). Left hemisphere EEG coherence in infancy predicts infant declarative pointing and preschool epistemic language. *Social Neuroscience*, *11*(1), 49–59. https://doi.org/10.1080/17470919.2015.1024887

Lengua, L. J. (2006). Growth in temperament and parenting as predictors of adjustment during children's transition to adolescence. *Developmental Psychology*, *42*(5), 819–832. https://doi.org/10.1037/0012-1649.42.5.819

Levin, A. R., Varcin, K. J., O'Leary, H. M., Tager-Flusberg, H., & Nelson, C. A. (2017). EEG power at 3 months in infants at high familial risk for autism. *Journal of Neurodevelopmental Disorders*, *9*, 34. https://doi.org/10.1186/s11689-017-9214-9

LoBue, V., Coan, J. A., Thrasher, C., & DeLoache, J. S. (2011). Prefrontal asymmetry and parent-rated temperament in infants. *PLoS ONE*, *6*(7), e22694. https://doi.org/10.1371/journal.pone.0022694

Lubar, J. F. (1991). Discourse on the development of EEG diagnostics and biofeedback for attention-deficit/hyperactivity disorders. *Biofeedback and Self-Regulation*, *16*(3), 201–225. https://doi.org/10.1007/BF01000016

Lusby, C. M., Goodman, S. H., Yeung, E. W., Bell, M. A., & Stowe, Z. N. (2016). Infant EEG and temperament negative affectivity: Coherence of vulnerabilities to mothers' perinatal depression. *Development and Psychopathology*, *28*, 895–911.

MacNeill, L. A., Ram, N., Bell, M. A., Fox, N. A., & Pérez-Edgar, K. (2018). Trajectories of infants' biobehavioral development: Timing and rate of A-Not-B performance gains and EEG maturation. *Child Development*, *89*(3), 711–724. https://doi.org/10.1111/cdev.13022

Marshall, P. J., Bar-Haim, Y., & Fox, N. A. (2002). Development of the EEG from 5 months to 4 years of age. *Clinical Neurophysiology*, *113*(8), 1199–1208. https://doi.org/10.1016/S1388-2457(02)00163-3

Marshall, P. J., & Fox, N. A.; the BEIP Core Group. (2004). A comparison of the electroencephalogram between institutionalized and community children in Romania. *Journal of Cognitive Neuroscience*, *16*, 1327–1338.

Massar, S. A. A., Kenemans, J. L., & Schutter, D. J. L. G. (2014). Resting-state EEG theta activity and risk learning: Sensitivity to reward or punishment? *International Journal of Psychophysiology*, *91*(3), 172–177. https://doi.org/10.1016/j.ijpsycho.2013.10.013

Mize, K. D., & Jones, N. A. (2012). Infant physiological and behavioral response to loss of maternal attention to social rival. *International Journal of Psychophysiology*, *83*, 16–23. https://doi.org/10.1016/j.ijpsycho.2011.09.018

Moffitt, T., Arseneault, L., Belsky, D., Dickson, N., Hancox, R. J., Harrington, H., … Caspi, A. (2011). A gradient of childhood self- control predicts health, wealth, and public safety. *Proceedings of the National Academy of Sciences, USA*, *108*, 2693–2698.

Morasch, K. C., & Bell, M. A. (2011). The role of inhibitory control in behavioral and physiological expressions of toddler executive function. *Journal of Experimental Child Psychology*, *108*(3), 593–606. https://doi.org/10.1016/j.jecp.2010.07.003

Oldehinkel, A. J., Hartman, C. A., De Winter, A. F., Veenstra, R., & Ormel, J. (2004). Temperament profiles associated with internalizing and externalizing problems in preadolescence. *Development* *and Psychopathology*, *16*(02). https://doi.org/10.1017/S0954579404044591

Orekhova, E. V., Stroganova, T. A., Posikera, I. N., & Elam, M. (2006). EEG theta rhythm in infants and preschool children. *Clinical Neurophysiology*, *117*(5), 1047–1062. https://doi.org/10.1016/j.clinph.2005.12.027

Perone, S., Almy, B., & Zelazo, P. D. (2018). Toward an understanding of the neural basis of executive function development. In *The neurobiology of brain and behavioral development* (pp. 291–314). San Diego, CA: Academic Press.

Perone, S., Molitor, S. J., Buss, A. T., Spencer, J. P., & Samuelson, L. K. (2015). Enhancing the executive functions of 3-year-olds in the dimensional change card sort task. *Child Development*, *86*(3), 812–827. https://doi.org/10.1111/cdev.12330

Perone, S., Palanisamy, J., & Carlson, S. M. (2018). Age-related change in brain rhythms from early to middle childhood: Links to executive function. *Developmental Science*, e12691. https://doi.org/10.1111/desc.12691

Perone, S., & Simmering, V. R. (2017). Applications of dynamic systems theory to cognition and development. In *Advances in child development and behavior*, Vol. *52* (pp. 43–80). Burlington, VT: Academic Press.

Perone, S., & Spencer, J. P. (2013). Autonomy in action: Linking the act of looking to memory formation in infancy via dynamic neural fields. *Cognitive Science*, *37*(1), 1–60. https://doi.org/10.1111/cogs.12010

Preszler, J. R., & Gartstein, M. A. (2018). Latent state-trait modeling: A new tool to refine temperament methodology. *International Journal of Behavioral Development*, *42*, 445–452.

Putman, P., van Peer, J., Maimari, I., & van der Werff, S. (2010). EEG theta/beta ratio in relation to fear-modulated response-inhibition, attentional control, and affective traits. *Biological Psychology*, *83*(2), 73–78. https://doi.org/10.1016/j.biopsycho.2009.10.008.

Putnam, S. P., Rothbart, M. K., & Gartstein, M. A. (2008). Homotypic and heterotypic continuity of fine-grained temperament during infancy, toddlerhood, and early childhood. *Infant and Child Development*, *17*, 387–405.

Rothbart, M. K. (2011). *Becoming who we are: temperament and personality in development*. New York, NY: Guilford.

Rothbart, M. K., Ahadi, S. A., Hershey, K. L., & Fisher, P. (2001). Investigations of temperament at three to seven years: The children's behavior questionnaire. *Child Development*, *72*, 1394–1408. https://doi.org/10.1111/1467-8624.00355

Ruff, H. A., & Rothbart, M. K. (1996). *Attention in early development*. New York, NY: Oxford University Press.

Schutter, D. J. L. G., & Van Honk, J. (2005). Electrophysiological ratio markers for the balance between reward and punishment. *Cognitive Brain Research*, *24*(3), 685–690. https://doi.org/10.1016/j.cogbrainres.2005.04.002

St. John, A. M., Kao, K., Liederman, J., Grieve, P. G., & Tarullo, A. R. (2016). Variation in infant EEG power across social and nonsocial contexts. *Journal of Experimental Child Psychology*, *152*, 106–122. https://doi.org/10.1016/j.jecp.2016.04.007

Tarullo, A. R., Obradović, J., Keehn, B., Rasheed, M. A., Siyal, S., Nelson, C. A., & Yousafzai, A. K. (2017). Gamma power in rural Pakistani children: Links to executive function and verbal ability. *Developmental Cognitive Neuroscience*, *26*, 1–8. https://doi.org/10.1016/j.dcn.2017.03.007

Tomalski, P., Moore, D. G., Ribeiro, H., Axelsson, E. L., Murphy, E., Karmiloff-Smith, A., … Kushnerenko, E. (2013). Socioeconomic status and functional brain development - associations in early infancy. *Developmental Science*, *16*(5), 676–687. https://doi.org/10.1111/desc.12079

Willoughby, M. T., Waschbusch, D. A., Moore, G. A., & Propper, C. B. (2011). Using the ASEBA to screen for callous unemotional traits in early childhood: Factor structure, temporal stability, and utility. *Journal of Psychopathology and Behavioral Assessment*, *33*(1), 19–30. https://doi.org/10.1007/s10862-010-9195-4

Wolfe, C. D., & Bell, M. A. (2007). The integration of cognition and emotion during infancy and early childhood: Regulatory processes associated with the development of working memory. *Brain and Cognition*, *65*(1), 3–13. https://doi.org/10.1016/j.bandc.2006.01.009

Zelazo, P. D. (2015). Executive function: Reflection, iterative reprocessing, complexity, and the developing brain. *Developmental Review*, *38*, 55–68. https://doi.org/10.1016/j.dr.2015.07.001

Zelazo, P. D., & Carlson, S. M. (2012). Hot and cool executive function in childhood and adolescence: Development and plasticity. *Child Development Perspectives*, n/a-n/a., https://doi.org/10.1111/j.1750-8606.2012.00246.x

How to cite this article: Perone S, Gartstein MA. Mapping cortical rhythms to infant behavioral tendencies via baseline EEG and parent-report. *Developmental Psychobiology*. 2019;61:815–823. https://doi.org/10.1002/dev.21867