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RESEARCH ARTICLE

Interactions among stress, behavioral inhibition, and delta–beta coupling predict adolescent anxiety during the COVID-19 pandemic

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Abstract

The COVID-19 pandemic brought about unprecedented changes and uncertainty to the daily lives of youth. The range of adjustment in light of a near-universal experience of COVID restrictions highlights the importance of identifying factors that may render some individuals more susceptible to heightened levels of anxiety during stressful life events than others. Two risk factors to consider are temperamental behavioral inhibition (BI) and difficulties in emotion regulation (ER). As such, the current paper focused on BI examined prior to COVID, because of its developmental link to anxiety and ER, as difficulties may be associated with differences in anxiety. We examined a neurocognitive marker of ER processes, delta–beta coupling (DBC). The current paper had two goals: (1) to examine BI in relation to COVID-related worry and social anxiety experienced during the pandemic, and (2) to explore the role of individual differences in early DBC in the relationship between BI and anxiety outcomes 6 months apart during COVID-19 ($n = 86$; T1 $M_{age} = 15.95$, $SD = 1.73$; T6 $M_{age} = 16.43$, $SD = 1.73$). We found support for the moderating role of DBC in the relationship between BI levels and social anxiety disorder (SAD) symptom severity during the pandemic. Here, high BI was predictive of increased SAD symptom levels in adolescents with stronger DBC.

KEYWORDS
adolescents, anxiety, behavioral inhibition, COVID-19, delta–beta coupling, emotion regulation

1 | INTRODUCTION

The pandemic triggered by the novel coronavirus (SARS-CoV-2) and coronavirus disease 2019 (COVID-19) brought about unprecedented changes to the daily lives and routines of people worldwide, including government-implemented quarantine, social distancing, work-from-home orders, and school closures. Increases in depression, anxiety, and posttraumatic stress were the most common clinical psychological reactions to the pandemic in adults (Brooks et al., 2020). Youth faced extraordinary interruptions to their daily and social lives (e.g., school curriculums moving online, disruptions to extracurricular activities, and restrictions on seeing non-household members) and experienced prolonged states of loneliness and forced social isolation, exacerbating rates of mental illness in youth (Cost et al., 2022; Lavigne-Cerván et al., 2021; Loades et al., 2020; Xie et al., 2020; Zhou et al., 2020).

Previous work examining traumatic and stressful life events suggests that adolescents may be particularly vulnerable to worsening mental health conditions such as posttraumatic stress disorder, anxiety disorders, and depression in response to such events (Comer et al., 2008; McLaughlin & Hatzenbuehler, 2009; Zavos et al., 2012). Adolescence is a unique developmental period during which distinct changes across almost every area of life are occurring. These changes

include physiological and hormonal development (i.e., puberty [Laviola et al., 2003] and brain development [Spear, 2013]), changes in cognitive and emotional capabilities (Casey et al., 2008; Rosenblum & Lewis, 2003), as well as changes in social environments including relationships with family and peers (Csikszentmihalyi et al., 1977). The multitude of changes occurring simultaneously results in a "pile-up" of life events (Simmons, 1987) and stressors (Larson & Ham, 1993) that adolescents must learn to navigate. Many of the new challenges facing adolescents are emotion related, as they often report relatively more negative and fewer positive emotions day-to-day than in childhood (Larson & Ham, 1993). As such, the emotional challenges adolescents face may be influenced by their ability to regulate their emotional responses to negative events (Steinberg, 2008), such as the COVID-19 pandemic.

Studies early in the pandemic provided support for initial concerns regarding increased rates of mental health difficulties among youth (O'Sullivan et al., 2021; Panchal et al., 2023; Stavridou et al., 2020). Findings from a rapid review early in the pandemic pointed to an increase in the prevalence of distress, including anxiety and depressive symptoms during COVID-19 (Racine et al., 2020). For example, in two studies, ~19% (Xie et al., 2020) and ~37% (Zhou et al., 2020) of adolescents reported pervasive anxiety symptoms, both of which are much higher than the typical prevalence rate of ~13% (Polanczyk et al., 2015). A twofold increase in social anxiety has also been reported during the pandemic relative to prior years (2013 and 2015), with 47% of adolescents self-reporting elevated levels of social anxiety in 2021 (Ranta, et al., 2024). Furthermore, increases in anxiety symptoms were highest among children and adolescents with preexisting mental health concerns (Cost et al., 2022). The range of responses to and outcomes despite a common COVID restrictions highlights the importance of identifying factors that may render some individuals more susceptible to heightened levels of anxiety during stressful life events than others.

Two risk factors to consider are temperamental behavioral inhibition (BI) and difficulties in emotion regulation (ER). BI is an established predictor of anxiety, with research suggesting that approximately 40% of children high in BI will develop clinical levels of anxiety by adolescence or early adulthood (Clauss & Blackford, 2012; Sandstrom et al., 2019). Early BI has been linked to later deficits in the ability to effectively understand, react to, and manage one's emotional experiences (Penela et al., 2015) and to the maintenance of anxiety-related disorders (Aldao et al., 2010; Mennin et al., 2007). Delta–beta coupling (DBC), the correlation between relative power in the delta and beta frequency bands (Knyazev et al., 2006), is derived from electroencephalogram (EEG) measures of neural activity and has been conceptualized as a neural index reflecting the capacity for ER. DBC has also been associated with both BI in children and adults (Putman, 2011; van Peer et al., 2008) and anxiety in adults (Knyazev, 2011; Miskovic, Moscovitch, et al., 2011; Schutter & Van Honk, 2005). As such, the current paper aims to examine anxiety and worry experienced during the pandemic, particularly in the context of elevated risk due to BI, to understand the impact on stress and anxiety throughout a 6-month window in the first year of the pandemic. In addition, we examine how DBC, as a marker for ER substrates, may moderate these associations.

1.1 | BI, risk for social anxiety, and ER as a moderator

BI is one of the most robust predictors for the development of an anxiety disorder (Rapee et al., 2009; Sandstrom et al., 2019). BI is an early emerging temperament style characterized by sensitivity to novelty and the avoidance of unfamiliar contexts or people (Fox et al., 2005; Kagan et al., 1984). The link between BI and social anxiety disorder (SAD) is particularly strong, with previous research indicating a four- to sevenfold increase in the risk for developing later SAD among children exhibiting high BI (Chronis-Tuscano et al., 2009; Clauss & Blackford, 2012). However, the developmental outcomes of BI children are highly variable; not all BI children display continuity of this temperamental trait nor do all BI children go on to develop social anxiety (Clauss & Blackford, 2012). Regulatory or control processes deployed by BI children in response to threatening events differentially impact a child's risk for anxiety (Henderson et al., 2015). BI children who deploy more automatic, stimulus-driven processes (e.g., inhibitory control, freezing behaviors), rather than planned/controlled goal-directed processes (e.g., task switching), when faced with threats may be at heightened risk for anxiety and may be more likely to develop maladaptive social and emotional functional profiles, even if not rising to clinical levels (Buzzell et al., 2021; Valadez et al., 2021; White et al., 2011).

For example, high-BI toddlers who used more reactive control processes during adolescence exhibited higher levels of anxiety relative to those adolescents using more proactive control processes (Troller-Renfree et al., 2019). Employing rapid, automatic control processes may lead to an overgeneralized, rigid pattern of responding (e.g., restraint, rigid overcontrol) in efforts to regulate either internal or external emotional states, and implementation in inappropriate contexts (Eisenberg et al., 2002). Therefore, difficulties with ER may be an individual difference factor among BI children associated with later social difficulties and increased social anxiety levels (Penela et al., 2015). As such, the current paper aims to examine how BI might moderate the impact of the pandemic on adolescent social anxiety. Specifically, the current paper explores how increased BI may mean higher sensitivity to the changes youth faced due to the COVID-19 outbreak, and ER may modulate some of that sensitivity to context leading to differential anxiety outcomes.

Individual differences in ER capacity are risk factors for, or protective factors against, psychopathology (Aldao et al., 2010). ER refers to the process by which individuals seek to monitor, evaluate, and redirect their emotional responses through the use of cognitive and/or behavioral strategies (Gross, 2002). D'Avanzato and colleagues (2013) found that adults with SAD and major depressive disorder (MDD) more often employed inflexible, maladaptive strategies such as rumination and emotion suppression instead of more adaptive ER strategies such as reappraisal and problem-solving. For example, individuals with SAD are more likely to use suppression techniques for both positive and negative emotions as well as less reappriasal of these emotions relative to heathly controls (Blalock et al., 2016). On the other hand, the use of adaptive ER strategies such as cognitive reappraisal, problem-solving,

and acceptance is associated with lower levels of depressive and anxiety symptoms (Gross, 2002; Weinberg & Klonsky, 2009). In addition to the use of specific strategies, the ability to flexibly employ different coping strategies across stressful contexts has been associated with better mental health (Aldao et al., 2010, 2015; Bonanno & Burton, 2013; Kashdan & Rottenberg, 2010). In the context of SAD, individuals report experiencing higher levels of anxiety during anxiety-provoking events relative to healthy controls and demonstrate more inflexibility in their use of ER strategies to cope (Goodman, et al., 2021). Additionally, greater use of flexible ER early in treatment was associated with less distress and impairment later on (Dalrymple & Herbert, 2007). The inability to successfully deploy ER skills also predicts higher levels of subsequent anxiety symptoms (Aldao et al., 2010; Berking et al., 2008; Hofmann et al., 2012; Mennin et al., 2009; Wirtz et al., 2014). In particular, difficulty regulating emotions such as worry has been linked to elevated levels of anxiety and fear in adolescents (Weems et al., 2000).

Adolescence is an important time for the development of ER, with significant changes in cortical–subcortical circuitry associated with regulatory flexibility during this time (Ahmed et al., 2015). Evidence from neuroimaging research suggests that brain regions and networks central to ER (i.e., the prefrontal cortex [PFC]) continue to develop through adolescence and into adulthood (Paus et al., 2008). In addition to cortical regions, subcortical and limbic regions (such as the amygdala) involved in ER also show developmental changes during the adolescent period. The connections between these regions and the PFC continue to mature, highlighting adolescence as a time of plasticity for these regions and therefore a critical period for the development of ER.

While the behaviors characteristic of BI children (e.g., withdrawal, avoidance) may serve to reduce high levels of arousal during social situations, these behaviors may also contribute to the development of poor regulatory skills. In novel, stressful social situations, BI children employ excessive vigilance and self-monitoring (McDermott et al., 2009) and what they conceive as appropriate and adaptive control and regulation may not align with reality. The resulting rigidity and restraint expressed may reflect overcontrol (Eisenberg et al., 2002). This overcontrol may limit children in their ability to deploy flexible ER strategies to adjust and cope in stressful situations. Such overt rigid behavior has been linked to internalizing problems (Eisenberg et al., 2010; Nigg, 2000). For example, overcontrol has been seen to be a moderating factor predicting increased risk for SAD among high-BI children (White et al., 2011) and children exhibiting early social fear (Brooker et al., 2016). Therefore, ER ability may work to buffer against increased social anxiety during stressful life events particularly among those high in BI.

1.2 | DBC marker of regulation

One emerging electrocortical activation pattern that has been examined in relation to ER is DBC. DBC is the correlation between relative power in EEG-derived delta and beta frequency bands (Knyazev et al., 2006). The cross-frequency coupling of fast (beta) and slow (delta) oscillations at rest is thought to reflect the coherence between cortical and subcortical networks of the brain (Knyazev & Slobodskaya, 2003) involved in the regulation of emotion (Anaya et al., 2021a) and stress (Poppelaars et al., 2018). Delta power reflects subcortical emotion generation (Knyazev et al., 2003), and beta power is enhanced in contexts that call for self-regulation (Engel et al., 2001; Knyazev & Slobodskaya, 2003) linking increased power to the allocation of regulatory processes.

In the context of typical development, greater levels of DBC may be beneficial for adaptive neural regulatory processes and the use of effective ER strategies during emotional challenging contexts (Myruski et al., 2022). Here, increased communication between the cortical areas involved in top-down regulation and the subcortical systems linked to emotional processes may work to deploy active ER strategies (i.e., engagement in behaviors unrelated to the task at hand). However, elevated coupling in clinical samples may reflect rigid and overcontrolled regulation.

Relative to nonsocially anxious adults, greater DBC was observed among socially anxious adults during the anticipation of a public speech (Miskovic et al., 2010). Here, increased DBC may reflect the inability to successfully regulate emotional distress when faced with a stressful event among socially anxious individuals. Conversely, decoupling has been observed in participants with greater avoidance of threat during a dot-probe task (Putman, 2011). As attention to threat plays a key role in the etiology and maintenance of anxiety-related disorders (Amir et al., 2009; Bar-Haim et al., 2007; Susa et al., 2012; Valadez et al., 2022), this association between lower levels of DBC and reduced attention to threat may point to effective ER strategies in efforts to keep anxiety low. High DBC has been seen in infants (Brooker et al., 2016) and adults with higher salivary cortisol, an endocrinological marker of both BI and anxiety (Schutter & Van Honk, 2005). After the administration of cortisol, a significant increase in coupling between the delta and beta bands was observed with a stronger correlation seen in adults scoring higher on the Behavioral Inhibition Scale (BIS) compared to those adults scoring lower on the BIS (van Peer et al., 2008).

Recent research supports the relation between DBC and BI, with children scoring higher in BI exhibiting greater coupling compared to children scoring low in BI (Poole et al., 2020). Furthermore, greater DBC has been seen among toddlers with dysregulated fear, an early predictor of anxiety risk, potentially reflecting overcontrol of ER, which may contribute to an unnecessary readiness to respond to perceived threat (Phelps et al., 2016). DBC has also been specifically associated with SAD (Anaya et al., 2021a; Miskovic et al., 2010; Miskovic, Campbell, et al., 2011; Miskovic, Moscovitch, et al., 2011), such that a greater, more positive delta–beta correlation has been observed in socially anxious compared to low socially anxious youth. Indeed, Miskovic et al. (2011) saw reductions in DBC among youth with social anxiety after 12 weekly sessions of cognitive behavioral therapy (CBT), a structured form of psychotherapy that incorporates strategies aimed at identifying and modifying thoughts and behaviors that contribute to emotional distress (Barlow, 2008).

In adults, DBC is sensitive to external influences such as performance-based feedback. In particular, greater coupling was associated with the expectation of pending bad news (Knyazev et al., 2005, 2006), which could require a regulatory response. Stronger

coupling between the delta and beta frequency bands has been seen in individuals with higher state levels of anxiety during an anxiogenic situation (Knyazev, 2011) and in situations of uncertainty (Knyazev et al., 2006). Thus, higher DBC may reflect the capacity of regulatory networks to downregulate tonically high arousal levels in the subcortical networks. This neural overcontrol is thought to contribute to the difficulties with ER associated with BI and anxiety. Overall, in the context of inhibited temperament and anxiety, greater DBC could indicate the requirement for increased cortical regulation of brain regions responsible for generating emotions and/or an amplified emotional response, while de-coupling has been associated with a relaxed, nonanxious state (Schutter et al., 2006). Therefore, the current paper posits that greater coupling between the delta and beta bands may be a marker of heightened vulnerability to increased states of social anxiety during the COVID-19 pandemic, particularly for youth high in BI.

1.3 | The current study

Because of the established link between BI and social anxiety, and elevated risk among BI for difficulties with ER, the current paper focused on social anxiety during the pandemic. The current study therefore sought to identify risk factors for worsening social anxiety symptoms in adolescents during the pandemic, particularly in the context of BI. By leveraging data collected prior to the start of the pandemic (further referred to as Pre-COVID), we were able to examine how early measures of BI and DBC might impact adolescent social anxiety and worry experienced throughout the beginning of the pandemic. Adolescent social anxiety and COVID-related worry were assessed at two timepoints during the pandemic, with the first timepoint (T1) aligning with the start of a new virtual learning school year, and the last timepoint (T6) approximately 6 months later. Therefore, the two major goals of this study were to (1) understand adolescent well-being during the pandemic particularly in the context of BI and (2) explore the role of individual differences in a neural correlate of ER in the relationship between BI and anxiety during COVID-19.

During the initial stages of the pandemic, news and media coverage of the COVID-19 virus was seemingly constant. It is reasonable to assume adolescents would report increased anxiety given previous research noting heightened levels of worry among young people experiencing ongoing uncertainty (Peleg & Mass-Friedman, 2013) and following a natural disaster (Newnham et al., 2020). Additionally, there were significant disruptions to the context of normative developmental experiences in adolescence, such as the shift from spending most of their time with parents to peers, the emergence of romantic relationships, and identity exploration (Rogers, Ha, et al., 2021). For individuals with SAD, such disruptions may be thought to provide symptomatic relief; however, prolonged involuntary social isolation may exacerbate SAD symptomology (Loades et al., 2020). Lockdown measures during the pandemic limited adolescents' contact and social interactions with friends and peers providing individuals who experience social phobia with positive reinforcement for avoiding situations that they may otherwise be encouraged to engage in. Additionally, adolescents who previously did not have social phobia may have begun to experience worries and concerns around social situations, particularly as schools began to reopen (Lim et al., 2022). Recent work examining the association between anxiety and COVID-related worry found that anxiety sensitivity, including social concerns, was a significant predictor of COVID-19 worry (Rogers, Bogiaizian, et al., 2021). The relation between worry and anxiety has long been established, with worry as a key contributor to anxiety maintenance (Dickson et al., 2012; McLaughlin et al., 2007; Newman et al., 2013; Weems et al., 2000).

BI has also been linked to anxiety through specific associations with worry, such that high-BI youth reporting elevated levels of anxiety also reported higher levels of worry (Muris et al., 1999). Furthermore, recent work found a specific pathway from early BI to elevated social anxiety levels during COVID-19 in young adulthood through adolescent worry dysregulation (Zeytinoglu et al., 2021). Taken together, the established link between BI and SAD may create risk for increased worry during the pandemic. Therefore, the current study anticipated positive associations among BI, COVID-related worry, and social anxiety experienced during the pandemic.

There is evidence to suggest that ER strategies associated with BI, such as less active/more passive strategies (Suarez et al., 2021), may not be the most optimal when coping with stressful events. These strategies that involve inhibiting or restraining negative emotion have been seen to moderate the relation between stressful events and negative mood (Langens & Stucke, 2005). Greater coupling between the delta and beta frequency bands is thought to reflect cortical overcontrol, which is indicative of difficulties with ER associated with anxiety. Therefore, the current paper postulates that early patterns of DBC, as a proxy for individual differences in the capacity to regulate emotional responses, may be associated with varying levels of anxiety throughout COVID-19. During the COVID-19 pandemic, individuals exhibiting greater ER abilities reported experiencing less generalized anxiety disorder (GAD) symptoms (Munoz-Navarro et al., 2021). It is therefore anticipated that DBC will moderate the relation between BI and adolescent anxiety levels such that adolescents exhibiting higher BI and greater DBC prior to COVID would report increased anxiety levels throughout the pandemic. With a well-established relation between BI and SAD (Clauss & Blackford, 2012; Fox et al., 2021), and evidence linking increased SAD symptoms in high-BI youth to poor ER (Suarez et al., 2021), we also anticipated seeing associations between greater DBC and SAD symptomatology at higher levels of BI.

2 | METHODS

2.1 | Participants

Participants from two large, longitudinal studies, Attention and Social Behavior in Children (BRAINS; Anaya et al., 2021a, 2021b; Liu et al., 2018) and the Temperament, Evolving Emotions and Neuroscience Study (TEENS), which collected BI and anxiety data prior to the start of the COVID-19 pandemic (Pre-COVID), were invited to participate in a study aimed at investigating the effects of the pandemic on adolescent mental health ($n = 295$). Data from 86 families who provided

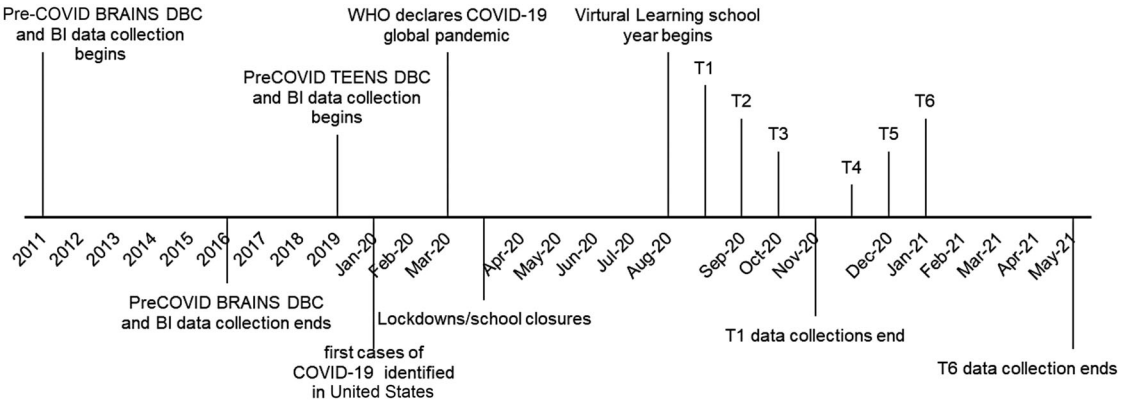

FIGURE 1 Study timeline. DBC , delta–beta coupling; BI, behavioral inhibition; WHO, World Health Organization; Pre-COVID, collected prior to COVID-19 onset; T1, timepoint 1, when initial surveys were sent out; T2–T5, timepoints 2 through 5, surveys sent ~1 month apart; T6, timepoint 6, final survey sent ~6 months after T1.

data at T1, approximately 6 months after initial government implemented lockdowns and school closures in response to the COVID-19 outbreak, and about 6 months later at T6[1] (see Figure 1 for graphical depiction of the study timeline), were used in the current study (M_{age} at T1 = 15.95 years, *SD* = 1.72, 51% female). For approximately 67% of the sample (BRAINS), Pre-COVID data were collected on average 6.38 years (range: 4.37–8.84 years) prior to the onset of COVID-19 and collection of T1 measures ($n = 58$, $M_{age} = 10.17$ years, $SD = 1.06$, 51.7% female), and for the remaining 33% of the sample (TEENS; $n = 28$, $M_{age} = 13.62$ years, $SD = 0.65$, 50% female), Pre-COVID data were collected 1.03 years prior (range: 0.55–1.88 years), for a total sample size of 86 adolescents (Table 1S).

The majority of families in this combined sample were college-educated (some college or technical degree = 15.7%, college degree = 38.6%, graduate degree or graduate training = 42.1%, high school degree = 3.6%). At T1, 56.6% of parents were employed full-time, 24.1% were employed part-time, and 19.3% were unemployed, with 76.8% reporting a salary of $60,000 or greater in 2019. Adolescent race was reported as 90.4% White, 2.4% Black/African American, and 7.2% more than one race. Ninety-five percent of youth were reported as Not Hispanic or Latinx, and 4.8% reported as being of Hispanic or Latinx decent. No adolescents reported being Asian, American Indian/Alaska Native, or Native Hawaiian/other Pacific Islander.

2.2 | EEG data collection, reduction, and analysis

2.2.1 | EEG data

Continuous EEG data were collected from 45 adolescents prior to the onset of the COVID-19 pandemic during an alternating 1-min eyes-open, eyes-closed resting-state task.[2] For adolescents from the BRAINS study ($n = 30$), EEG activity was recorded during a 6-min resting task using a 128-channel geodesic sensor net (Electrical Geodesics Inc.), using Cz as the reference electrode. The remaining 15 participants from the TEENS study ($n = 15$) completed a 4-min resting task and were fitted with an actiCAP snap electrode cap (EASYCAP GmbH) with 32 channels and gel-based Ag/AgCl active sensors (Brain Products GmbH), with all electrode sites referenced to FCz during collection. Electrodes were positioned equidistantly according to the spherical montage of the cap. Mastoid electrodes were applied directly to the skin overlaying the bones behind the ears. Impedances were kept below 10 Ω; however, EEG data were analyzed if impedances were less than 20 kΩ (Kappenman & Luck, 2010). The raw data were sampled at 1000 Hz. Electro-oculogram (EOG) electrodes were applied directly to the skin underneath and around the eyes to collect horizontal and vertical eye movements.

EEG data were processed using Brain Vision Analyzer (Brain Products GmbH). Data were re-referenced to the average of the right and left mastoid. EEG data were resampled offline using a zero-phase shift Butterworth high-pass filter with a 0.1-Hz cutoff (3 dB or half-power point) and 12-dB octave roll-off, and the low-pass filter was a zero-phase shift Butterworth type with a 40-Hz cutoff (3 dB or half-power point) and 12-dB octave roll-off.

Ocular correction was performed to identify and correct blinks and horizontal eye movements (Gratton et al., 1983), using VEOG and HEOG channels. Data were segmented by trial (open, close) and further divided into 1-s bins, then baseline-corrected for the entire segment. Semiautomatic artifact rejection was applied using the following automatic criteria to remove channels from analyses by segment: voltage steps exceeding 30 μV, changes within a given segment greater than 150 μV, and activity under 0.5 μV persistent for 100 ms or more. Each

[1] Measures not used in the current study were collected at approximately 1 month increments between T1 and T6. The current study uses only measures obtained at the initial survey (T1) and 6 months later (T6), and the notations T1 and T6 are used to maintain consistency across studies using this dataset.

[2] For approximately 66% of the sample (BRAINS; $n = 30$, $M_{age} = 16.97$ years, $SD = 1.74$), EEG data were collected 6.77 years prior to the onset of the COVID-19 pandemic, and for the remaining 33% of the sample (TEENS; $n = 15$, $M_{age} = 14.69$ years, $SD = 0.72$), these data were collected 1.03 years prior to the pandemic.

segment was then subjected to visual inspection to eliminate further artifacts not previously captured.

2.2.2 | DBC data

To compute DBC, second-by-second EEG power from the delta (1–4 Hz) and beta (13–25 Hz) frequency bands were exported from an eyes-open, eyes-closed resting-state task (Anaya et al., 2021b). To obtain a measure of baseline, participants were instructed to relax and sit quietly for 4 or 6 min. Experimenters kept time and instructed participants to open or close their eyes in an alternating fashion; eyes were kept open (facing a black computer monitor) for the first, third, and fifth minutes. Artifact-free data were submitted to Fast Fourier Transformation (FFT) with a 50% Hamming window overlap. All EEG delta and beta power values were natural log (ln) transformed to reduce skewness. To derive the measure of DBC, the correlation between delta and beta was calculated from the average of target electrode sites to create composite regions including frontal (F3/Fz/F4), central (C3/Cz/C4), and parietal (P3/Pz/P4) for analysis (Myruski et al., 2022; Phelps et al., 2016). As there were no significant differences between the eyes-open and eyes-closed conditions in the target composite regions (frontal: $t(44) = -0.48$, $p = .63$; central: $t(44) = -0.08$, $p = .94$; parietal: $t(44) = -0.16$, $p = .88$), they were combined into a common baseline condition to provide a more reliable and stable estimate relative to examining separate EO and EC conditions. Missing EEG data due to COVID-19 mandated pauses in research ranged from 48.3% to 50.6%.

2.3 | Measures

2.3.1 | Behavioral inhibition

Parents reported on their child's BI using the Behavioral Inhibition Questionnaire (Bishop et al., 2003), a 30-item instrument that measures the frequency of BI-linked behavior in the domains of social and situational novelty, on a 7-point scale ranging from 1 (*hardly ever*) to 7 (*almost always*), with higher scores indicating greater BI at Pre-COVID. Example items include "*Approaches new situations or activities very hesitantly*" and "*Seems nervous or uncomfortable in new situations.*" The BIQ has been shown to be a reliable and valid measure for assessing BI not only in young children (Bishop et al., 2003), but also in adolescents (Broeren & Muris, 2010). This measure generates a summed total score that was used as the primary measure of BI. Missing data for the Total BIQ score was 0.02% ($n = 1$), with 1 extreme value. The current sample yielded excellent internal consistency reliability ($\alpha = .96$).

2.3.2 | Social anxiety symptomology

Parents reported on adolescent anxiety at Pre-COVID, T1, and again about 6 months later (T6; $M = 5.32$ months, $SD = 1.09$) using the Parent (P) version of the Screen for Child Anxiety Related Emotional Disorders (SCARED; Birmaher et al., 1997). The SCARED assesses anxiety symptoms experienced in the last 3 months using 41 items scored on a 3-point response scale from (0) *not true or hardly ever true* to (2) *very true or often true*. This measure yields one total anxiety score and five subscales corresponding to DSM anxiety disorder classifications including GAD, separation anxiety disorder (SEP), SAD, significant school avoidance, and panic disorder or significant somatic symptoms. At T1, 13 adolescents met the clinical cutoff of ≥25 for the presence of an anxiety disorder, and 21 adolescents met this cutoff at T6. For the SAD subscale, a score of ≥8 indicates the presence of social phobia. At T1, 14 adolescents met this cutoff, and at T6, 12 adolescents met this cutoff.

At T1, missing data for the SAD subscale were 4.7% ($n = 4$) and 19.8% ($n = 17$) at T6. The 41-item SCARED has been shown to have good internal consistency ($\alpha = .90$), with subscales yielding coefficient values between .78 and .87 (Birmaher et al., 1999). The current sample yielded good internal consistency reliability as indicated by the omega coefficient (T1 SAD: .90; T6 SAD: .92). Within the smaller subsample ($n = 45$), missing data for the SAD subscale were 6.7% ($n = 3$; extreme values $n = 1$) at T6 and 20% ($n = 9$) at T6.

2.3.3 | COVID-related stress

Parents completed the CoRonavIruS Health Impact Survey (CRISIS; Nikolaidis et al., 2021) at T1 and T6 of the current study. The CRISIS aims to capture the extent and impact of life changes induced by the COVID-19 pandemic on the mental health and behavior of individuals and families across six domains—exposure/infection, worries, life changes, mood states, substance use, and daily behaviors. While the full scale was administered, we focused on the COVID Worries subscale (see Table 2S for full list of questions) identified by Nikolaidis and colleagues (2021). This five-item subscale asked parents to rate how "worried" their child has been about being infected, their friends or family being infected, their physical and mental/emotional health being influenced by COVID-19, and their level of hope that the crisis would end soon (scale from *not at all* to *extremely*), as well as the time spent reading or talking about COVID-19 (scale from *never* to *most of the time*). The items are rated on a 5-point Likert scale and were averaged to create a total COVID worry score, with higher scores indicating greater COVID-related worry. At T1, parents were instructed to report on these items since the onset of the pandemic ($\alpha = .76$) and were asked to reflect on the past month at T6 ($\alpha = .74$). Missing data ranged from 3.5% (T1, $n = 3$) to 19.8% (T6, $n = 17$).

2.4 | Statistical analysis plan

2.4.1 | Missing data

Extreme values were truncated to be within ±3 standard deviations of the mean. Missing data analyses revealed no associations with demographic variables, including child's sex, race, ethnicity, parental

education level or income, or BI, anxiety, or COVID-worry (p values >.05). An analysis of missing data conducted using SPSS 23 suggested that missing data likely occurred at random, yielding nonsignificant Little's Missing Completely at Random (MCAR) tests ($\chi^2_{(292)} = 75.10$, $p = .44$); therefore, the Multiple Imputation by Chained Equations (MICE) package in R (van Buuren, 2007) was used to account for missing data. Following recommendations for handling data with ~50% missing information, a total of five imputations were performed (Schafer, 1999). Further, Meyer et al. (2020, p. 410) discuss the impact of COVID-19-related missingness and state "Most data that are missing due to pandemic reasons may be argued to be MCAR or missing at random (MAR), especially if missingness is due to structural reasons" (e.g., government-enforced closures or sites stopping study-related activities). The collection of EEG data from the TEENS sample for the current study was impacted by government-imposed lockdown measures in response to the COVID-19 pandemic, thus creating missing data randomly across the entire sample. While not testable, it is reasonable to assume that DBC would have likely been similar among missing participants had there not been a pandemic interrupting data collection.

2.4.2 | Analyses

Age at T1 was entered as covariates for all analyses. Because of the notable timing difference for the collection of the prior-to-COVID measures between the two subsamples, this difference was controlled for in all analyses using Pre-COVID measures. As females were reported as experiencing higher levels of COVID worry at T1 (female: $M = 2.83$, male: $M = 2.42$, $t(84) = -2.79$, $p = .01$) and T6 (female: $M = 2.26$, male: $M = 2.45$, $t(84) = -1.39$, $p = .08$), sex was entered as a covariate for all analyses examining worry. Partial correlations were used to explore the relations between Pre-COVID BI and COVID-related anxiety and social anxiety experienced during the pandemic. As calculating numerous correlations increases the risk of a type I error, and falsely concluding the presence of a significant correlation, Bonferroni correction (Curtin & Schulz, 1998) was applied within each single correlation analysis.

The role of DBC

Hierarchical linear regression analyses were conducted to examine the role of DBC in the relationship between BI and social anxiety levels during the COVID-19 pandemic. Adolescent age at T1 was controlled for in all analyses. Because of the timing difference between measures obtained prior to COVID across the two subsamples, we controlled for this difference in all analyses. Analyses conducted using SCARED measures at T6 were also explored controlling for SCARED scores at T1. Analyses were conducted on SCARED SAD scores at time 1 and 2. DBC was examined at frontal, central, and parietal regions. In efforts to reduce collinearity among predictors that may be highly correlated with one another, all variables in each regression model making up their respective interaction term were mean-centered prior to analysis. Interaction terms were therefore computed using the mean-centered terms of BIQ and DBC. All analyses were conducted using IBM SPSS Statistics version 23.0 and the macro-program PROCESS 3.5 model 1 (Hayes, 2017), with BIQ scores entered as the predictor, SCARED scores entered as the dependent variable, and DBC as the moderator. To explore significant interaction effects and regions of significance, graphical displays were created based on the convention for plotting interactions (Carden et al., 2017).

3 | RESULTS

3.1 | Descriptive statistics and correlations

Table 1 displays descriptive statistics for measures of BI and DBC obtained prior to the onset of the COVID-19 pandemic (Pre-COVID), as well as SAD and COVID-related worry examined at the start of the current study during COVID-19 (T1) and approximately 6 months following T1 (T6). As there were no significant associations between BIQ scores and CRISIS COVID worry, no further analyses were conducted.

3.2 | DBC and BI data collected prior to COVID and social anxiety during COVID

The overall model including BIQ scores and parietal DBC significantly predicted SAD scores at T1 and T6. At T1, the overall model including Pre-COVID BIQ scores and parietal DBC significantly predicted SAD scores ($F(5, 80) = 9.34$, $R = .61$, $R^2 = .37$, $p = .000$). The interaction term BIQ scores by DBC was marginally significant in the prediction of T1 SAD ($\Delta R = .03$, $F(5, 80) = 3.73$, $b = .14$, $t = 1.93$, $p = .057$, 95% confidence interval [CI] [.00, .29]); however, the standardized slope for the effect of SAD scores was significant when levels of DBC were at mean ($\beta = .05$, $t = 4.35$, $p = .000$, 95% CI [.03, .07]) and 1 *SD* above the mean ($\beta = .07$, $t = 5.47$, $p = .000$, 95% CI [.04, .10]) (Figure 2). See Table 3S for full regression model.

The overall model regressing SAD scores onto the interaction between Pre-COVID BIQ scores and Pre-COVID DBC significantly predicted T6 SAD scores ($F(5, 80) = 9.21$, $R = .53$, $R^2 = .28$, $p = .000$), specifically at the parietal region. The interaction between Pre-COVID BI and DBC accounted for a significant amount of the variance in SAD symptomology at T6 ($\Delta R = .05$, $F(5, 80) = 6.01$, $b = .19$, $t = 2.45$, $p = .016$, 95% CI [.04, .35]). The standardized slope for the effect of SAD scores was significant when DBC was at mean levels ($\beta = .03$, $t = 2.64$, $p = .010$, 95% CI [.01, .05]) and 1 *SD* above the mean ($\beta = .06$, $t = 4.51$, $p = .000$, 95% CI [.03, .09]) (Figure 3). This interaction was further probed using the Johnson–Neyman technique (Carden et al., 2017; Johnson & Neyman, 1936) and revealed a positive association between BI and SAD when parietal DBC is greater than 0.12 (Figure 4). See Table 4S for full regression models.

TABLE 1 Descriptive statistics and partial correlations for Pre-COVID BIQ and DBC, and SCARED SAD and CRISIS worry measured at T1 and T6.

	1	2	3	4	5	6	7	8
Pre-COVID measures								
1) BIQ								
DBC								
2) Frontal	−.06							
3) Central	.03	.10						
4) Parietal	−.04	.33*	.36**[a]					
T1 measures								
5) SAD	.5**[a]	−.08	−.02	−.21†				
6) CRISIS worry	.01	−.11	.01	.02	.30*			
T6 measures								
7) SAD	.38**[a]	−.03	.01	−.17	.71**[a]	.29*		
8) CRISIS worry	−.03	.06	−.03	.23*	.09	.46**[a]	.17	
M	96.12	0.10	0.10	0.18	3.73	2.63	3.90	2.36
SD	34.19	0.12	0.14	0.16	3.47	0.70	3.46	0.66

Abbreviations: BIQ, Behavioral Inhibition Questionnaire; CRISIS, CoRonavIruS Health Impact Survey; DBC, delta–beta coupling; Pre-COVID, collected prior to COVID-19 onset; SAD, social anxiety disorder subscale of the SCARED; SCARED, Screen for Child Anxiety Related Emotional Disorders; T1, timepoint 1; T6, timepoint 6.

[a]Significance maintained when corrected for multiple comparisons.

*$p < .05$; **$p < .001$; †$p < .01$.

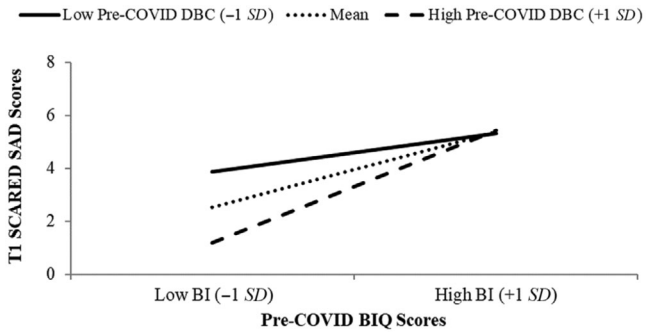

FIGURE 2 The interaction between Pre-COVID BI and parietal DBC predicting social anxiety symptomology during the initial phase of the COVID-19 pandemic. DBC, delta–beta coupling; BIQ, Behavioral Inhibition Questionnaire; BI, behavioral inhibition; Pre-COVID, collected prior to COVID-19 onset; T1, timepoint 1; DBC, delta–beta coupling; SD, standard deviation; SAD, social anxiety disorder subscale scores from the Screen for Child Anxiety Related Emotional Disorders (SCARED).

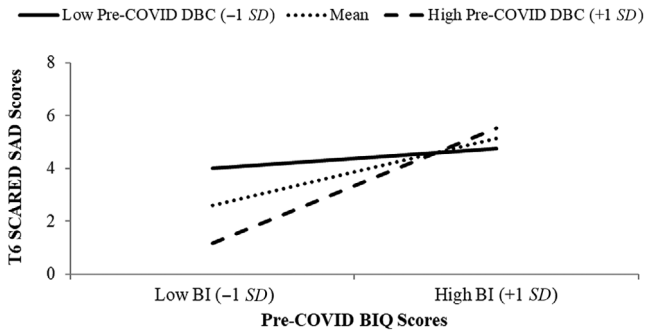

FIGURE 3 The interaction between Pre-COVID BI and parietal DBC in predicting social anxiety symptomology during the COVID-19 pandemic. DBC, delta–beta coupling; BIQ, Behavioral Inhibition Questionnaire; BI, behavioral inhibition; Pre-COVID, collected prior to COVID-19 onset; T6, timepoint 6; SD, standard deviation; SAD, social anxiety disorder subscale scores from the Screen for Child Anxiety Related Emotional Disorders (SCARED).

4 | DISCUSSION

The current study examined factors associated with heightened risk of worsening anxiety symptoms during the pandemic. Therefore, the two major goals of this paper were to (1) examine prepandemic BI and ER that might contribute to social anxiety and COVID-related worry experienced during the pandemic and (2) explore the role of individual differences in a neural correlate of ER in the relationship between BI and social anxiety during COVID-19. To address these goals, the current study used parent-reported measures of BI as well as adolescent EEG data collected prior to the start of the COVID-19 pandemic as indicators of adolescent social anxiety and worry experienced during the pandemic. Adolescent social anxiety and COVID-related worry were assessed at two timepoints during the pandemic, with T1 aligning with the start of a new virtual learning school year and T6 approximately 6 months later.

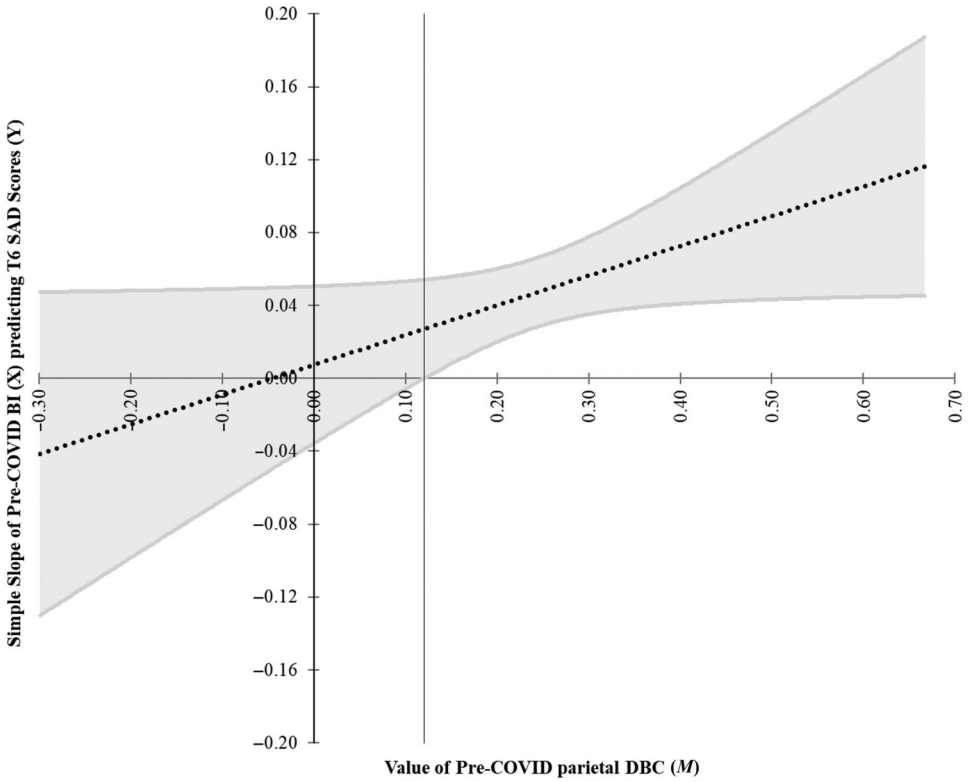

FIGURE 4 The Johnson–Neyman graph for the moderation effect of Pre-COVID parietal DBC on the association between Pre-COVID BI and levels of social anxiety during the pandemic (T6). Notice the effect of Pre-COVID BI on T6 social anxiety symptomology is only significant for high levels of coupling. For any values of the moderator for which the confidence bands contain 0, the effect of the independent variable on the dependent variable is not significant. DBC, delta–beta coupling; BI, Behavioral inhibition Questionnaire; Pre-COVID, collected prior to COVID-19 onset; T6, timepoint 6; SAD, social anxiety disorder subscale scores form the Screen for Child Anxiety Related Emotional Disorders (SCARED).

4.1 | Pre-COVID BI and DBC, and social anxiety and worry experienced during the pandemic

As expected, higher levels of BI prior to the onset of COVID-19 were related to higher levels of social anxiety at both timepoints during the COVID-19 pandemic. While there is growing research providing support for the association between increased anxiety symptoms during the pandemic and preexisting mental health concerns (Cost et al., 2022), research is limited regarding how prior BI levels alone might impact social anxiety symptom severity during such a stressful period. As not all BI children go on to develop an anxiety disorder (Clauss & Blackford, 2012; Fox et al., 2005, 2021), understanding how BI may impact mental health during major life events may help to illuminate those at greatest risk when preexisting conditions such as anxiety are not evident. Intrinsic and extrinsic factors may contribute to the risk for developing an anxiety disorder (Lahat et al., 2011). Mumper and colleagues (2020) saw that high-BI children reported greater later anxiety symptoms after exposure to high levels of stress. Our BI–anxiety finding aligns with these results, while also emphasizing concurrent social anxiety symptom severity instead of postexposure anxiety. These findings contribute new data to the literature highlighting BI as a vulnerability for increased risk of adolescent anxiety during stressful life events.

We did not find evidence for significant direct associations between DBC and BI or SAD. These findings come somewhat unexpectedly given previous research linking heightened BI (van Peer et al., 2008) and social anxiety (Miskovic et al., 2010) with a greater, more positive delta–beta correlation. However, there are a few differences worth noting. While van Peer and colleagues (2008) did find an association between high DBC and high BI, the BIS was used to select a priori high- and low-BI groups, calculating DBC separately for each group, using a between-group design. In contrast, we used a within-subjects design to derive DBC, resulting in each individual having their own delta–beta correlation value, as opposed to only having a group-level value. Indeed, prior work with a subsample of adolescents in the current study (Anaya et al., 2021a) found that the relation between BI and DBC varied with the assessment method. Additionally, while the BIS and temperamental BI are conceptually similar, the BIS assesses sensitivity to punishment and avoidance motivation (Gray, 1981), while temperamental BI is conceptualized as a trait associated with fear and wariness in response to novelty and unfamiliar contexts or people (Kagan et al., 1984; Fox et al., 2005). With regard to our social anxiety findings, there is research to linking greater DBC with lower social anxiety levels (Myruski et al., 2022; Poppelaars et al., 2018). Here, greater DBC may be more adaptive among individuals low in social anxiety, potentially working to effectively downregulate stress and thus keeping anxiety low.

4.2 | The moderating role of Pre-COVID DBC in the relationship between early BI and social anxiety during COVID-19

We found evidence for the moderating role of DBC examined prior to COVID in the relationship between BI and anxiety during COVID-19. Specifically, adolescents whose parents reported them as high in BI and exhibited greater DBC prior to the onset of COVID-19 were reported as experiencing higher levels of SAD symptomology during the pandemic. This finding is in line with the abundance of research linking DBC (Anaya et al., 2021a; Miskovic et al., 2010; Miskovic, Campbell, et al., 2011; Miskovic, Moscovitch, et al., 2011) and BI (Chronis-Tuscano et al., 2009; Clauss & Blackford, 2012) to social anxiety. Adolescents with a history of high BI and greater DBC across parietal regions were reported by parents as experiencing higher levels of social anxiety throughout the pandemic (T1 and T6). Low-BI adolescents with greater DBC were reported as expressing low levels of social anxiety at T6. Taken together, these results may suggest that when BI is low, greater DBC may work to buffer against heightened levels of SAD symptomology during stressful life events associated with a great deal of uncertainty. However, elevated DBC among high-BI adolescents may potentially signal overcontrol in efforts to downregulate high emotional states when faced with stressful and uncertain situations.

Greater DBC may reflect inflexible neural pattern of overcontrol and overregulation, characteristics associated with anxiety and BI (Liu et al., 2018). Our results demonstrating elevated levels of SAD during the pandemic among high-BI adolescents exhibiting greater DBC, but not among adolescents exhibiting low BI, seem to speak to this notion, as overcontrolled individuals struggle with change and lack of structure, which may result in increased withdrawal during stressful situations. Here, our results with respect to increased SAD may be specific to those adolescents who exhibit both heightened BI and greater DBC, as youth low in BI with greater DBC seem to experience lower levels of SAD symptoms. Throughout the initial phases of COVID-19, government-implemented quarantine, social distancing, work-from-home orders, and school closures forced significant changes on the daily lives of youth. BI youth often quickly encode potential signs of threat (Henderson et al., 2015), and such disruptions in structure and schedule may have exacerbated SAD symptoms among adolescents exhibiting exaggerated neural regulation.

Greater DBC may be reflective of more automatic control processes, therefore rendering high-BI adolescents more vulnerable to experiencing higher levels of social anxiety during stressful life events. The tendency to rapidly engage automatic orienting responses heightens risk for anxiety in BI children (Henderson et al., 2015). However, among low-BI adolescents where this tendency may not be present, increased DBC may reflect adaptive regulation around stressful situations and mitigate SAD symptoms (Myruski et al., 2022). The interaction between BI and DBC was seen at both the first timepoint after the initial onset of the COVID-19 pandemic (T1) and was still evident 6 months later (T6), which may speak to the importance of considering elevated DBC in the maintenance of anxiety, particularly social anxiety among high-BI adolescents who may show less effective adaptation to stressful life events over time. While this study cannot address this question, it is worth considering in future work whether DBC is important to the maintenance of anxiety symptom. The interaction between BI and DBC was seen to predict social anxiety symptomology at both timepoints during the pandemic, suggesting an overall increase in social anxiety symptom severity. Results suggest that differences in the capacity to regulate emotional responses at a neural level may leave those who are temperamentally inhibited more susceptible to experiencing heightened levels of social anxiety during stressful life events.

Our DBC findings were specific to parietal electrodes sites. While we did not have specific hypotheses regarding regions, our findings do algin with other work associating greater DBC with BI and SAD at parietal regions (Anaya et al., 2021a; Poole & Schmidt, 2020; Poppelaars et al., 2021). Previous work has also implicated parietal areas in ER processes (Dedovic et al., 2009). Poppelaars et al. (2021) saw an association between increased DBC across the parietal region and larger cortisol increases in response to stress. In line with this, and the notion that DBC is associated with exaggerated neural regulation (Phelps et al., 2016), our findings suggest that BI adolescents, particularly those with increased DBC in parietal regions, may be at greater risk of experiencing increased anxiety during stressful life events that involve a great deal of change and uncertainty. Here, exaggerated coupling across parietal regions may be particularly important to consider for difficulties with ER during stressful life events such as the COVID-19 pandemic.

4.3 | Limitations

This study has limitations; therefore, reported findings and interpretations should be regarded with caution. First, although controlled for in all analyses, the timing difference between the collection of the Pre-COVID measures of BI and DBC across the two samples has the potential to affect findings. Data collection for the BRAINS study took place between the years 2011 and 2016, while collection for the TEENS study began in 2018 continued through March 2020. Thus, the time window between initial testing and T1 ranged from 0.55 to 8.84 years. Second, some aspects of EEG data collection varied across study subsamples. Specifically, the EEG recording systems and resting-state tasks differed; ~67% of the DBC subsample completed a 6-min resting task with EEG being recorded on a 128-channel sponge-based system, while the remaining 33% were administered a 4-min resting task with EEG data being collected on a 32-channel gel-based system. However, identical EEG processing parameters were used across the samples. Additionally, although the Bonferroni correction for multiple comparisons (Curtin & Schulz, 1998) was applied within each single correlation analysis within the larger sample ($n = 86$), the total number of comparisons was still relatively large. If possible, future research should aim to replicate these findings in a larger sample for increased power. Further, our measures of DBC were obtained prior to the onset

of COVID-19 and we did not collect concurrent measures; therefore, we cannot make claims about concurrent regulatory processes. However previous research has shown stability in DBC (Myruski et al., 2022). Lastly, one other limitation is that our sample is majority White, upper-middle class. Studies have shown that the pandemic disproportionately impacted marginalized communities (Tai et al., 2021). Thus, our findings may not be generalizable to other populations.

5 | CONCLUSION

The strengths of the present study include the use of longitudinal data to further our understanding of risk for anxiety symptoms during stressful life events. Unlike previous research around stressful and traumatic life events, the circumstances around COVID-19 provided us the unique opportunity to assess distress *during* a major, stressful period with population-wide impact. This further allowed the current study to examine how early measures of BI and ER might predict distress throughout a major life event.

To conclude, the current study sought to identify adolescents who may be at risk of increased distress during the COVID-19 pandemic. We examined early BI, as it is linked to the development of anxiety (Rapee et al., 2009), and ER, as differences in the capacity to regulate one's emotions may be associated with the differences in anxiety (Schäfer et al., 2017). Adolescents may be particularly vulnerable to the detrimental effects of the pandemic on mental health due to neurodevelopment underlying ER, coupled with peak social anxiety onset during this developmental window. Therefore, the current study examined individual differences in DBC, an electrocortical pattern thought to reflect one's capacity for ER (Knyazev, 2007; Knyazev et al., 2006).

Given the existing literature on the relations between BI, anxiety, and maladaptive coping, it is reasonable to assume that individual differences in the capacity to regulate stress and emotion might differentially impact those youth already at risk of experiencing greater distress during such a major life event as COVID-19. The current study also saw support for the moderating role of DBC, a neurocognitive proxy for ER processes, in the relationship between BI levels measured prior to COVID and social anxiety symptom severity during the pandemic. Here, high BI was predictive of SAD symptom levels in those adolescents with stronger DBC. Taken together, this study demonstrates that earlier measures of BI and neural regulation may be useful for identifying adolescents who may be more vulnerable to heightened levels of anxiety and distress during major life events.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflicts of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available upon reasonable request from Kristin A. Buss.

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SUPPORTING INFORMATION

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