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Induced error-related theta activity, not error-related negativity, predicts task performance as well as anxiety and worry during real-life stress in a youth sample

Gil Shner-Livne[1] | George A. Buzzell[2] | Nathan A. Fox[3] | Tomer Shechner[1]

[1]School of Psychological Sciences and the Integrated Brain and Behavior Research Center, University of Haifa, Haifa, Israel

[2]Department of Psychology and the Center for Children and Families, Florida International University, Miami, Florida, USA

[3]Department of Human Development and Quantitative Methodology, University of Maryland, College Park, Maryland, USA

Correspondence
Tomer Shechner, School of Psychological Sciences and the Integrated Brain and Behavior Research Center, University of Haifa, Abba Hushi 199, Mt Carmel, Haifa, Israel.
Email: tshechner@psy.haifa.ac.il

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Abstract

Objective: The study examined differences between induced error-related theta activity (4–7 Hz) and error-related negativity (ERN) in youth and their unique associations with task performance as well as anxiety and worry during real-life stress a year later. We hypothesized that induced theta, but not the ERN, would predict task performance. We also hypothesized that induced theta would predict less anxiety and worries during situational stress a year later, while ERN would predict more anxiety and worries.

Method: Participants included 76 children aged 8–13 years who completed a flanker task while electroencephalogram (EEG) and behavioral data (t_0) were collected. Approximately 1 year later (t_1), during the first COVID-19 lockdown, 40 families from the original sample completed a battery of online questionnaires to assess the children's stress-related symptoms (anxiety, negative emotions and worries). We employed an analytical method that allowed us to differentiate between induced error-related theta and the evoked ERN.

Results: Induced error-related theta, but not ERN, was associated with behavioral changes during the task, such as post-error speeding. Furthermore, induced error-related theta, but not ERN, was prospectively associated with less anxiety, worries, and fewer negative emotions a year later during COVID-19 lockdown.

Conclusions: Findings suggest ERN and error-related theta are dissociable processes reflecting error monitoring in youth. Specifically, induced error-related theta is more robustly associated with changes in behavior in the laboratory and with less anxiety and worries in real-world settings.

KEYWORDS

anxiety, EEG error-monitoring, error-related negativity, theta, youth

1 | INTRODUCTION

Cognitive control refers to a set of neurocognitive abilities enabling individuals to monitor performance, facilitating optimal responses to changing or unfavorable circumstances/feedback (Cohen, 2014). An essential component of cognitive control is *error monitoring* (Taylor et al., 2007; Ullsperger et al., 2014) or the ability to self-monitor performance and detect when one deviates from task goals by committing an error. Error monitoring develops across childhood and adolescence (Buzzell, Richards, et al., 2017; Davies et al., 2004; Luna, 2009; Tamnes et al., 2013) and is thought to support goal-directed behavior by triggering changes in control allocation and/or shifting behavioral strategies (Danielmeier & Ullsperger, 2011; Wessel, 2018). At the electrophysiological level, error monitoring can be indexed by error-related changes in EEG activity recorded over the mediofrontal cortex via the *error-related negativity* (ERN) event-related potential (ERP) in the time domain, or error-related increases in 4–7Hz 'theta' oscillations within the time-frequency domain. However, prior work investigating the role of error monitoring in anxiety has focused almost exclusively on ERN, demonstrating error monitoring is enhanced in youth and adults with anxiety (although the direction of this association may be reversed in young children, e.g., Meyer et al., 2012). Enhanced ERN (i.e., more negative) predicts concurrent and prospective anxiety levels, including risk for anxiety following stressful life events (Meyer, Danielson, et al., 2017), such as the COVID-19 pandemic (Morales et al., 2022). Yet the ERN represents only one method of analyzing error-related EEG, and limited work investigates how error-related theta relates to anxiety in youth. This represents a critical gap in the literature, as emerging work suggests error-related theta more robustly predicts behavioral changes than ERN (Beatty et al., 2020, 2021; Valadez & Simons, 2018; Weinberg et al., 2012). Thus, work is needed to directly investigate whether and how error-related theta in youth relates to in-task behavioral performance and to their anxiety and worry levels in response to real-world situations. To these ends, the current study employed a peri-adolescent sample of youth (aged 8–13years) to investigate the ERN and error-related theta in relation to: (1) behavioral changes within a concurrent laboratory task; (2) levels of anxiety and worries 1year later during the COVID-19 pandemic, a real-world stressful situation.

Abundant developmental research has examined the association between the ERN elicited during a laboratory task and clinical characteristics, establishing the notion that anxiety is associated with enhanced error monitoring, at least when error monitoring is indexed via ERN (Buzzell et al., 2018; Fox et al., 2021; Meyer, 2022; Moser et al., 2013). Clinically anxious youth exhibit larger magnitude (i.e., more negative) ERN than non-anxious youth (for a review, see Meyer, 2017). Moreover, more negative ERN prospectively predicts anxiety disorder onset (Meyer, Nelson, et al., 2018) and increased symptom levels among clinically anxious youth across development (Meyer et al., 2021). Finally, more negative ERN during childhood or adolescence is linked to increased anxiety symptom levels when coping with future real-life stressful events, such as a natural disaster (Meyer, Danielson, et al., 2017) or the COVID-19 pandemic (Morales et al., 2022). Interestingly, larger ERN is more closely related to increase in worry and concerns about performance in anxiety disorders when assessed in a standard laboratory setting (Buzzell, Troller-Renfree, et al., 2017; Moser et al., 2013; Niu et al., 2023).

The ERN reflects mediofrontal EEG activity that could be explained, at least partially, by the phase-locking of 4–7Hz theta band oscillations ('evoked' activity) in response to errors (Cavanagh & Frank, 2014; Luu et al., 2004; Trujillo & Allen, 2007). In contrast, error-related theta power is typically derived in a way that captures both phase-locked ('evoked') and non-phase-locked ('induced') theta band activity in response to errors. When computed in this way, error-related theta power is sometimes referred to as 'total' power, as it is comprised of both phase-locked and non-phase-locked theta activity (Cohen, 2014). Thus, error-related ('total') theta power contains unique information absent from the ERN signal. Indeed, emerging work has identified dissociations in the functional roles of ERN and error-related theta power. While error-related theta power tends to more robustly predict changes in behavior (response time and/or accuracy) following errors, ERN is less consistently associated with such changes in post-error behavior within and across studies (Valadez & Simons, 2018; Weinberg et al., 2012). Extending this line of inquiry, two recent studies (Beatty et al., 2020, 2021) employed a signal processing technique allowing isolated measurement of the non-phase-locked ('induced') aspects of error-related theta power, after first removing all phase-locked activity shared with the ERN (for further details, see Cohen & Donner, 2013). This approach allowed, first, the isolation of the unique information present in the error-related theta power dynamics and, second, a more direct test of whether the phase-locked ERN or the non-phase-locked error-related theta power was more closely associated with changes in behavior. Consistent with prior work, error-related theta more robustly related to post-error behavioral dynamics than ERN (Beatty et al., 2020, 2021). Collectively, these findings reinforce the notion that ERN and error-related theta reflect dissociable aspects of error monitoring.

Despite recent progress distinguishing how ERN and error-related theta relate to changes in behavior, two unanswered questions remain. First, as such work has been performed almost exclusively in adult samples, it is unclear whether ERN and error-related theta also exhibit differential associations with post-error behavior in youth. Second, if the ERN and error-related theta differentially relate to in-task changes in behavior, this naturally leads to the question of whether they also differentially relate to risk for anxiety and worries. For example, prior work demonstrates that enhanced (i.e., more negative) ERN is a risk factor for increased anxiety in the context of stressful life events (Meyer, Danielson, et al., 2017; Morales et al., 2022). However, if error-related theta is more closely tied to positive responding, then it may serve as a protective factor (e.g., through associations with helpful coping strategies), not a risk factor for anxiety. In fact, recent work found error-related theta can be a protective factor against general psychopathology risk (Buzzell et al., 2020). However, limited work has investigated the role of error-related theta in predicting risk for anxiety symptomology in general or in response to stressful life events in particular.

To investigate these issues, we collected a community sample of youth aged 8–13 years. In the current study, we followed this sample for 1 year. The baseline (t_0) assessment involved EEG and behavioral data collection in the laboratory, along with collection of parents' self-reports of the children's levels of anxiety symptoms. The second time point (t_1) was approximately 1 year later, during the first COVID-19 lockdown in Israel, a stressful event characterized by increased worry, anxiety, and uncertainty (Nearchou et al., 2020; Perl et al., 2021; Samji et al., 2022). T_1 measurements included parent-report questionnaires to assess their children's anxiety, stress-related symptoms, worries, and negative emotions. We aimed to differentiate between induced error-related theta-band activity and ERN and to examine the unique association between each measure and task performance first in the lab and then in the context of real-life stress during the lockdown. We hypothesized that induced error-related theta, not ERN, would be associated with changes in task behavior (changes in response time and/or accuracy), echoing recent findings in adults. We also hypothesized that error-related induced theta at t_0 would predict less anxiety and worries when coping with stress and uncertainty a year later at t_1, while ERN would predict increment in worry, negative emotions, and levels of anxiety during real-life stress.

2 | METHOD

2.1 | Participants

Seventy-six children aged 8 to 13 years ($M = 10.45$ years, $SD = 1.49$; 49.3% females) participated in the first (baseline) visit to the laboratory (t_0), as part of a larger longitudinal study that examined the relationship between temperamental and neural characteristics in childhood and early adolescence and the onset of anxiety disorders in mid- and late adolescence. Participants were recruited through online advertisements on social media and by word of mouth. All participants completed an initial phone screening during which parents were asked about current or past psychiatric disorders. Those who reported no current/past psychiatric diagnoses, except of attention deficits (i.e., ADD/ADHD), were invited to a lab visit. During t_0, participants completed self-reported questionnaires and were interviewed using the semi-structured Anxiety Disorder Interview Schedule (ADIS-IV-P/C) to confirm they did not meet any diagnostic criteria for anxiety disorders, PTSD, OCD, mood disorders, ASD, eating disorders or psychotic spectrum disorders (Silverman & Albano, 1996). Only youth who did not meet current or past diagnoses were invited to participate in this longitudinal study. After the lab visit (t_0), two participants were excluded because of behavioral data recording issues, and another 11 were excluded for low behavioral performance (<50% overall accuracy). An additional eight were excluded from EEG analysis because of technical issues in the EEG ($n = 3$), noisy EEG data ($n = 1$), because they used psychotropic medication within 24 hours before their visit ($n = 2$), or because they did not have enough valid trials for reliable EEG indices ($n = 2$). Ultimately, 56 participants were included in the ERP analysis, 55 participants were included in the time-frequency analysis, and 63 participants in the behavioral analysis at t_0. For detailed information about participants excluded from the analyses at t_0, see Table S1.

Approximately 1 year later ($M = 13.84$ months, $SD = 4.72$, range: 7.8–21 months), during the first COVID-19 lockdown in Israel (March–April 2020), we approached 66 families who participated at t_0, and whose children were at least 10 years old at t_1. The age cutoff for participation was chosen to ensure all participants could understand and adequately complete the online questionnaires themselves. Forty families agreed to participate and filled out a battery of online questionnaires (t_1, $M = 11.85$ years, $SD = 1.2$; 40% females). No differences were observed between children who participated and those who declined to participate (t_1) in levels of anxiety symptoms or EEG patterns measured during the first visit; all $ps > .13$. For detailed information, see Table S2.

For each visit (t_0 and t_1), participants received a modest gift card valued at approximately US$15 for compensation. The study procedure was approved by the Institutional Review Board of the university. The legal guardians of child participants signed a consent form, and children signed assent forms prior to participation. All participants were verbally informed that they could stop the experiment at any time.

2.2 | Procedure and measurements

2.2.1 | Baseline visit (t_0)

At t_0, participants completed a flanker task (Eriksen & Eriksen, 1974) while EEG was recorded. Levels of anxiety were assessed using parent self-reported questionnaires.

Screen for Child Anxiety Related Emotional Disorders (SCARED)

The SCARED questionnaire is a commonly used measure for the assessment of anxiety symptoms in children (Birmaher et al., 1997). The questionnaire consists of 41 items assessing anxiety on five subscales related to specific clinical presentations: panic disorder, generalized anxiety disorder (GAD), separation anxiety disorder, social anxiety disorder, and significant school avoidance. We used the parent version of the questionnaire (SCARED-P) completed by the parent who accompanied the child to the laboratory. Each statement is rated on a 3-point Likert scale, from 0 ('not true or hardly ever true') to 1 ('somewhat true or sometimes true') and 2 ('very true or often true'). The maximum total anxiety score for each version is 82.

Flanker task

An arrow version of the flanker task was used to elicit error-related ERP and frequency activity (Eriksen & Eriksen, 1974). The task was presented on a computer screen in front of the child participants at approximately 50 cm viewing distance. Five horizontal arrowheads were presented in each trial. In 40%–60% of the trials, all arrows were congruent, pointing in the same direction ('<<<<<' or '>>>>>'). In the remaining trials, the middle arrow was incongruent in its direction ('<<><<' or '>><>>'). The congruent and incongruent trials were randomly presented. Each stimulus was presented for 200 ms, followed by an inter-task interval (ITI) that varied in length from 2300 to 2800 ms. Participants were instructed to press the right or the left mouse button according to the direction of the middle arrow.

Participants first completed a practice block of 30 trials. They were asked to respond as quickly and as accurately as possible. Following the practice, participants performed the task, comprising 11 blocks of 30 trials (total of 330 trials). After each block, participants received feedback based on their performance to ensure an adequate number of errors (Gehring et al., 2012). If the correct responses represented 75% of the total responses or less, they received the message 'Please try to be more accurate'; if their performance exceeded 90% correct answers, the message 'Please try to respond faster' was displayed. All other conditions were followed by the message 'You're doing a great job'.

EEG recording

Children's EEG was recorded using an elastic cap and an ActiveTwo BioSemi system (Biosemi, Amsterdam, Netherlands). A 32-channel electrode cap (AgAgCl electrodes, Biosemi) was used based on a 10/20 electrode placement system, with two more electrodes on the right and left mastoids. The data were digitized at a 24-bit resolution and sampled at a rate of 2048 Hz using a band-pass online filter of 0.16–100 Hz. Each active electrode was online referenced to the Common Mode Sense (CMS) active electrode. Before starting the experiment, the impedance of all electrodes was kept below 25 kΩ.

2.2.2 | Visit 2 (t_1)

About a year later (t_1), during the first COVID-19 lockdown, parents completed online parent-report questionnaires on their child experience. These questionnaires measured anxiety levels and COVID-19-related behaviors in their children, focusing on the children's negative emotions, worries and stress-related symptoms.

Screen for Child Anxiety Related Emotional Disorders (SCARED)

Anxiety assessment (via the SCARED-P) followed the same procedure as at t_0 (see above).

CoRonavIruS Health Impact Survey (CRISIS)

The CRISIS questionnaire was designed to measure the specific effects of the COVID-19 pandemic on youth and adults (Nikolaidis et al., 2021). The original English version was translated into Hebrew using a back-translation method. The survey has six parts that measure various aspects of the effect of the pandemic on youth: coronavirus health exposure status; COVID-19 particular worries; life changes due to the pandemic; mood states; daily behaviors; substance use. Caregivers are asked to rate mood states, daily behavior patterns, media use, and substance use for two time points: 3 months before the COVID-19 crisis and during the preceding 2 weeks. Two domains on the CRISIS questionnaire have shown excellent psychometric properties and thus were used in our statistical analyses (Nikolaidis et al., 2021):

1. *Emotions/worries* (during the last 2 weeks of the lockdown, and during the last 3 months before COVID-19,

December 2019 until February 2020): These are measured by ten items describing emotional states and feelings. Parents are asked to rate their level of agreement with each item on a 5-point Likert scale, from 1 ('not at all') to 5 ('extremely'). The score is computed by adding up the items' scores and ranges from 10 (indicating lower levels of worries and negative emotions) to 50 (indicating higher levels of worries and negative emotions). Examples include 'How worried was your child generally?'; 'How much was your child able to enjoy his/her usual activities?'; 'How lonely was your child?'.

2. *COVID-19 particular worries* (during the last 2 weeks of the lockdown): Parents are asked to rate how worried their child has been in various domains on a 5-point Likert scale, from 1 ('not at all') to 5 ('extremely'). The score is obtained by summing up the individual item scores, and it ranges between 5 (suggesting no worries) and 25 (suggesting extreme levels of worry). Examples include 'How worried has your child been about being infected?'; 'How worried has your child been about his/her physical health being influenced by Coronavirus/COVID-19?'; 'How worried has your child been about friends or family being infected?'

Additional subscales from the CRISIS questionnaire were not included in our analysis because of their lower internal consistency, as identified in a questionnaire validation study (Nikolaidis et al., 2021). Therefore, it was not advisable to use these subscales or dimensions in our analysis.

2.3 | Data analysis

2.3.1 | Flanker task behavioral data

Behavioral measures included the accuracy of each participant, expressed as a percentage of trials with correct responses, and average reaction times (RTs) in error and correct trials. To confirm the presence of standard flanker task effects, we computed mean accuracy as a function of trial congruency (congruent, incongruent), and we computed mean RTs as a function of congruency (congruent, incongruent) and response accuracy (error, correct). To maintain consistency with the electrophysiological analyses (and avoid confounding response accuracy and trial congruency), our analyses of post-error vs. post-correct behavior focused specifically on trials following incongruent error/correct trials.

As response time distributions were positively skewed, all response times were transformed to the natural logarithm (ln) of the response time to approximate a normal distribution more closely (Buzzell, Beatty, et al., 2017). For convenience of interpretation, RT descriptive data are presented without ln transformation. Post Error Slowing (PES) was defined as the difference between the averaged RT for correct trials following errors and averaged RT for correct trials following correct responses in the incongruent condition. Post Error Accuracy (PEA) was defined as the difference in accuracy for responses following errors and each individual's baseline accuracy for responses following correct trials (Beatty et al., 2020, 2021).

2.3.2 | EEG processing

EEG processing and analysis were performed using the FieldTrip toolbox (Oostenveld et al., 2011) and custom MATLAB scripts (MathWorks, Natick, MA). The data were lowpass filtered at 30 Hz and re-referenced to the average of the two mastoids. To correct for eye blinks and movements, we used an Independent Component Analysis (ICA) algorithm (Jung et al., 2000) on an identical copy of the raw data set (Winkler et al., 2015). First, we applied a 1-HZ high-pass filter and cut the data arbitrarily into epochs of 1000 ms. Epochs with significant noise were detected and removed if after fast Fourier analysis, the power in the 20–40 Hz band was greater than 30 dB or if raw voltage amplitude was ±1000 μV within a given epoch. If a channel contained more than 20% rejected data, the channel was removed entirely (Buzzell, Troller-Renfree, et al., 2017). We then ran ICA on the 1 Hz high-pass filtered data, using the Runica routine (Jung et al., 2000). Artifactual components representing blinks or saccades were detected manually by visual inspection (0 to 3 components for each participant). The ICA weights were then copied back to the original continuous data set (with 30 Hz low-pass filter), and all ICA components identified as artifacts were subtracted from the data and corrected.

For ERP, the data were segmented into epochs from 500 ms before the response to 1000 ms following the response (1.5 s) and then baseline-corrected in the time domain based on a 200 ms window between −500 and −300 ms before the response onset (Klawohn et al., 2020). For time-frequency representation and induced theta, the data were segmented into 4-s epochs (2000 ms before to 2000 ms after the response) to enable sufficient time-frequency resolution. Final artifact detection and rejection were conducted using an automated procedure. Trials were rejected if one of the following criteria was detected: a voltage difference exceeding 300 μV; a voltage step of more than 50 μV between sample points; a maximum voltage difference of <0.5 μV within 100 ms intervals (Meyer et al., 2012). Participants with more than 20% rejected data in the channels (Fz, Cz, Pz, FC1, and FC2) and time (500 ms before to 1000 ms following the response) of interest were excluded from analysis. Given the focus on error-related processing, and as errors typically occur in incongruent trials in the flanker task (Eriksen & Eriksen, 1974), all EEG analyses focused exclusively on error/correct incongruent trials to avoid confounding congruency with response accuracy (Buzzell et al., 2019). Participants included in the analysis of ERPs had an average of 1.85% rejected error trials (range: 0%–16.66%) and 1.81% rejected correct trials (range: 0%–20%). Participants included in the analysis of induced theta activity had an average of 1.88% rejected error trials (range: 0%–16.66%) and 1.77% rejected correct trials (range: 0%–20%).

2.3.3 | ERP analysis

The response-related ERPs were averaged separately for correct and error response trials (for incongruent trials only). ERN and CRN were calculated based on mean amplitude between 0 and 100 ms (Buzzell, Troller-Renfree, et al., 2017; Meyer, Carlton, et al., 2018). Error-related EEG activity tends to be maximal at FCz channel locations (Klawohn et al., 2020; Meyer et al., 2021; Olvet & Hajcak, 2008). However, the FCz channel was not included in the experiment's EEG system, so we used the average of frontocentral sites (Fz, Cz, FC1, and FC2) surrounding the FCz channel location (Buzzell, Troller-Renfree, et al., 2017; Klawohn et al., 2020). To isolate error-specific neural response, we have utilized regression-based difference scores (Meyer, Lerner, et al., 2017). First, we computed the ERN_{resid} by retaining the residual variance obtained from the regression using the CRN as a predictor of the ERN. Second, we computed CRN_{resid} by using the residual variance obtained from the regression using the ERN as a predictor of the CRN.

2.3.4 | Induced theta oscillation analysis

To isolate the activity of induced theta oscillation, we removed the average ERP waveform (phase-locked activity) from each epoch of the EEG signal before running time-frequency analysis (Beatty et al., 2020, 2021; Cohen & Donner, 2013). To measure induced theta power, we ran a time-frequency analysis on trial-level data using convolution in the time domain, with a set of complex Morlet wavelets. The frequency of the wavelets ranged from 2 to 15 Hz, with a width of 4.5 for each frequency band, to achieve an adequate trade-off between temporal and frequency resolution (Cavanagh et al., 2009). Next, we baseline-corrected the data within the frequency domain to a time window between −500 and −300 ms before the response onset and performed a decibel conversion (dB) to normalize the data.

For the statistical analysis, we calculated condition-specific induced theta power based on the average, across trials, of power between −100 and 300 ms after the response commission (Beatty et al., 2020) at pooled frontocentral sites (Fz, Cz, FC1, and FC2) (Buzzell et al., 2020), within the 4–7 Hz frequency range. To isolate error-specific theta response, we have utilized regression-based difference scores (Meyer, Lerner, et al., 2017). First, we computed Induced error-related theta power $(dB)_{resid}$ by using the residual variance obtained from the regression using the induced theta in correct trials as a predictor of the induced theta in error trials. Second, we calculated the Induced correct-related theta power $(dB)_{resid}$, by using the residual variance obtained from the regression using the induced theta in error trials as a predictor of the induced theta in correct trials.

2.3.5 | Statistical analysis

All statistical analyses were conducted using SPSS (version 23).

Flanker task behavioral data (t_0)

We performed preliminary analyses to assess overall task accuracy and to confirm the presence of standard flanker task congruency effects in the accuracy and RT data. We used a paired-sample *t* test to compare mean accuracy of congruent vs. incongruent. For RT, we employed a Congruency (congruent, incongruent) × Accuracy (error, correct) RM-ANOVA to test for the expected significant main effects of congruency and accuracy. Paired-sample *t* tests were employed to compare mean accuracy following incongruent error/correct trials and to compare mean RT of correct trials following incongruent error/correct trials.

Flanker task EEG data (t_0)

We conducted paired-sample *t* tests to examine differences in neural responses in error and correct trials in the flanker task. We also used Pearson's correlation to assess the association between all neural indices (induced theta and ERPs) and self-reported anxiety.

Using EEG indices (t_0) to predict concurrent flanker task behavioral performance

We used Pearson's correlation to assess the association between all neural indices (induced theta and ERPs) and behavioral performances and post-error behavioral adaptations.

Anxiety, negative emotions, and worries during COVID-19 lockdown (t_1)

To examine differences in self-reports before and during the lockdown, we conducted a paired-sample *t* test.

Using EEG indices (t_0) to prospectively predict anxiety, negative emotions, and worries during COVID-19 lockdown (t_1)

We used Pearson's correlation to assess the association between all neural indices at t_0 (induced theta and ERPs) and later anxiety and negative emotions/worries at t_1.

Examination of the moderating effect of age on the association between EEG indices (t_0) and anxiety, negative emotions, and worries during COVID-19 lockdown (t_1)

We conducted three moderation analyses wherein the relationship between error-related EEG indices at t_0 and anxiety and worry levels at t_1 (using the CRISIS and SCARED questionnaires) was moderated by the age of the participants at t_0. These were conducted using the SPSS Hayes macro PROCESS (Preacher & Hayes, 2004), model number 1, which provides an estimate of the indirect effect between the independent and dependent variables, an estimated standard error, and 95% confidence intervals for the population value of the indirect effect.

Internal consistency of self-reported questionnaires and EEG indices

We computed the internal consistency of self-reported questionnaires using Cronbach's alpha coefficients of the individual items constitute each subscale and total score. Detailed information on the internal consistency of the self-reported questionnaires is presented in Table S5. We calculated the internal consistency of the EEG indices based on generalizability theory using the ERP Reliability Analysis (ERA) Toolbox version 0.5.2, employing Markov Chain Monte Carlo (MCMC) simulations with 3 chains and 10,000 iterations to estimate variance components (Clayson et al., 2021; Clayson & Miller, 2017a, 2017b). For the ERP and time-frequency indices of interest, we computed the minimal number of trials needed to achieve a reliability threshold of Φ (dependability coefficient) >0.6, as well as overall Φ values for the sample included in all statistical analyses (after removing individuals with insufficient trials to achieve the reliability threshold). Identified trial thresholds (minimum needed to achieve reliability) were as follows: ERN, 13; CRN, 13; induced theta power in error trials, 17; induced theta power in correct trials, 49. After removing participants with insufficient trials, observed Φ coefficients and 95% credible intervals (CI) for the sample used in all subsequent statistical analyses were as follows: ERN, 0.83 (95% CI: 0.75–0.89); CRN, 0.93 (95% CI: 0.91–0.96), induced theta power in error trials, 0.79 (95% CI: 0.70–0.86), induced theta power in correct trials, 0.78 (95% CI: 0.68–0.85).

3 | RESULTS

3.1 | Flanker task behavioral data (t_0)

3.1.1 | Preliminary analyses

For the participants included in the behavioral analyses (following exclusion of participants with <50% accuracy), the overall task accuracy was 79.25%. As expected, a paired-sample *t* test demonstrated participants responded more accurately on congruent trials ($M = 86.91\%$, $SD = 9.13$) than incongruent trials ($M = 71.68\%$, $SD = 12.41$), $t(62) = -12.69$, $p < .001$. For RT, a Congruency (congruent, incongruent) × Accuracy (error, correct) RM-ANOVA yielded the expected significant main effect of congruency, $F(1, 62) = 113.87$, $p < .001$, $\eta^2 = 0.65$, such that participants showed overall slower RTs in incongruent trials ($M = 479.31$ ms, $SD = 102.15$) than congruent trials ($M = 412.48$ ms, $SD = 96.36$). Furthermore, a significant main effect of accuracy emerged, $F(1, 62) = 565.06$, $p < .001$, $\eta^2 = 0.90$; as expected, participants responded faster in error trials ($M = 362.82$ ms, $SD = 84.85$) than correct trials ($M = 528.97$ ms, $SD = 117.79$).

In line with previous findings (Buzzell, Richards, et al., 2017; Meyer et al., 2012), older children responded faster in both error and correct trials in the incongruent condition, $r(63) = -.414$, $p < .001$, $r(63) = -.460$, $p < .001$, respectively. Moreover, older children did not exhibit lower accuracy, $r(63) = -.078$, $p = .541$, suggesting more efficient performance.

3.1.2 | RT and accuracy following incongruent error/correct trials

Means and standard deviations for behavioral data following incongruent error/correct trials are presented in Table 1.

No significant differences emerged between RTs for correct trials following incongruent-error and incongruent-correct responses, $t(62) = .727$, $p = .470$, suggesting no specific post-error slowing (PES) effect at the group level. However, a significant difference emerged between accuracy following incongruent-error and accuracy following incongruent-correct responses (Post-Error Accuracy (PEA)), $t(62) = -2.264$, $p = .027$.

3.2 | Flanker task EEG data: ERP domain (t_0)

A paired sample t test revealed a significant difference between ERN and CRN, $t(55) = -7.751$, $p < .001$. As expected, ERN magnitude ($M = 5.072$, $SD = 9.263$) was larger (relatively more negative) than CRN magnitude ($M = 12.306$, $SD = 8.438$); see Figure 1.

A negative correlation emerged between age and ERN residual scores (ERN_{resid}) only at a trend level, $r(56) = -.256$, $p = .057$, such that older children exhibited more negative (increased magnitude) ERN (ERN<CRN).

3.3 | Flanker task EEG data: frequency domain (t_0)

3.3.1 | Induced theta

A paired sample t test revealed an increase in induced theta power magnitude in response to error ($M = 1.566$, $SD = 1.414$) compared to correct trials ($M = 0.263$, $SD = .893$), $t(54) = 7.824$, $p < .001$; see Figure 2.

At t_0, significant correlations emerged between age and induced theta power in error trials, and error-related induced theta (expressed by the residual scores), $r(57) = .501$, $p < .000$, $r(57) = .461$, $p < .000$, respectively. Older children showed greater error-specific induced theta power.

3.4 | Using EEG indices (t_0) to predict concurrent flanker task behavioral performance

First, we analyzed the association between brain indices and general performance during the task. As depicted in Table 2, smaller (more positive) ERN_{resid} was associated with slower overall RT in error-trials. Furthermore, induced theta power in error and correct incongruent trials, and error-related theta using residual scores were negatively correlated with RT in both error and correct trials. Error-related theta activity was not associated with changes in overall accuracy, while enhanced theta in correct trials predicted worse accuracy rates. Such an association might imply a less effective investment of cognitive resources, which in turn caused poorer performance.

TABLE 1 RT and accuracy following incongruent error/correct trials.

Variables	*M*	*SD*
RT correct trials following incongruent-error trials	536.80 ms	137.13
RT correct trials following incongruent-correct trials	528.58 ms	121.39
Accuracy following incongruent-error trials	81.04%	12.71
Accuracy following incongruent-correct trials	83.86%	9.46

Abbreviation: RT, reaction time.

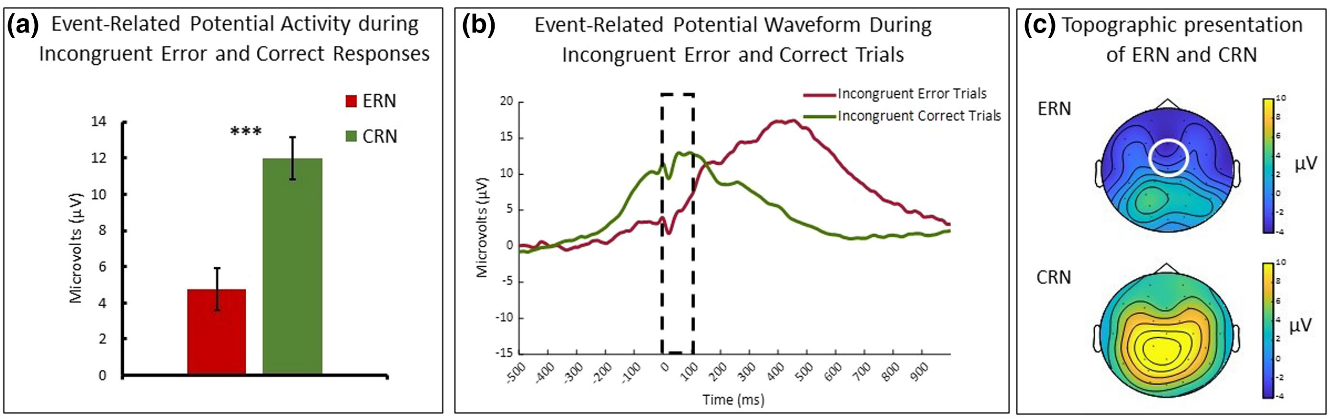

FIGURE 1 (a) Difference in response-locked event-related potential during incongruent error and correct trials: ERN and CRN averaged across frontocentral electrodes FCz (Fz, Cz, FC1, and FC2) during the first 100 ms following response. (b) Average waveforms across all participants during incongruent error and correct trials in frontocentral electrodes (Fz, Cz, FC1, and FC2). (c) Topographic presentation of ERN snd CRN between 0 and 100 ms following response. Dashed rectangle denotes the time window used for statistical analyses of ERP (0–100 ms). White circle denotes the electrodes used for statistical analyses of ERP (Fz, Cz, FC1, and FC2).

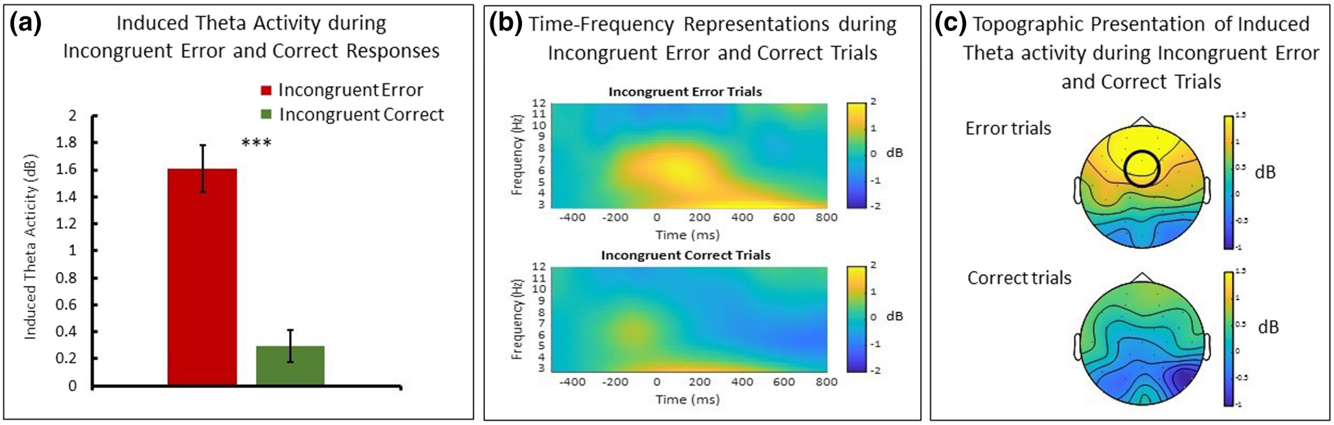

FIGURE 2 (a) Difference in response-related induced theta (4–7 Hz) in incongruent error and correct trials, averaged across frontocentral electrodes surrounding FCz (Fz, Cz, FC1, and FC2) between −100 ms before the response and 300 ms following the response. (b) Time-frequency representations of incongruent error and correct trials in frontocentral electrodes (Fz, Cz, FC1, and FC2), with decibel normalization to a baseline window (−500 to −300 ms); 0 ms corresponds to the time of response. (c) Topographic presentation of induced theta activity (4–7 Hz) during error and correct trials between −100 and 300 ms following response. Black circle denotes the electrodes used for statistical analyses of the induced theta activity (Fz, Cz, FC1, and FC2).

Second, we have analyzed the association between brain indices and post-response behavior during the task. On average, no significant effect of PES was identified. Therefore, we separately analyzed the link between error/correct theta and post-error/post-correct RT. For consistency, post-error and post-correct accuracy data were analyzed in the same way. Nonetheless, in the supplemental materials, we provide a comprehensive exploration of the data, including correlations of post-error slowing (PES) and post-error accuracy (PEA) difference scores with electrophysiological subtraction difference scores and correct-related theta activity and CRN_{resid}. As depicted in Table 2, ERN/CRN/ERN_{resid} did not correlate with any post-error/post-correct trial behavioral data. In contrast, induced theta power in error-incongruent trials negatively correlated with post-error response time (post-error speeding), although such relations were not specific to error and post-error trials, as similar associations were identified for correct and post-correct trials. To complement the analyses of ERN, CRN, and theta power in error and correct trials, we have added analyses of subtraction (error-correct) difference scores in the supplemental materials (see Table S3).

3.5 | Baseline anxiety symptoms (t_0)

Children's levels of overall anxiety, as assessed by the SCARED questionnaire ($M = 13.18$, $SD = 8.88$, range: 0–38), did not reach the clinical cutoff (>25), indicating relatively low levels of anxiety in the sample at t_0. Neither ERN/CRN/ERN_{resid} (all $ps > .663$) nor error/correct induced theta power or error-related theta residual scores (all $ps > .103$) were associated with the SCARED total score at baseline (t_0).

3.6 | Anxiety, negative emotions, and worries during COVID-19 lockdown (t_1)

Children's levels of overall anxiety as assessed by the SCARED questionnaire were not significantly different between t_0 ($M = 14$, $SD = 8.88$, range: 0–38) and t_1 ($M = 14.00$, $SD = 9.47$, range: 0–42), $t(39) = -1.487$, $p = .145$. However, significant differences emerged in two of the SCARED subscales, GAD $t(39) = -2.69$, $p = .010$ and School $t(39) = -2.97$, $p = .005$, indicating an increase in symptoms in specific anxiety dimensions between t_0 (GAD: $M = 4.10$, $SD = 3.48$; School: $M = 0.45$, $SD = 0.84$) and t_1 (GAD: $M = 5.3$, $SD = 3.88$; School: $M = 0.9$, $SD = 1.08$). Of note, the school avoidance subscale of the SCARED exhibited low internal consistency ($\alpha = 0.524$) at t_1. Therefore, findings related to this subscale should be interpreted with caution. Detailed information on the internal consistency of the self-reported questionnaires is presented in Table S5.

Children's level of negative emotions/worries as assessed by the CRISIS questionnaire (t_1) was higher during the lockdown ($M = 19.90$, $SD = 5.99$, range: 10–32) than during the 3 months before the pandemic ($M = 17.95$, $SD = 3.81$, range: 10–26), $t(39) = -2.28$, $p = .028$, thus indicating a situational increase in stress. Children's level of COVID-19 specific worries as assessed by the CRISIS questionnaire (t_1), ranged between 6 and 20 ($M = 10.07$, $SD = 3.13$, range: 6–20).

TABLE 2 Correlations between brain indices and behavioral performance at t_0.

Variables	Overall RT in error trials	Overall RT in correct trials	RT correct trials following errors	RT correct trials following correct trials	Overall accuracy	Accuracy following errors	Accuracy following correct trials
Induced theta power (dB) after error responses	−0.411**	−0.457**	−0.539**	−0.494**	−0.092	−0.070	0.077
Induced theta power (dB) after correct responses	−0.246	−0.461**	−0.477**	−0.427**	−0.442**	−0.277*	−0.283*
Induced error-related theta power $(dB)_{resid}$	−0.330*	−0.256	−0.341*	−0.319*	0.155	0.083	0.258
ERN	0.166	0.108	0.039	0.081	0.109	0.151	0.195
CRN	−0.091	0.002	−0.135	−0.054	0.134	0.241	0.290*
ERN_{resid}	0.320*	0.147	0.188	0.166	0.019	−0.029	−0.016

Abbreviations: CRN, correct-related negativity; ERN, Error-related negativity; ERN_{resid}, residual measures of error-related ERP activity; induced error-related theta power $(dB)_{resid}$, residual scores of error-related theta activity; RT, reaction time.

*$p < .05$ (2-tailed). **$p < .01$ (2-tailed).

TABLE 3 Correlations between induced theta power (dB) and event-related potentials (t_0); parent-reported CRISIS and SCARED questionnaires during COVID-19 (t_1).

Variables	CRISIS COVID-19 related worry during lockdown	CRISIS negative emotions/ worries during lockdown	CRISIS negative emotions/ worries before lockdown	SCARED total score
Induced theta power (dB) after error responses	−0.315	−0.435*	−0.338	−0.383*
Induced theta power (dB) after correct responses	0.097	−0.124	−0.230	−0.195
Induced error-related theta power $(dB)_{resid}$	−0.423*	−0.435*	−0.261	−0.333
ERN	0.023	−0.167	−0.111	−0.147
CRN	−0.313	−0.158	0.080	−0.259
ERN_{resid}	0.333	−0.034	−0.204	0.088

Abbreviations: CRISIS, CoRonavIruS Health Impact Survey; CRN, correct-related negativity; ERN, Error-related negativity; ERN_{resid}, residual measures of error-related ERP activity; Induced error-related theta power $(dB)_{resid}$, residual scores of error-related theta activity; SCARED, Screen for Anxiety Related Disorders.

*$p < .05$ (2-tailed).

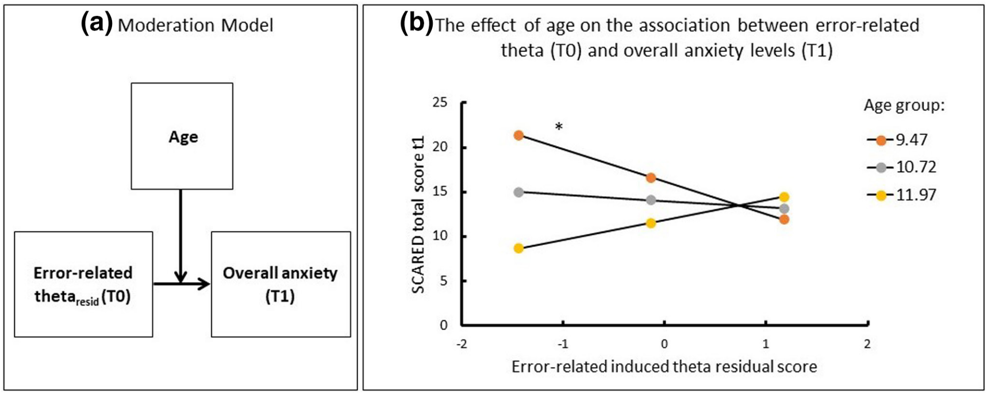

FIGURE 3 (a) Moderation model: association between error-related induced theta residual scores and overall anxiety levels during the lockdown (t_1) is moderated by age. (b) Post-hoc analysis: correlation between error-related theta overall anxiety levels during the lockdown (t_1) are moderated by age.

3.7 | Using EEG indices (t_0) to prospectively predict anxiety, negative emotions, and worries during COVID-19 lockdown (t_1)

As presented in Table 3, no significant correlations were found between ERN/CRN/ERN$_{resid}$ at baseline (at t_0) and later SCARED or CRISIS questionnaire indices (at t_1). In contrast, greater theta power in error trials (but not correct trials) at baseline (t_0) correlated prospectively with fewer negative emotions/worries during the COVID-19 lockdown. Similarly, greater theta power in error trials (but not correct trials) at baseline (t_0) correlated prospectively with lower anxiety levels (SCARED-Total) assessed approximately 1 year later (t_1). Furthermore, greater error-related theta (using residual scores) in t_0, predicted fewer COVID-19 specific worries, and less negative emotions and worries during the lockdown. To complement the analyses of ERN, CRN, and theta power in error and correct trials, we have added analyses of subtraction (error-correct) difference scores in the supplemental materials (see Table S4).

For exploratory regression analysis examining the longitudinal association between error-related EEG indices and anxiety, negative emotions and worries during the lockdown (t1), see pp. 9–12 in the supplemental materials. Finally, Table S6 presents correlations between all variables included in the current study.

3.8 | Examination of the moderating effect of age on the association between EEG indices (t_0) and anxiety, negative emotions, and worries during COVID-19 lockdown (t_1)

First, we examined the moderating effect of age on the associations between error-related induced theta (using residual scores) and anxiety levels during the COVID-19 lockdown period (measured by the SCARED total score at t_1). In this analysis, we controlled for anxiety levels at t_0 (SCARED total score) and ERN residual scores (ERN$_{resid}$). Results revealed a significant interaction effect, $B = 2.342$, $F(1, 25) = 4.487$, $p = .044$. Post-hoc analyses demonstrated that greater induced theta power during error trials was associated with lower anxiety symptoms in the youngest group, $B = -3.625$, $t = -2.274$, $p = .032$ (i.e., around 9.47 years, one standard deviation below the mean age), but not in the two older groups, $B = -.705$, $t = -.582$, $p = .566$, and $B = 2.215$, $t = 1.081$, $p = .290$, respectively. No interaction effect emerged when we examined the moderating effect of age on the associations between ERN$_{resid}$ and anxiety levels during the COVID-19 lockdown period while controlling for anxiety levels at t_0 (SCARED total score) and error-related induced theta, $F(1, 26) = .062$, $p = .806$. See Figure 3.

Second, we examined the moderating effect of age on the associations between error-related induced theta (using residual scores) and COVID-19 specific worries during the lockdown (measured by the CRISIS domain of COVID-19 specific worries). The analysis controlled for the same variables as in the first model. The results revealed no significant interaction effect emerged $F(1, 25) = 2.283$, $p = .143$. Furthermore, no interaction effect emerged when we examined the moderating effect of age on the associations between ERN$_{resid}$ and COVID-19 specific worries while controlling for anxiety levels at t_0 (SCARED total score) and error-related induced theta, $F(1, 26) = .185$, $p = .671$.

Third, we examined the moderating effect of age on the associations between error-related induced theta (using residual scores) and negative emotions and worries during the lockdown (measured by the CRISIS domain of negative emotions/worries in the last 2 weeks), while controlling for the same variables as in the first two models.

The results revealed no significant interaction effect $F(1, 25) = .274$, $p = .605$. Furthermore, no interaction effect emerged when we examined the moderating effect of age on the associations between $\text{ERN}_{\text{resid}}$ and negative emotions and worries during the lockdown while controlling for anxiety levels at t_0 (SCARED total score) and error-related induced theta, $F(1, 26) = .131$, $p = .721$.

4 | DISCUSSION

The study had two primary goals: first, to test in a youth sample how the ERN and induced error-related theta power relate to in-task changes in behavior; second, to determine how these two electrophysiological indices of error monitoring relate to levels of anxiety, worries and negative emotions during the first COVID-19 lockdown. To these ends, in a sample of children aged 8 to 13 years, we measured induced error-related theta and ERN at one time point (t_0, before COVID-19) and examined their associations with concurrent behavioral performances on the same task (t_0) and their prospective relations with anxiety symptomology during real-life situational stress a year later (t_1, during COVID-19 lockdown). We found that enhanced error-related theta was associated with changes in concurrent, in-task behavior (speeding in RT in error and correct trials), while blunted $\text{ERN}_{\text{resid}}$ was associated with slower RT only in error trials. Moreover, induced error-related theta, not ERN, was prospectively associated with less anxiety and worries during situational stress a year later during the lockdown. This association was moderated by age such that increased error-related theta predicted lower anxiety levels only among younger participants. Collectively, these data demonstrate ERN and error-related theta capture dissociable aspects of error monitoring in youth, with error-related theta more closely linked to in-task performance in the lab and to lower levels of anxiety and worry in real-world settings, at least among younger participants.

Previous research conducted on adults has consistently demonstrated a strong association between error-related theta power and changes in behavior following errors (response time and/or accuracy), while the error-related negativity (ERN) has been found to be less consistently associated with post-error behavior (Beatty et al., 2020, 2021; Valadez & Simons, 2018; Weinberg et al., 2012). However, our study focusing on youth only partially supports these findings. We did not find any associations between error-related EEG indices and error-specific changes in response time or accuracy. Instead, we observed that induced theta activity was generally linked to faster response times in both error and correct trials, while ERN was only associated with response time in error trials. These findings align with recent studies that have shown an association between theta activity and faster response times in children (Chevalier et al., 2021), and between induced error-related theta and post-error speeding in adults (Beatty et al., 2021). These results suggest that ERN and error-related theta reflect different aspects of error monitoring and have distinct patterns of association with in-task performance. However, mixed findings in post-response behavioral changes may also be influenced by methodological differences such as task-specific demands, instructions, or analysis methods (Schroder et al., 2020). Therefore, while our study provides new insights into the association between error-related theta and task performance in youth, caution is advised in interpreting these results.

Differences between induced error-related theta activity and ERN were also apparent in predicting levels of anxiety and worries a year later during the COVID-19 lockdown. Children who exhibited more induced error-related theta activity showed fewer worries and less anxiety a year later. Furthermore, error-related induced theta predicted lower overall anxiety particularly among younger participants. In contrast, ERN did not predict change in anxiety symptomology and worries, which is inconsistent with our initial hypothesis and with previous research. One plausible explanation for the lack of association involving ERN could be the exclusion of participants who met the diagnostic criteria for anxiety disorders from our study sample. Excluding individuals with anxiety disorders may have reduced sample variability, potentially limiting our ability to detect the effects of interest. Nonetheless, these findings are broadly in line with previous studies highlighting that error-related theta activity reflects a different neurocognitive mechanism than ERN and is linked to more preferable behavioral performance, such as increased accuracy (Beatty et al., 2020, 2021). Together, higher error-related induced theta may signify an enhanced ability to recognize the need for control or the direct implementation of control. This could result in more efficient responses to unfavorable situations, which, in turn, could lead to a lesser increase in anxiety and worries during stressful life events.

Prior research has examined how ERN retrospectively relates to stressful life events, finding that a history of adverse life experiences is associated with enhanced ERN (Banica et al., 2022; Lackner et al., 2018; Mehra et al., 2022; Wu et al., 2021). Moreover, ERN has been found to prospectively relate to internalizing symptoms following a real-life stressful event (Meyer, Danielson, et al., 2017) and the emergence and increase of anxiety disorders and symptoms (Meyer et al., 2015, 2021; Meyer, Nelson, et al., 2018) Nonetheless, such associations with stressful life events and/or anxiety have not commonly been studied in relation to error-related theta activity. Two previous studies examined total theta activity (without differentiating between phase-locked and non-phase-locked activity) in clinical populations of adults with GAD (Cavanagh et al., 2017) and youth with OCD (Suzuki et al., 2023), although relations with stressful life events were not considered. These studies reported findings that may initially appear contradictory to our results, demonstrating enhanced theta activity in clinical samples compared to healthy controls. However, it is important to note that, when considering the potential moderating role of age, results of the current study and prior work may actually be complementary: we found that error-induced theta activity was only associated with reduced anxiety among younger participants. To our knowledge, our study is the first to explore the relationship between induced error-related theta activity and future levels of anxiety and worries during real-life stressful situations, while also examining the potential moderating role of age in such relations.

Our initial findings suggest that the relations between induced error-related theta activity and anxiety levels varies depending on age. Specifically, we observed that an increase in error-related theta at t_0 predicted lower anxiety levels approximately a year later, during t_1, but only among younger participants (i.e., around 9.47 years old, one standard deviation below the mean age). Interestingly, we found a non-significant association in the opposite direction among the oldest group (i.e., around 11.97 years old, one standard deviation above the mean age). These results are in line with previous research demonstrating a developmental shift in the nature of relations between error monitoring (as indexed via the ERN) and normative variations in anxiety symptoms (for a review, see Meyer, 2017). For example, a study examining children aged 8–13 years from a community sample reported that only among older children an increase in ERN (more negative ERN) was associated with more anxiety symptoms but not among the younger age group (Meyer et al., 2012). Similar findings on the moderating effect of age emerged in an additional study employing older adolescents (ages 13–15 years) (Weinberg et al., 2016). Thus, although the current study identified several differences between induced error-related theta activity and ERN, at a broader level, we also observed developmental similarities in how error-related theta relates to anxiety, when compared with prior ERN work.

Speculatively, there are at least two possible explanations for the developmental shift in associations between error-related theta and anxiety. First, error monitoring and cognitive control are known to exhibit protracted development across childhood and adolescence (Bethlehem et al., 2022; Buzzell, Richards, et al., 2017; Tamnes et al., 2013). Thus, during earlier stages of development, when normative levels of error-related theta are presumably lower, individuals exhibiting levels of theta higher than their peers may be more likely to do so at a level that still falls within the normative range for error-related theta. However, during later stages of development, when normative levels of error-related theta are presumably higher, individuals with theta levels higher than their peers may also be more likely to exceed a normative range of error-related theta that might result in "overcontrol". Consistent with this interpretation, prior work has shown that higher error-related theta is associated with increased anxiety among older youth and adults (Cavanagh et al., 2017; Suzuki et al., 2023). A second possible explanation, in line with similar arguments by Meyer (2017) on changing relations between ERN and anxiety with age, posits that this developmental shift reflects a change in the nature of anxiety across development. That is, while in early childhood, normative fears often involve external threats such as darkness or separation, as children grow, their concerns shift towards social evaluation, competition, and a focus on one's own performance, potentially leading to increased error sensitivity and stronger associations with neural responses to errors (Meyer, 2017). These two possibilities are not mutually exclusive and both may explain the developmental shift in associations between error-related neural responses (theta, ERN) and anxiety. Given the novelty of our findings and their exploratory nature, it is crucial to replicate and further examine similar developmental differences in larger samples to better understand the associations between induced error-related theta, ERN, and anxiety.

Together with other recent studies, our findings highlight the unique role of error-related theta in predicting behavioral performance in relation to standard laboratory tasks and clinical symptomology in real-world settings. Furthermore, our data suggest that in contrast to the well-established notion that enhanced ERN reflects a risk factor for anxiety in response to stressful life events, error-related theta may be associated with lower levels of anxiety and worries, at least in youth populations. Building on these findings, possible implications for future research are worth mentioning. Measuring an individual's induced error-related theta levels during laboratory tasks may have the potential to identify individuals who may be prone to experience enhanced anxiety and worries during real-life stress. This is particularly relevant for pediatric populations, as the frontal cortex, which underlies error monitoring and cognitive control more generally, undergoes protracted development across adolescence and into early adulthood (Bethlehem et al., 2022; Buzzell, Richards, et al., 2017; Tamnes et al., 2013). Although our current sample had relatively low self-reported anxiety scores, it is possible that enhanced anxiety and worries during periods of stress and unpredictability might persist and pose a risk for developing anxiety disorders, at least among some individuals. However, as no studies have examined induced error-related theta among clinical populations, further research is needed to fully understand the clinical implications. Because the COVID-19 lockdowns were unique and unprecedented, future studies should examine the implication of other acute situations that share similar characteristic with the COVID-19 pandemic within clinical and developmental populations. For example, situations that produce elevated stress, drastic changes in daily life routines, or create conditions of social isolation. Furthermore, error-related theta could potentially serve as a neural target among clinical populations and in future might inform the development of novel, brain-based therapeutics that seek to directly modulate error-related theta through neural feedback or stimulation-based approaches (Grover et al., 2021; Reinhart, 2017; Reinhart et al., 2015).

Of note, work is already underway to employ ERN as an index of error monitoring to identify individuals at heightened risk for anxiety and/or to leverage ERN as a marker of clinical change (Meyer, 2022). Our results suggest the assessment of error-related theta could comprise a complementary tool in the development of novel assessment, intervention, or treatment approaches for pediatric anxiety. However, considering the novelty of our findings, the unusual circumstances during COVID-19 first lockdowns and the lack of similar research focusing on clinical populations, future studies employing other acute real-life events are needed.

Our study has two main limitations. First, the follow-up measurement (t_1) was conducted online during the first COVID-19 lockdown in Israel. Due to COVID-19 restrictions and the limited time for data collection, the t_1 sample size is relatively small. Second, given the exploratory nature of the study, our results should be interpreted with caution. The relatively small sample size yields limited power to investigate possible moderating effects of age or other demographic characteristics. Future work should seek to replicate and extend our findings with larger samples of children and adolescents using prospective designs in different real-life stressful contexts. Such work may further delineate the communalities of and differences between error-related theta and ERN, including their associations with anxiety and worries during real-life situations.

In conclusion, although ERN and induced error-related theta are both electrophysiological measures associated with error monitoring in youth, they are fundamentally dissociable constructs exhibiting qualitatively distinct relations with changes in behavior both in the laboratory and in real-world settings. Induced error-related theta is associated with concurrent, changes in performance in a laboratory task, and prospectively associated with less anxiety and worries during stressful circumstances in real-life settings. Such findings may have clinical implications in terms of providing brain-based methods to identify at-risk populations and informing novel, brain-based therapeutics for pediatric anxiety disorders.

AUTHOR CONTRIBUTIONS

Gil Shner-Livne: Conceptualization; data curation; formal analysis; software; visualization; writing – original draft. **George Buzzell:** Conceptualization; writing – review and editing. **Nathan Fox:** Writing – review and editing. **Tomer Shechner:** Conceptualization; data curation; formal analysis; resources; supervision; writing – original draft; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare they have no known conflict of interest.

DATA AVAILABILITY STATEMENT

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

ORCID

Gil Shner-Livne https://orcid.org/0000-0001-9729-8875

REFERENCES

Banica, I., Sandre, A., Shields, G. S., Slavich, G. M., & Weinberg, A. (2022). Associations between lifetime stress exposure and the error-related negativity (ERN) differ based on stressor characteristics and exposure timing in young adults. *Cognitive, Affective, & Behavioral Neuroscience*, *22*(4), 672–689. https://doi.org/10.3758/s13415-021-00883-z

Beatty, P. J., Buzzell, G. A., Roberts, D. M., & McDonald, C. G. (2020). Contrasting time and frequency domains: ERN and induced theta oscillations differentially predict post-error behavior. *Cognitive, Affective, & Behavioral Neuroscience*, *20*(3), 636–647. https://doi.org/10.3758/s13415-020-00792-7

Beatty, P. J., Buzzell, G. A., Roberts, D. M., Voloshyna, Y., & McDonald, C. G. (2021). Subthreshold error corrections predict adaptive post-error compensations. *Psychophysiology*, *58*(6), e13803. https://doi.org/10.1111/psyp.13803

Bethlehem, R. A. I., Seidlitz, J., White, S. R., Vogel, J. W., Anderson, K. M., Adamson, C., Adler, S., Alexopoulos, G. S., Anagnostou, E., Areces-Gonzalez, A., Astle, D. E., Auyeung, B., Ayub, M., Bae, J., Ball, G., Baron-Cohen, S., Beare, R., Bedford, S. A., Benegal, V., … Alexander-Bloch, A. F. (2022). Brain charts for the human lifespan. *Nature*, *604*(7906), 525–533. https://doi.org/10.1038/s41586-022-04554-y

Birmaher, B., Khetarpal, S., Brent, D., Cully, M., Balach, L., Kaufman, J., & Neer, S. M. K. (1997). The screen for child anxiety related emotional disorders (SCARED): Scale construction and psychometric characteristics. *Journal of the American Academy of Child and Adolescent Psychiatry*, *36*(4), 545–553. https://doi.org/10.1097/00004583-199704000-00018

Buzzell, G. A., Barker, T. V., Troller-Renfree, S. V., Bernat, E. M., Bowers, M. E., Morales, S., Bowman, L. C., Henderson, H. A., Pine, D. S., & Fox, N. A. (2019). Adolescent cognitive control, theta oscillations, and social observation. *NeuroImage*, *198*, 13–30. https://doi.org/10.1016/j.neuroimage.2019.04.077

Buzzell, G. A., Beatty, P. J., Paquette, N. A., Roberts, D. M., & McDonald, C. G. (2017). Error-induced blindness: Error detection leads to impaired sensory processing and lower accuracy at short response–stimulus intervals. *Journal of Neuroscience*, *37*(11), 2895–2903. https://doi.org/10.1523/JNEUROSCI.1202-16.2017

Buzzell, G. A., Richards, J. E., White, L. K., Barker, T. V., Pine, D. S., & Fox, N. A. (2017). Development of the error-monitoring system from ages 9–35: Unique insight provided by MRI-constrained source localization of EEG. *NeuroImage*, *157*, 13–26. https://doi.org/10.1016/j.neuroimage.2017.05.045

Buzzell, G. A., Troller-Renfree, S. V., Barker, T. V., Bowman, L. C., Chronis-Tuscano, A., Henderson, H. A., Kagan, J., Pine, D. S., & Fox, N. A. (2017). A neurobehavioral mechanism linking behaviorally inhibited temperament and later adolescent social anxiety. *Journal of the American Academy of Child and Adolescent Psychiatry*, *56*(12), 1097–1105. https://doi.org/10.1016/j.jaac.2017.10.007

Buzzell, G. A., Troller-Renfree, S. V., Morales, S., & Fox, N. A. (2018). Relations between behavioral inhibition, cognitive control, and anxiety: Novel insights provided by parsing subdomains of cognitive control: Integrating theory, research, and clinical perspectives. *Behavioral Inhibition*, *2019*, 213–215. https://doi.org/10.1007/978-3-319-98077-5

Buzzell, G. A., Troller-Renfree, S. V., Wade, M., Debnath, R., Morales, S., Bowers, M. E., Zeanah, C. H., Nelson, C. A., & Fox, N. A. (2020). Adolescent cognitive control and mediofrontal theta oscillations are disrupted by neglect: Associations with transdiagnostic risk for psychopathology in a randomized controlled trial. *Developmental Cognitive Neuroscience*, *43*, 100777. https://doi.org/10.1016/j.dcn.2020.100777

Cavanagh, J. F., Cohen, M. X., & Allen, J. J. B. (2009). Prelude to and resolution of an error: EEG phase synchrony reveals cognitive control dynamics during action monitoring. *Journal of Neuroscience*, *29*(1), 98–105. https://doi.org/10.1523/JNEUROSCI.4137-08.2009

Cavanagh, J. F., & Frank, M. J. (2014). Frontal theta as a mechanism for cognitive control. *Trends in Cognitive Sciences*, *18*(8), 414–421. https://doi.org/10.1016/j.tics.2014.04.012

Cavanagh, J. F., Meyer, A., & Hajcak, G. (2017). Error-specific cognitive control alterations in generalized anxiety disorder. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*, *2*(5), 413–420. https://doi.org/10.1016/j.bpsc.2017.01.004

Chevalier, N., Hadley, L. V., & Balthrop, K. (2021). Midfrontal theta oscillations and conflict monitoring in children and adults. *Developmental Psychobiology*, *63*(8), e22216. https://doi.org/10.1002/dev.22216

Clayson, P. E., Carbine, K. A., Baldwin, S. A., Olsen, J. A., & Larson, M. J. (2021). Using generalizability theory and the ERP reliability analysis (ERA) toolbox for assessing test-retest reliability of ERP scores part 1: Algorithms, framework, and implementation. *International Journal of Psychophysiology*, *166*, 174–187. https://doi.org/10.1016/j.ijpsycho.2021.01.006

Clayson, P. E., & Miller, G. A. (2017a). ERP reliability analysis (ERA) toolbox: An open-source toolbox for analyzing the reliability of event-related brain potentials. *International Journal of Psychophysiology*, *111*, 68–79. https://doi.org/10.1016/j.ijpsycho.2016.10.012

Clayson, P. E., & Miller, G. A. (2017b). Psychometric considerations in the measurement of event-related brain potentials: Guidelines for measurement and reporting. *International Journal of Psychophysiology*, *111*, 57–67. https://doi.org/10.1016/j.ijpsycho.2016.09.005

Cohen, M. X. (2014). A neural microcircuit for cognitive conflict detection and signaling. *Trends in Neurosciences*, *37*(9), 480–490. https://doi.org/10.1016/j.tins.2014.06.004

Cohen, M. X., & Donner, T. H. (2013). Midfrontal conflict-related theta-band power reflects neural oscillations that predict behavior. *Journal of Neurophysiology*, *110*(12), 2752–2763. https://doi.org/10.1152/jn.00479.2013

Danielmeier, C., & Ullsperger, M. (2011). Post-error adjustments. *Frontiers in Psychology*, *2*, 233. https://doi.org/10.3389/fpsyg.2011.00233

Davies, P. L., Segalowitz, S. J., & Gavin, W. J. (2004). Development of response-monitoring ERPs in 7- to 25-year-olds. *Developmental Neuropsychology*, *25*(3), 355–376. https://doi.org/10.1207/s15326942dn2503_6

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, *16*(1), 143–149. https://doi.org/10.3989/arbor.2000.i650.965

Fox, N. A., Buzzell, G. A., Morales, S., Valadez, E. A., Wilson, M., & Henderson, H. A. (2021). Understanding the emergence of social anxiety in children with behavioral inhibition. *Biological Psychiatry*, *89*(7), 681–689. https://doi.org/10.1016/j.biopsych.2020.10.004

Gehring, W. J., Liu, Y., Orr, J. M., & Carp, J. (2012). The error-related negativity (ERN/Ne). In *The oxford handbook of event-related potential components*. Oxford University Press. https://doi.org/10.1093/oxfordhb/9780195374148.013.0120

Grover, S., Nguyen, J. A., & Reinhart, R. M. G. (2021). Synchronizing brain rhythms to improve cognition. *Annual Review of Medicine*, *72*, 29–43. https://doi.org/10.1146/annurev-med-060619-022857

Jung, T. P., Makeig, S., Westerfield, M., Townsend, J., Courchesne, E., & Sejnowski, T. J. (2000). Removal of eye activity artifacts from visual event-related potentials in normal and clinical subjects. *Clinical Neurophysiology*, *111*(10), 1745–1758. https://doi.org/10.1016/S1388-2457(00)00386-2

Klawohn, J., Meyer, A., Weinberg, A., & Hajcak, G. (2020). Methodological choices in event-related potential (ERP) research and their impact on internal consistency reliability and individual differences: An examination of the error-related negativity (ERN) and anxiety. *Journal of Abnormal Psychology*, *129*(1), 29–37. https://doi.org/10.1037/abn0000458.supp

Lackner, C. L., Santesso, D. L., Dywan, J., O'Leary, D. D., Wade, T. J., & Segalowitz, S. J. (2018). Adverse childhood experiences are associated with self-regulation and the magnitude of the error-related negativity difference. *Biological Psychology*, *132*, 244–251. https://doi.org/10.1016/j.biopsycho.2018.01.006

Luna, B. (2009). Developmental changes in cognitive control through adolescence. In *Advances in child development and behavior* (Vol. *37*). Elsevier. https://doi.org/10.1016/S0065-2407(09)03706-9

Luu, P., Tucker, D. M., & Makeig, S. (2004). Frontal midline theta and the error-related negativity: Neurophysiological mechanisms of action regulation. *Clinical Neurophysiology*, *115*(8), 1821–1835. https://doi.org/10.1016/j.clinph.2004.03.031

Mehra, L. M., Hajcak, G., & Meyer, A. (2022). The relationship between stressful life events and the error-related negativity in children and adolescents. *Developmental Cognitive Neuroscience*, *55*, 101110. https://doi.org/10.1016/j.dcn.2022.101110

Meyer, A. (2017). A biomarker of anxiety in children and adolescents: A review focusing on the error-related negativity (ERN) and anxiety across development. *Developmental Cognitive Neuroscience*, *27*, 58–68. https://doi.org/10.1016/j.dcn.2017.08.001

Meyer, A. (2022). On the relationship between the error-related negativity and anxiety in children and adolescents: From a neural marker to a novel target for intervention. *Psychophysiology*, *59*, e14050. https://doi.org/10.1111/psyp.14050

Meyer, A., Carlton, C., Crisler, S., & Kallen, A. (2018). The development of the error-related negativity in large sample of adolescent females: Associations with anxiety symptoms. *Biological Psychology*, *138*, 96–103. https://doi.org/10.1016/j.biopsycho.2018.09.003

Meyer, A., Danielson, C. K., Danzig, A. P., Bhatia, V., Black, S. R., Bromet, E., Carlson, G., Hajcak, G., Kotov, R., & Klein, D. N. (2017). Neural biomarker and early temperament predict increased internalizing symptoms after a natural disaster. *Journal of the American Academy of Child and Adolescent Psychiatry*, *56*(5), 410–416. https://doi.org/10.1016/j.jaac.2017.02.005

Meyer, A., Hajcak, G., Torpey-Newman, D. C., Kujawa, A., & Klein, D. N. (2015). Enhanced error-related brain activity in children predicts the onset of anxiety disorders between the ages of 6 and 9. *Journal of Abnormal Psychology*, *124*(2), 266–274. https://doi.org/10.1037/abn0000044

Meyer, A., Lerner, M. D., De Los Reyes, A., Laird, R. D., & Hajcak, G. (2017). Considering ERP difference scores as individual difference measures: Issues with subtraction and alternative approaches. *Psychophysiology*, *54*(1), 114–122. https://doi.org/10.1111/psyp.12664

Meyer, A., Mehra, L., & Hajcak, G. (2021). Error-related negativity predicts increases in anxiety in a sample of clinically anxious female children and adolescents over 2 years. *Journal of Psychiatry and Neuroscience*, *46*(4), E472–E479. https://doi.org/10.1503/JPN.200128

Meyer, A., Nelson, B., Perlman, G., Klein, D. N., & Kotov, R. (2018). A neural biomarker, the error-related negativity, predicts the first onset of generalized anxiety disorder in a large sample of adolescent females. *Journal of Child Psychology and Psychiatry, and Allied Disciplines*, *59*(11), 1162–1170. https://doi.org/10.1111/jcpp.12922

Meyer, A., Weinberg, A., Klein, D. N., & Hajcak, G. (2012). The development of the error-related negativity (ERN) and its relationship with anxiety: Evidence from 8 to 13 year-olds. *Developmental Cognitive Neuroscience*, *2*(1), 152–161. https://doi.org/10.1016/j.dcn.2011.09.005

Morales, S., Zeytinoglu, S., Buzzell, G. A., Valadez, E. A., Troller-Renfree, S. V., Bowers, M. E., Chronis-Tuscano, A., Degnan, K. A., Almas, A. N., Pine, D. S., & Fox, N. A. (2022). Neurocognitive profiles in adolescence predict subsequent anxiety trajectories during the COVID-19 pandemic. *Biological psychiatry: Cognitive neuroscience and neuroimaging*, *7*(2), 192–200. https://doi.org/10.1016/j.bpsc.2021.06.004

Moser, J. S., Moran, T. P., Schroder, H. S., Donnellan, M. B., & Yeung, N. (2013). On the relationship between anxiety and error monitoring: A meta-analysis and conceptual framework. *Frontiers in Human Neuroscience*, *7*, 466. https://doi.org/10.3389/fnhum.2013.00466

Nearchou, F., Hennessy, E., Flinn, C., Niland, R., & Subramaniam, S. S. (2020). Exploring the impact of covid-19 on mental health outcomes in children and adolescents: A systematic review. *International Journal of Environmental Research and Public Health*, *17*(22), 8479. https://doi.org/10.3390/ijerph17228479

Nikolaidis, A., Paksarian, D., Alexander, L., Derosa, J., Dunn, J., Nielson, D. M., Droney, I., Kang, M., Douka, I., Bromet, E., Milham, M., Stringaris, A., & Merikangas, K. R. (2021). The Coronavirus Health and Impact Survey (CRISIS) reveals reproducible correlates of pandemic-related mood states across the Atlantic. *Scientific Reports*, *11*(1), 8139. https://doi.org/10.1038/s41598-021-87270-3

Niu, Y., Li, Z., Pettit, J. W., Buzzell, G. A., & Zhao, J. (2023). Context and domain matter: The error-related negativity in peer presence predicts fear of negative evaluation, not global social anxiety, in adolescents. *Psychological Medicine*, 1–11. https://doi.org/10.1101/2022.07.01.498524

Olvet, D. M., & Hajcak, G. (2008). The error-related negativity (ERN) and psychopathology: Toward an endophenotype. *Clinical Psychology Review*, *28*(8), 1343–1354. https://doi.org/10.1016/j.cpr.2008.07.003

Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J. M. (2011). FieldTrip: Open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience*, *2011*, 156869. https://doi.org/10.1155/2011/156869

Perl, L., Oren, A., Klein, Z., & Shechner, T. (2021). Effects of the COVID19 pandemic on transgender and gender nonconforming Adolescents' mental health. *Psychiatry Research*, *302*, 114042. https://doi.org/10.1016/j.psychres.2021.114042

Preacher, K. J., & Hayes, A. F. (2004). SPSS and SAS procedures for estimating indirect effects in simple mediation models. *Behavior Research Methods, Instruments, & Computers*, *36*(4), 717–731. https://doi.org/10.3758/bf03206553

Reinhart, R. M. G. (2017). Disruption and rescue of interareal theta phase coupling and adaptive behavior. *Proceedings of the National Academy of Sciences of The United States of America*, *114*(43), 11542–11547. https://doi.org/10.1073/pnas.1710257114

Reinhart, R. M. G., Zhu, J., Park, S., & Woodman, G. F. (2015). Synchronizing theta oscillations with direct-current stimulation strengthens adaptive control in the human brain. *Proceedings of the National Academy of Sciences of The United States of America*, *112*(30), 9448–9453. https://doi.org/10.1073/pnas.1504196112

Samji, H., Wu, J., Ladak, A., Vossen, C., Stewart, E., Dove, N., Long, D., & Snell, G. (2022). Review: Mental health impacts of the COVID-19 pandemic on children and youth – A systematic review. *Child and Adolescent Mental Health*, *27*(2), 173–189. https://doi.org/10.1111/camh.12501

Schroder, H. S., Nickels, S., Cardenas, E., Breiger, M., Perlo, S., & Pizzagalli, D. A. (2020). Optimizing assessments of post-error slowing: A neurobehavioral investigation of a flanker task. *Psychophysiology*, *57*(2), e13473. https://doi.org/10.1111/psyp.13473

Silverman, W. K., & Albano, A. M. (1996). *The anxiety disorders interview schedule for DSM–IV—Child and parent versions*. Psychological Corporation.

Suzuki, T., Gu, P., Grove, T. B., Hammond, T., Collins, K. M., Pamidighantam, P., Arnold, P. D., Taylor, S. F., Liu, Y., Gehring, W. J., Hanna, G. L., & Tso, I. F. (2023). Abnormally enhanced Midfrontal theta activity during response monitoring in youths with obsessive-compulsive disorder. *Biological Psychiatry*, *93*, 1031–1040. https://doi.org/10.1016/j.biopsych.2022.10.020

Tamnes, C. K., Walhovd, K. B., Torstveit, M., Sells, V. T., & Fjell, A. M. (2013). Performance monitoring in children and adolescents: A review of developmental changes in the error-related negativity and brain maturation. *Developmental Cognitive Neuroscience*, *6*, 1–13. https://doi.org/10.1016/j.dcn.2013.05.001

Taylor, S. F., Stern, E. R., & Gehring, W. J. (2007). Neural systems for error monitoring: Recent findings and theoretical perspectives. *The Neuroscientist*, *13*(2), 160–172. https://doi.org/10.1177/1073858406298184

Trujillo, L. T., & Allen, J. J. B. (2007). Theta EEG dynamics of the error-related negativity. *Clinical Neurophysiology*, *118*(3), 645–668. https://doi.org/10.1016/j.clinph.2006.11.009

Ullsperger, M., Danielmeier, C., & Jocham, G. (2014). Neurophysiology of performance monitoring and adaptive behavior. *Physiological Reviews*, *94*(1), 35–79. https://doi.org/10.1152/physrev.00041.2012

Valadez, E. A., & Simons, R. F. (2018). The power of frontal midline theta and post-error slowing to predict performance recovery: Evidence for compensatory mechanisms. *Psychophysiology*, *55*(4), e13010. https://doi.org/10.1111/psyp.13010

Weinberg, A., Meyer, A., Hale-Rude, E., Perlman, G., Kotov, R., Klein, D. N., & Hajcak, G. (2016). Error-related negativity (ERN) and sustained threat: Conceptual framework and empirical evaluation in an adolescent sample. *Psychophysiology*, *53*(3), 372–385. https://doi.org/10.1111/psyp.12538

Weinberg, A., Riesel, A., & Hajcak, G. (2012). Integrating multiple perspectives on error-related brain activity: The ERN as a neural indicator of trait defensive reactivity. *Motivation and Emotion*, *36*(1), 84–100. https://doi.org/10.1007/s11031-011-9269-y

Wessel, J. R. (2018). An adaptive orienting theory of error processing. *Psychophysiology*, *55*(3), e13041. https://doi.org/10.1111/psyp.13041

Winkler, I., Debener, S., Müller, K.-R., & Tangermann, M. (2015). On_the_influence_of_high-pass_filtering_on_ICA-based_artifact_reduction_in_EEG-ERP.pdf (pp. 4101–4105). 37th annual international conference of the IEEE engineering in medicine and biology society (EMBC).

Wu, J., Liu, Y., Fang, H., Qin, S., Kohn, N., & Duan, H. (2021). The relationship between childhood stress and distinct stages of dynamic behavior monitoring in adults: Neural and behavioral correlates. *Social Cognitive and Affective Neuroscience*, *16*(9), 937–949. https://doi.org/10.1093/scan/nsab041

SUPPORTING INFORMATION

Additional supporting information can be found online in the Supporting Information section at the end of this article.

Table S1. Demographics of participants excluded from final analysis because of low behavioral performance and participants included in analysis.

Table S2. Demographics of children who participated and who declined to participate at t_1.

Table S3. Correlations between brain indices and behavioral performance at t_0.

Table S4. Correlations between induced theta power (dB) and event-related potentials (t_0); Parent-Reported CRISIS and SCARED questionnaires during COVID-19 (t_1).

Table S5. Cronbach's alpha values for clinical questionnaires in t_0 and t_1.

Table S6. Correlations of all variables included in the current manuscript.

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