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Delta-beta correlation predicts adaptive child emotion regulation concurrently and two years later

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ABSTRACT

Emotion regulation (ER), the ability to flexibly monitor and modify emotions, is related to positive adjustment throughout the lifespan. Biological indexes of ER in childhood that predict behavior are valuable for clinical applications and our understanding of affective neurodevelopment. Delta-beta correlation (DBC), or the coupling between resting state slow-wave (delta) and fast-wave (beta) neural oscillations derived from EEG, may be a metric of the functional coherence between subcortical and cortical neural circuitry implicated in ER. Yet, little is understood about how DBC corresponds to observed ER during emotional challenges. To address this question, in the present study, resting-state EEG was recorded to generate DBC when children were 5–7 years old (T1) and again two years later (T2). Children also completed two emotionally challenging behavioral tasks [delay of gratification (DoG) task and waiting task (WT)] from which observed ER strategies were subsequently coded. Results showed that higher DBC was associated with greater use of adaptive, and relatively active, ER strategies. Specifically, higher frontal DBC at T1 longitudinally predicted greater use of the ER strategy alternative activity engagement and greater parent-reported positive ER at T2. These findings add to growing evidence supporting the use of resting state DBC as a neurophysiological index of ER with clinically and developmentally relevant predictive power.

Emotion regulation (ER), or the ability to monitor and modify the expression and experience of emotion (Gross & Thompson, 2007), predicts positive adjustment throughout the lifespan (Berking & Wupperman, 2012; Zeman, Cassano, Perry-Parrish, & Stegall, 2006; Compas et al., 2017). A key feature of adaptive ER is the capacity to manage behavior during a range of emotional challenges. For example, managing frustration and delaying gratification are common regulatory challenges in childhood, and children can vary in their use of adaptive or maladaptive ER behaviors during these challenges. Yet relatively little is known about neurocognitive individual differences that may signify developing ER vulnerabilities and strengths. The current study investigated the utility of delta-beta correlation (DBC) as a candidate neural index of ER capacity in childhood by examining predictive links with observed ER.

DBC is obtained from as little as 2 min of resting state electroencephalography (EEG) measurement, and has been used as a low-burden index of the functional coherence of cortical-limbic circuitry underlying ER in children and adults (e.g. Phelps, Brooker, & Buss, 2016; Schutter & Knyazev, 2012). DBC is generated from neural oscillations in the beta and delta frequency bands. Beta waves are fast-frequency oscillations originating in the cortex and are thought to reflect top-down cognitive processes like attentional control, whereas delta waves are slow-frequency oscillations reflecting subcortical brain activity and reflect more bottom-up affective processes (Knyazev, 2007). Thus, DBC ostensibly reflects the balance between cognitive and emotional processes in the brain, and thus likely reflects critical neural ER processes (e.g. Knyazev, 2007; Knyazev, Schutter, & van Honk, 2006; Morillas-Romero, Tortella-Feliu, Balle, & Bornas, 2015; Putman, 2011; Putman, Arias-Garcia, Pantazi, & van Schie, 2012; Velikova *et al.* 2010).

Studies with adults suggest that low levels of DBC reflect disrupted cortical-limbic functional coherence, which may characterize high trait anxiety (Putman, 2011; Velikova et al., 2010), blunted attentional control (Morillas-Romero et al., 2015), and poor response inhibition in the face of threat (Putman et al., 2012). In other words, low resting-state

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DBC may indicate an imbalance in favor of bottom-up, stimulus-driven attention capture by affective stimuli, which could undermine ER capacity.

Yet, findings have been inconsistent regarding the functional significance of high versus low levels of resting-state DBC. In clinical samples of children and adults, high levels of DBC may reflect exaggerated, resource-intensive regulation of cortical-limbic circuitry. For example, a recent study found that high DBC was associated with social anxiety in older children (i.e., 10 years; Anaya et al., 2020). Further, high levels of behavioral inhibition, a temperamental profile predictive of elevated anxiety, has been associated with greater DBC in adults (Knyazev et al., 2006; van Peer, Roelofs, & Spinhoven, 2008). Elevated levels of DBC have been documented in toddlers with dysregulated fear (Phelps et al., 2016), as well as, in school-aged children with behavioral inhibition (Poole, Anaya, & Pérez-Edgar, 2020), social anxiety and elevated basal cortisol levels (Poole & Schmidt, 2019). In the context of anxiety and exaggerated fear, high DBC may reflect the need to exert greater cortical control of emotion-generating brain regions and/or exaggerated emotional reactivity during resting state.

While prior research has focused on clinical samples or identifying subsamples with trait-level risk factors for psychopathologies, little is known about direct links between resting-state DBC and ER in typically developing children. Given prior research with non-clinical samples (Morillas-Romero et al., 2015; Putman, 2011; Putman et al., 2012; Velikova et al., 2010), high DBC, reflecting 'balanced communication' between subcortical and cortical-cortical neural activity, may be a hallmark of healthy neurodevelopment that supports effective ER. To test this hypothesis, resting-state DBC must be directly examined in relation to established measures of ER.

Decades of research on the development of ER has relied on observation-based assessments of ER behavior, involving specific types of emotional challenges (Cole, Martin, & Dennis, 2004). Among the most well-studied are tasks that require delay of gratification and elicit frustration. For example, the classic delay of gratification task (i.e. marshmallow task; Mischel & Ebbesen, 1970) requires a child to self-inhibit the desire to eat a treat in favor of a larger reward later. Successful delay of gratification involves the effortful deployment and shifting of attentional resources to focus away from a temptation or towards an alternative activity (Eigsti et al., 2006; Gusdorf, Karreman, van Aken, Dekovic, & van Tuijl, 2011; Mischel, Ebbesen, & Zeiss, 1972). The observed ability to do so in childhood has been linked to fewer symptoms of psychopathology, greater social competence (e.g. Mischel, Shoda, & Rodriguez, 1989), and greater ability to cope with stress (Mischel & Shoda, 1998). Furthermore, performance on the delay of gratification task in childhood has been linked to adolescent functioning (Shoda, Mischel, & Peake, 1990), and has been shown to have a mediating effect on various interpersonal difficulties and adaptive functioning in adulthood (Ayduk *et al.* 2000).

While the delay of gratification task challenges a child while they are alone, the frustrating waiting task (Carmichael-Olson, Greenberg, & Slough, 1985; Cole et al., 2011; Cole, Teti, & Zahn-Waxler, 2003; Dennis, Cole, Wiggins, Cohen, & Zalewski, 2009) requires children to wait to open a gift until their parent completes paperwork in the same room. Individual differences in psychophysiological metrics of ER have been examined in relation to child and parent behavior during the waiting task (Kessel, Huselid, Decicco, & Dennis, 2013; Noll, Clark, & Skowron, 2015; Skowron, Cipriano-Essel, Gatzke-Kopp, Teti, & Ammerman, 2014). In particular, prior research has demonstrated the adaptive benefit of active distraction. One study found that children's ability to actively change their attention during the waiting task was associated with reduced display of anger (Cole et al., 2011). Another study demonstrated that greater use of active alternative activities to cope with the frustration of waiting was associated with a neurocognitive index of ER in school-aged children (Babkirk, Rios, & Dennis, 2015). These findings highlight the utility of using observed behavioral measures to examine individual differences in child ER in relation to neural measures.

The developmental transition from early to middle childhood is characterized by an increase in internally generated ER, supported by increasing proficiency at effortful, cognitive ER processes due to maturation of prefrontal-subcortical connections (e.g., Zeman et al., 2006, review; Calkins, 2007; Ochsner & Gross, 2004). Prior studies have documented that greater neurocognitive ER capacity, indexed by event-related potentials during a directed ER task, in this age range is associated with reduced anxiety symptoms (DeCicco, O'Toole & Dennis, 2014) and greater use of adaptive behavioral ER during emotional challenges concurrently and two years later (Babkirk *et al.* 2015). This suggest that neural maturation throughout the school-aged developmental period may underlie individual differences in observed ER.

1. The Present Study

The goal of the present longitudinal study was to clarify the functional significance of high versus low levels of resting-state DBC in typically developing children during the transition from early to middle childhood, aged 5–7. While prior developmental studies examining DBC have tested links with fear and anxiety-related symptoms, which may emerge or be maintained by difficulties with ER (e.g., Compas et al., 2017; review), little is known about direct links between DBC and ER behaviors and traits. In the present study, in addition to collecting parent report of child ER strengths and vulnerabilities, we observed child ER behavior during two emotional challenges: a solo delay of gratification task and a frustrating waiting task with parent present. This allowed us to examine the longitudinal, predictive power of DBC in relation to observed ER across distinct emotion-generating contexts. We tested the hypothesis that higher levels of DBC will be associated with greater parent-reported adaptive child ER and greater observed use of effective ER strategies, particularly those involving active behavioral engagement in the service of shifting attention away from prohibited objects.

2. Method

2.1. Participants

Participants were 57 children,[1] aged 5–7 (27 females), and one parent (52 mothers, 5 fathers) for each child. Four participants were excluded from analyses due to missing/unusable EEG recordings. Thus, 53 children (23 female), aged 5–7 years ($M = 6.19$; $SD = 0.54$) were included in analysis at T1. At T1, 21 (39.6%) participants were White, 18 (34%) were Black/African American, 8 (15.1%) were Hispanic/Latino, 2 (3.8%) were Asian, 2 (3.8%) were Hispanic and another category, and 2 (3.8%) selected "other". Twenty-four (45.3%) of the children had at least one parent with a bachelor's degree or higher. The median annual household income for all the families was between $40,000 to $50,000, and the overall range was from less than $1000 to $150,000 or above.

Thirty-four children (14 female) aged 6–9 years ($M = 7.63$; $SD = 0.67$), and their parents returned for a second (T2) visit two years later. At T2, 13 (38.2%) participants were White, 11 (32.4%) were Black/African American, 7 (20.6%) were Hispanic/Latino, 2 (5.9%) were Hispanic and another category, and 1 (2.9%) reported other. The median annual household income was $50,000, and the overall range was from less than $1000 to $150,000 or above.

An a priori power analysis was conducted via G*Power (3.1.9.2) to

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[1] Data from this sample was reported in prior publications (Babkirk, Rios, & Dennis, 2015; DeCicco, O'Toole & Dennis, 2014; Solomon, DeCicco, & Dennis, 2012; DeCicco, Solomon, & Dennis, 2012) which investigated other neurophysiological or behavioral measures. The current sample was selected by including all participants who completed the EEG baseline task and both behavioral tasks.

determine the required sample size for T1 analyses to detect medium to large effect sizes ($0.15 \leq f^2 \leq .35$) at 80% power consistent with prior studies examining DBC (e.g., Poole, et al., 2020). For regression analyses with 3 target predictors (frontal, central, parietal DBC) with covariates, a size of a minimum of 36–77 individuals was required. A sensitivity power analysis confirmed that T1 sample of 53 children was sufficiently powered for approximately medium/large effect sizes ($f^2 = .22$). However, our sample was underpowered for T2 concurrent and longitudinal analyses, with a sensitivity power analysis showing that our T2 sample was powered to detect effect sizes greater than the large cutoff criterion ($f^2 = .37$). Thus, results from the T2 sample should be interpreted as exploratory, as highlighted in the discussion.

This study was approved by the Institutional Review Board of Hunter College of the City University of New York [296432–3].

2.2. Materials and Procedure

At T1, following informed consent and assent, participants reported demographics and completed self-report questionnaires. Participants were then seated in an EEG recording booth approximately 65 cm away from a 17-inch monitor screen and EEG electrodes were applied for data acquisition. After the EEG application, participants completed the EEG baseline task during which DBC was measured for 2.5 mins. Following EEG clean-up, participants completed a series of behavioral tasks [delay of gratification (DoG)and waiting task (WT)]. The T2 assessment was identical to the T1 assessment. As part of a larger study examining biological signatures of child ER, each study visit lasted approximately 3 h. To reduce fatigue, children were given regular breaks throughout each visit, including one directly before the EEG baseline and before the behavioral tasks.

2.3. Questionnaires

2.3.1. Emotion Regulation Checklist (ERCL)

Parents completed the ERCL (Shields & Cicchetti, 1997), a 24-item measure of child's self-regulation. Each item is rated on a 4-point scale assessing the frequency of behaviors, from 1 being "almost always" to 4 being "never". There are two subscales: positive emotion regulation scale and the lability/negativity scale. The positive emotion regulation subscale measures emotional self-awareness, empathy, and situationally appropriate affective displays (e.g., "Can say when s/he is feeling sad, angry or mad, fear or afraid"). Higher scores indicate a greater capacity to manage and modulate one's emotional arousal. The lability/negativity scale measures inflexibility, dysregulated negative affect, and mood lability (e.g., "exhibits wide mood swings"). Higher scores indicate a condition of excessive emotional reactions and frequent mood changes. Internal consistency has been established for both the positive emotion regulation ($\alpha = 0.83$) and lability/negativity ($\alpha = 0.96$) subscales (Shields & Cicchetti, 1997), and was confirmed in the current sample [emotion regulation ($\alpha = 0.71$); lability/negativity ($\alpha = 0.77$)].

2.3.2. Child Behavioral Checklist (CBCL)

Parents completed the CBCL (Achenbach, Dumenci & Rescorla, 2001), which was used in the current study to investigate links between study variables and total behavioral problems to contextualize the implications of findings for psychological adjustment. The total problems scale captures internalizing, externalizing, and other problems, and has been shown to be internally consistent ($\alpha = 0.80$; Achenbach, Dumenci & Rescorla, 2001), which was confirmed in the current sample ($\alpha = 0.94$).

2.3.3. The Delay of Gratification Task (DoG)

In the DoG task (Mischel et al., 1972; Shields & Cicchetti, 1997), the child was instructed to sit at a table with a bell and a desirable treat (cookies) in the experimental room. At the beginning of the task, the experimenter told the child if he/she could wait until the experimenter comes back to the room, he or she would receive double the number of treats. The experimenter also explained that he/she would be back immediately if the child rang the bell on the table, but if so, the child would only receive a smaller treat. Once the child understood the instruction, the experimenter left the room. If the child continued to wait without ringing the bell, the experimenter would return after 15 min. The total amount of time waited in seconds was recorded. The DoG was video recorded for subsequent coding of ER strategies.

2.3.4. The Waiting Task (WT)

In the WT (Carmichael-Olson et al., 1985; Cole et al., 2003), parents and children were seated at a table upon which an attractively wrapped gift was placed. Prior to the start of the task, children were given a boring toy (i.e., monochromatic plastic fish with no moving parts), and parents were given a clip board with a questionnaire to complete. Parents read the following instructions to the child: "This is a surprise for you, but you must wait until I finish my work to open it." This task lasted 10 min and was video recorded for subsequent coding of ER strategies.

2.3.5. Coding of ER Strategies

Spontaneous child behavioral ER strategy use was coded in 30 s epochs during each behavioral task (DoG, WT) by two reliable coders (DoG: $\kappa = 0.84$; WT: $\kappa = 0.81$) following the Emotion Regulation Strategy Coding Scheme (Babkirk et al., 2015). Five strategies were coded: attentional avoidance, alternative activities, self-comforting, focusing on the prohibited object (i.e., treat in DoG task and gift in WT), and focusing on the undesired object (i.e., broken toy in WT). Attentional avoidance was documented when the child shifted focus away from the task or prohibited object via passive behaviors void of active engagement (e.g., covering one's eyes, sleeping/lying on the table, or 'staring into space'). Alternative activities were coded when the child shifted focus away from the task or prohibited object via active behaviors that involved engagement in something unrelated to the task at hand (e.g., 'playing' with surrounding objects such as chair, wall divider, making up a rhyme or game, or singing). In the WT, the only task in which a parent was present, interactions with the parent were also coded as alternative activities since they served to shift the child's attention away from the prohibited object or assist with coping with the frustration of waiting. Self-comforting was coded when the child exhibited behavior or verbalizations to comfort or initiate comfort without attempting to change the situation (e.g., thumb sucking, body rocking, seeking parent or caregiver). Focusing on the prohibited object was coded when the child's attention was actively oriented toward the prohibited object (e.g., reaching for the object, touching/picking up the object, or visual fixation on the object). Focusing on the undesired object was coded when the child engaged with the boring toy (e.g., touching/picking up the object, incorporating object in play).

Ratio scores were computed to control for individual differences in the general level of activity. The total frequency of each ER strategy behavior was divided by the total number of behaviors coded (across all strategies) throughout the tasks. Thus, ratio scores indicate the percentage of total behaviors which consisted of each of the target ER strategies (i.e., a ratio score of.25 for self-comforting means 25% of that child's ER behaviors were self-comforting).

2.3.6. Baseline EEG task

Resting state electroencephalography (EEG) was recorded (T1 and T2) while children were instructed via a computer program to either open or close their eyes for 20-second segments, for a total of 2.5 min. Children heard audio cues ("open", "close") that instructed them what to do for the subsequent segment. The order of open and close trials was counterbalanced to two specific sequences: COOCOCCO and OCCOCOOC ("O" representing open, and "C" representing closed). Children viewed a visual stimulus (i.e., a rocket ship) on the computer screen during the open trials.

2.3.7. EEG recording and data reduction

EEG data was recorded with 64 Ag/AgCl scalp electrodes on a Biosemi system (BioSemi; Amsterdam, Netherlands) during the baseline EEG task. Electrodes were applied to an EEG cap and arranged according to the International 10–20 system; the data was sampled at 512 Hz. Electro-oculogram (EOG) were used to track eye movements. Two electrodes were placed 1 cm above and below the left eye for the recording of vertical eye movements electrodes. In addition, two additional electrodes were applied 1 cm on the outer corner of each eye to record horizontal eye movements. Preamplification of the EEG signal took place at each electrode in order to improve the signal-to-noise ratio. During EEG acquisition, the voltage from each of the 64 electrodes was referenced online to the common mode sense active electrode, which produced a monopolar (nondifferential) channel. Brain Vision Analyzer (Version 2.2, GmbH; Munich, Germany) was used to prepare the data. Data were re-referenced offline to the average of the left and right mastoids and filtered with the following cut-off frequency: low-cut off frequency of 0.1 Hz and a high-cut off frequency of 30 Hz. Then artifacts were identified using the following criteria and removed from analyses: voltage steps greater than 75 μV, changes within a given segment greater than 150 μV, amplitudes exceeding + /- 100 uV in a given segment, and activity lower than 0.5 μV per 100 ms. In addition to this semi-automatic identification of artifacts, trials were also visually examined to eliminate further artifacts (i.e., trial-by-trial basis). Trial counts were not significantly correlated with DBC metrics (p's > 0.122).

2.3.8. EEG Processing: Delta-Beta Correlation

As in previous studies measuring DBC in children (e.g. Phelps et al., 2016; Poole et al., 2020; Poole & Schmidt, 2019), artifact-free data was averaged across segments and then submitted to a Fast-Fourier Transformation (FFT), with a Hamming window 50% segment width overlap. After transformation, spectral power density (μV^2/Hz) were estimated for the delta (0.5–2.0 Hz) and beta (11.0 – 18.0 Hz) bands, consistent with prior developmental studies (Phelps et al., 2016). The power values were further natural log-transformed to correct for positive skew. Delta and beta band activity was maximal at frontal (F3/F4/Fz), central (C3/C4/Cz), and parietal (P3/P4/Pz) recording sites, and mean power in each of these regions was targeted for analyses. While several studies have focused only on frontal DBC (e.g. Poole & Schmidt, 2019; Putman, 2011), others have also indexed central, and/or parietal DBC (e.g. Phelps et al., 2016; Poole et al., 2020). To clarify potential similarities or differences across these regions, and in line with the lack of specialization of neural cognitive and emotional processing in childhood (e.g. Phelps et al., 2016; Solomon, DeCicco, & Dennis, 2012), we examined DBC across frontal, central, and parietal cites.

The majority of prior studies (e.g. Knyazev et al., 2006; van Peer et al., 2008) have used subsample-level metrics to quantify DBC among median-split groups, an approach which limits the interpretation of past DBC findings as relevant to trait-like individual differences. A recent study (Poole et al., 2020) used both the group-based approach and a within-subject derived DBC metric. Although both approaches yielded similar results, a strength of a within-subject measure is that it is more conceptually reflective of an individual difference rather than a group-based attribute (e.g., Schutter & Knyazev, 2012). Thus, for the present study, individual delta-beta correlation scores were quantified by computing absolute value of residuals (delta predicting beta), separately for frontal, central, and parietal regions. Delta-beta correlation scores closer to zero indicate greater coherence.

3. Results

3.1. Descriptive Statistics

Table 1 presents descriptive statistics for all study variables.

Table 1
Descriptive Statistics.

	T1 ($n = 53$)		T2 ($n = 34$)	
	M	***SD***	***M***	***SD***
Delta Power (ln transformed)				
Frontal	-0.25	.29	-0.39	.27
Central	-0.31	.30	-0.48	.23
Parietal	-0.25	.32	-0.43	.27
Beta Power (ln transformed)				
Frontal	-1.73	.19	-1.79	.19
Central	-1.71	.24	-1.77	.20
Parietal	-1.63	.30	-1.67	.22
Delta-Beta Correlation				
Frontal	.14	.10	.14	.12
Central	.18	.14	.16	.12
Parietal	.20	.17	.17	.11
Observed ER				
Delay of Gratification Task				
Self-comforting	.12	.08	.11	.08
Prohibited Object	.44	.20	.34	.12
Alternative Activities	.16	.10	.20	.10
Attentional Avoidance	.29	.13	.34	.10
Waiting Task				
Self-comforting	.06	.06	.06	.06
Prohibited Object	.16	.10	.13	.08
Alternative Activities	.12	.03	.11	.03
Attentional Avoidance	.10	.07	.12	.08
Undesired Object	.20	.10	.24	.09
Parent-Reported Emotion Regulation				
ERCL				
Positive Emotion Regulation	3.40	.43	3.34	.41
Lability/Negativity	1.64	.46	1.53	.42

3.1.1. Associations with Demographics and Child Behavioral Problems

We tested whether study variables (DBC, parent-reported ER, observed ER) were related to family household income and parent-reported total behavioral problems.

Pearson's correlations showed that greater household income was significantly associated with greater parent-reported positive regulation ($r = 0.346, p = .014$), and greater time waited in the DoG ($r = 0.295, p = .036$), both at T1 only.

Greater behavioral problems were associated with greater parent-reported negativity/lability at T1 ($r = 0.666, p < .001$) and T2 ($r = 0.560, p < .001$). No significant associations were detected between total behavioral problems and DBC or observed child ER.

3.1.2. Age and Sex Effects

Pearson's correlations were conducted to examine associations among child age in months at each visit, DBC, parent-reported child ER, child observed ER during emotional challenges (DoG and WT) and waiting time in the DoG. Child age was not significantly correlated with DBC or parent-reported ER at either visit. At T1, older children showed marginally greater self-comforting in the DoG ($r = 0.264, p = .056$). No other correlations among study variables reached significance.

Independent samples t-tests were conducted to examine differences between males and females in DBC, parent-reported ER, during emotional challenges (DoG and WT), and waiting time in the DoG. At T2, females ($M = 835.89$, $SD = 222.98$) waited significantly longer compared to males in the DoG ($M = 639.65$, $SD = 317.57$), $t\,(36.99) = -2.27$, $p = .029$.

Age and sex were included as covariates in subsequent primary analyses.

3.1.3. Effective ER during the Delay of Gratification

To help conceptualize observed ER strategies as relatively more or less adaptive, we examined associations among ER strategies and total time waited in seconds during the DoG for each visit. Pearson correlations showed that, consistent with prior literature (e.g. Eigsti et al., 2006; Mischel et al., 1972), strategies which served to shift attention away from versus toward the prohibited object (i.e., treat) were relatively more effective in promoting delay time. At T1, greater time waited was significantly associated with greater use of self-comforting ($r = 0.498$, $p < .001$), attentional avoidance ($r = 0.392$, $p = .004$), and alternative activity engagement ($r = 0.437$, $p = .001$), and with *less* use of focusing on the prohibited object ($r = -0.710$, $p < .001$). At T2, greater time waited was significantly associated with greater use of attentional avoidance ($r = 0.320$, $p = .050$), and *less* use of focusing on the prohibited object ($r = -0.377$, $p = .020$).

Thus, self-comforting, alternative activity engagement, and attentional avoidance strategies were considered relatively more adaptive, while focusing on the prohibited object was considered relatively less adaptive. Since there was no undesired object in the DoG, and there was no comparable measure of success (i.e., total time) in the WT, analyses with the ER strategy of undesired object engagement were exploratory.

3.1.4. Developmental Stability of Observed ER

Paired-samples *t*-tests were conducted to examine consistency of observed ER behaviors from T1 to T2. In the DoG, focusing on the prohibited object significantly decreased over time [$t\,(37) = 2.401$, $p = .021$], while use of alternative activities significantly increased over time [$t\,(37) = -2.465$, $p = .018$]. In the WT, engagement with the undesired object (broken toy) significantly increased over time [$t\,(37) = -2.109$, $p = .042$].

3.1.5. Developmental Stability of DBC

Next, to examine differences among recording sites over time, a 3 (Location: frontal, central, parietal) x 2 (Time: T1, T2) repeated-measures ANOVA was conducted. A significant main effect of Location showed that DBC was significantly greater at frontal ($M = 0.136$, $SE = 0.015$) versus parietal ($M = 0.185$, $SE = 0.018$, $p = .010$) sites, $F\,(2, 32) = 3.654$, $p = .037$, $\eta_p^2 = .186$. There was no significant main effect of Time, or Location X Time interaction on DBC (p's > 0.10).

We also conducted Pearson correlations to examine whether power was significantly correlated between T1 and T2, separately for delta and beta frequency bands and recording sites. These patterns are presented in Table 2.

3.1.6. Recording Site Specificity of DBC

To examine patterns of associations among DBC metrics measured across scalp locations within each timepoint, Pearson correlations were also conducted among the frontal, central, and parietal DBC, separately at T1 and T2. At T1, significant positive correlations were detected between frontal and central DBC ($r = 0.289$, $p = .036$), and between central and parietal DBC ($r = 0.535$, $p < .001$), but frontal and parietal DBC were not significantly related ($r = 0.157$, $p = .261$). At T1, only central and parietal DBC were significantly correlated ($r = 0.468$, $p = .004$), while frontal and central DBC ($r = 0.197$, $p = .264$) and frontal and parietal DBC ($r = -0.038$, $p = .830$) were not significantly related.

Since frontal, central, and parietal DBC were not consistently intercorrelated, and since frontal and parietal DBC significantly differed, DBC metrics were examined separately in subsequent analysis to avoid blunting of significant effects by creating an aggregate score.

Table 2
Delta and Beta over Time.

T1	Correlation with corresponding T2 power *r (p)*
Delta - Frontal	.20 (0.25)
Delta - Central	.14 (0.43)
Delta - Parietal	.29 (0.10)
Beta - Frontal	.34 (0.05)*
Beta - Central	.63 (0.00)**
Beta - Parietal	.40 (0.02)*

* $p < .05$,
** $p < .001$

3.2. Primary Analyses

To test the hypothesis that greater DBC would be associated with adaptive ER strategy use during the emotional challenges (DoG and WT), we conducted a series of hierarchical linear regressions. For the DoG: 1st step: age in months[2] and sex; 2nd step: total delay of gratification time in seconds; 3rd step: DBC residual scores for frontal, central, and parietal regions (with lower scores indicating greater correlation). For the WT: 1st step: age in months and sex; 2nd step: DBC residual scores. Each regression was conducted separately for the following seven dependent variables: observed ER ratio scores [attentional avoidance, alternative activities, self-comforting, focusing on the prohibited object, and focusing on the undesired object (WT only)] and parent-reported ER (positive emotion regulation and lability/negativity). Because a total of 33 regressions were conducted [11 for concurrent T1, 11 concurrent T2, and 11 longitudinal (T1 to T2)], the Benjamini-Hochberg (Benjamini & Hochberg, 1995) procedure was applied to account for multiple comparisons. All tests with *p*-values less than 0.05 remained significant after applying this correction, thus raw *p*-values are reported below. Marginal effects ($p < .065$) are also included in results to inform future hypothesis generation. See Appendix for full regression tables.

3.3. Links between DBC and ER strategy use

3.3.1. Concurrent at T1

For the DoG, higher frontal DBC (indicated by lower residual scores) predicted greater use of self-comforting [$\beta = -0.27$; $t\,(50) = -2.12$, $p = .039$] and marginally lower frequency of focusing on the prohibited object [$\beta = 0.19$; $t\,(50) = 1.914$, $p = .062$]. Higher parietal DBC marginally predicted less use of attentional avoidance in the DoG [$\beta = 0.29$; $t\,(50) = 1.927$, $p = .060$]. For the WT, higher frontal DBC marginally predicted greater use of self-comforting [$\beta = -0.29$; $t\,(50) = -1.99$, $p = .053$]. Taken together, results indicate that high DBC corresponds to greater use of adaptive and relatively active (i.e., self-comforting) ER strategies and reduced use of more passive (i.e., attentional avoidance) or relatively less adaptive (i.e., focusing on prohibited object) ER strategies.

3.3.2. Concurrent at T2

For the DoG, higher parietal DBC predicted lower frequency of focusing on the prohibited object [$\beta = 0.44$; $t\,(35) = 2.10$, $p = .045$]. Similarly, for the WT, higher parietal DBC significantly predicted lower focusing on the prohibited object, the gift [$\beta = 0.49$; $t\,(35) = 2.55$, $p = .016$]. Taken together, results indicate that higher DBC corresponds to lower use of relatively less adaptive strategies across tasks.

3.3.3. Longitudinal T1 to T2

For the DoG, higher frontal DBC at T1 predicted greater alternative activity use at T2 [$\beta = -0.37$; $t\,(35) = -2.09$, $p = .045$, Fig. 1a]. For the WT, higher frontal DBC at T1 predicted greater alternative activity use at T2 [$\beta = -0.34$; $t\,(35) = -2.05$, $p = .049$, Fig. 1b]. Taken together, results indicate that higher DBC at 5–7 years old predicted greater use of active adaptive strategies (i.e., alternative activities) across tasks two years later.

3.3.4. Links between DBC and parent-reported child ER

DBC did not significantly predict parent-reported child ER concurrently at T1 (p's > 0.10). Concurrently at T2, higher parietal DBC predicted greater positive emotion regulation [$\beta = -0.42$; $t\,(35) = -2.17$, $p = .038$]. Longitudinally, higher frontal DBC at T1 predicted greater

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[2] Child age at T1 was entered in each regression including any T1 variables, and age at T2 was entered in each regression including any T2 variable. If both T1 and T2 variables were present in a regression, child age at both T1 and T2 were entered in the first step.

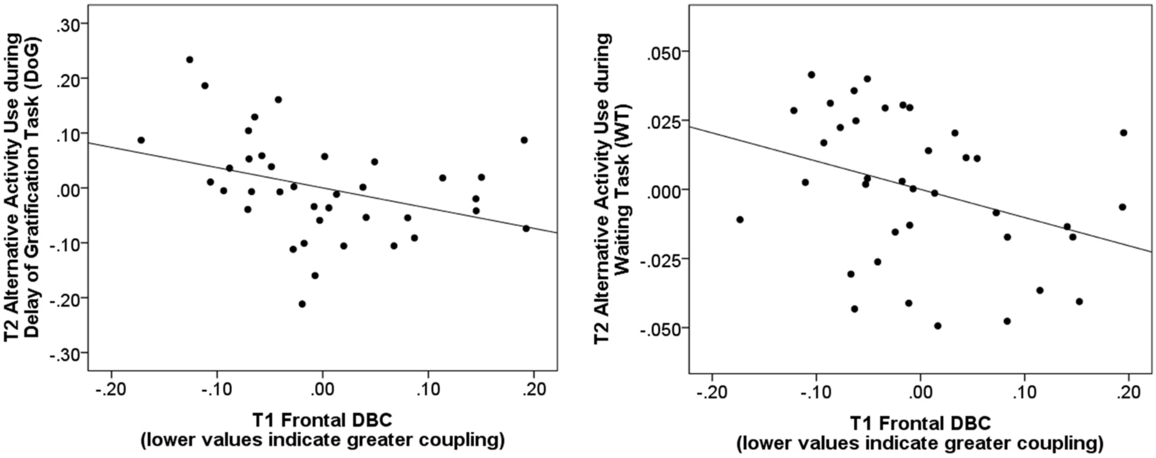

Fig. 1. Partial regression plots show greater frontal DBC, indicated by lower values, longitudinally predicted greater use of adaptive ER strategies two years later during both (a) the delay of gratification task and (b) the waiting task.

positive emotion regulation at T2 [β = −0.40; *t* (35) = −2.32, *p* = .027, Fig. 2].

4. Discussion

The present study was the first to directly link delta-beta correlation to observed ER among typically-developing children. Consistent with predictions, coherence between delta and beta frequency bands was concurrently and longitudinally associated with behavioral and parent-report measures of child ER. Both frontal and parietal (but not central) DBC was associated with observed spontaneous ER strategies and parent-reported positive ER.

Higher DBC was associated with observed ER behaviors across two emotionally challenging contexts. At T1, higher frontal DBC corresponded to greater use of self-comforting, a relatively adaptive strategy particularly for younger children, and this effect was significant in the DoG and marginal in the WT. Further, higher frontal DBC at T1 also marginally predicted less frequent focusing on the prohibited object in the DoG, which included looking at, touching, picking up, or tasting the desired treat - a strategy associated with less successful delay of gratification. Interestingly, higher parietal DBC was marginally related to reduced use of one adaptive strategy, attentional avoidance, which involved averting gaze away from the prohibited object for an extended period without actively engaging in another activity. While these marginal effects should be interpreted with caution, future research should examine whether high DBC corresponds to active but not passive attempts to manage unpleasant emotions.

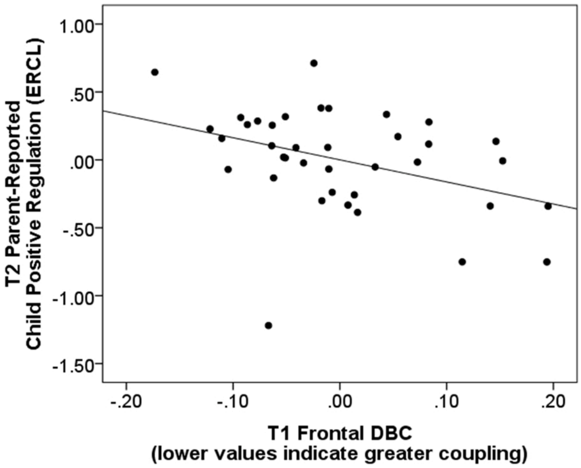

Fig. 2. Partial regression plot shows greater frontal DBC, indicated by lower values, longitudinally predicted greater parent-reported child ER two years later.

Concurrently at T2, higher parietal DBC corresponded to lower use of relatively less adaptive strategies (i.e., focusing on prohibited objects) across both behavioral tasks, as well as greater parent-reported positive ER. Thus, while frontal DBC frontal was consistently linked to observed ER when measured among 5- to- 7-year-olds, only parietal DBC was associated with observed ER among 6- to- 9-year-olds, indicating a potential developmental shift in the predictive validity of DBC across recording sites.

Longitudinally, higher frontal DBC at T1 predicted greater alternative activity use two years later, an adaptive and relatively mature strategy as it requires active attentional deployment and engagement. Higher frontal DBC at T1 predicted greater parent-reported positive ER at T2, further emphasizing the longitudinal link between higher frontal DBC and adaptive ER. Prior studies (Phelps et al., 2016) have suggested that lack of DBC specificity in younger children may be explained by neurodevelopment of earlier maturing posterior and later-maturing anterior brain regions. Thus, the predictive power of frontal DBC among younger children may indicate that the ability to achieve frontal coherence earlier in development confers regulatory advantages. By middle to late childhood, the majority of typically developing children may show frontal DBC but are still distinguished by parietal DBC. This highlights the need to examine DBC at multiple scalp locations in childhood.

Strengths of this study include the biobehavioral approach, longitudinal design, and focus on individual differences versus group-level quantification of DBC. Observed child ER was also examined across two emotionally challenging tasks, one of which the child was alone (DoG) and the other during which parents were present (WT). While results showed similar patterns in links between DBC and observed ER across these two contexts, recent research (Anaya, Vallorani, & Pérez-Edgar, 2021a and Anaya, Vallorani, & Pérez-Edgar, 2021b) indicated that greater DBC was associated with dyadic synchrony in social interactions. While it was not a goal of the present study to examine nuances of parent-child interactions during the WT, future research should clarify the role of social context on the behavioral correlates of DBC.

Several limitations of the present study must be considered. First, due to attrition, the sample size for T2 was substantially smaller than T1, limiting the sample available for longitudinal analyses. Therefore, we were underpowered to rigorously test longitudinal hypotheses, and thus findings should be interpreted as exploratory. Further, the limited sample size prevented the current study from leveraging more advanced statistical approaches (e.g., multilevel modeling) and include additional potentially relevant covariates (i.e., family demographics, child internalizing or externalizing symptoms), all of which should be examined in future work. Nonetheless, this study has the capacity to inform future biobehavioral research, and ideally will be replicated in studies with larger samples of typically developing children.

Next, while EEG data was processed in 1 s segments, mean power for delta and beta bands across the full 2-minute task was used to quantify DBC, consistent with prior studies (e.g. Phelps et al., 2016). Since the DBC metric is meant to capture synchrony between frequency bands and associated functional brain regions, this averaging approach may overlook meaningful individual differences that could appear in more finely-grained temporal dynamics by looking from one second to the next (Anaya et al., 2020). Future research should leverage more advanced statistical approaches (e.g., multi-level modeling) to track moment-to-moment dynamics of intra-individual DBC.

Finally, while the present study provided evidence for high DBC as adaptive among typically-developing school-aged children, prior research (e.g., Phelps et al., 2016; Poole et al., 2020; Poole & Schmidt, 2019) has shown that children with temperamental behavioral inhibition, dysregulated fear, or clinically-significant anxiety also show high DBC. While a strength of the present study is a focus on typically developing children, we were limited in terms of capturing distinctions between healthy levels of DBC and exaggerated DBC potentially indicating overcontrol. That is, perhaps the level of high DBC among typical children would be considered low or moderate DBC in a clinical sample. Future research should recruit large developmental samples including individuals with both healthy ER and clinically-relevant ER difficulties. This will allow for identification of benchmarks for potentially moderate DBC reflecting healthy ER and extreme DBC indicating over-control characteristic of psychopathology.

In sum, the current study advances the growing literature on DBC as a neural metric that reflects ER ability and informs future investigations of developmental changes in DBC throughout the lifespan. Taken together, results suggest that higher levels of DBC may underlie the ability to deploy active ER to delay gratification and manage frustration, and thus successfully self-inhibit during emotional challenges.

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Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.biopsycho.2021.108225.

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