Midfrontal theta power relates to response speeding following frustrative nonreward

Nellia Bellaert[a,b], Federico Cassioli[a,c], Michael J. Crowley[b], Hilary P. Blumberg[b,d], Mandy Rossignol[a], Christen M. Deveney[e], Wan-Ling Tseng[b]

a) Department of Cognitive Psychology and Neuropsychology, University of Mons, Mons, Belgium.
b) Yale Child Study Center, Yale School of Medicine, New Haven, CT, USA.
c) Department of Experimental Psychology, Ghent University, Ghent, Belgium.
d) Departments of Psychiatry and Radiology and Biomedical Imaging, Yale School of Medicine, New Haven, CT, USA.
e) Department of Psychology, Wellesley College, MA, USA.

Correspondence: nellia.bellaert@umons.ac.be (Nellia Bellaert)

Department of Cognitive Psychology and Neuropsychology, 26 Rue du Parc, 7000 Mons,
University of Mons, Belgium

ABSTRACT

Objectives: Irritability is a transdiagnostic symptom proposed to be characterized by heightened negative affect (i.e., frustration) and maladaptive responses to frustrative nonreward (FNR). Although FNR typically elicits adaptive behavioral adjustments, the neural mechanisms that support these adjustments and their trial-by-trial dynamics remain unexplored. Midfrontal theta power, a key marker of expectancy violation and cognitive control, is a strong candidate for indexing these mechanisms and their role in supporting adaptive responses. We investigated how fluctuations in midfrontal theta power following FNR relate to subsequent behavioral adjustments and whether these associations are moderated by individual differences in irritability and state frustration. **Methods:** Young adults completed a validated frustration paradigm and self-reported their irritability and state frustration. A multivariate approach was used to enhance the signal-to-noise ratio of single-trial theta activity. Linear mixed-effects models tested whether trial-by-trial theta power and feedback type (win vs. FNR) predicted reaction time on the following trial. **Results:** Higher theta power following FNR, but not win feedback, was associated with faster reaction times on the next trial, suggesting that theta oscillations support adaptive behavioral adjustments to frustrative outcomes. Reduced theta power to FNR was linked to greater self-reported frustration, while trait irritability and state frustration did not moderate the theta-behavior association. **Conclusion:** Midfrontal theta power increased following FNR and predicted faster subsequent responses, highlighting its role in adaptive adjustment to unexpected reward loss. These findings enhance understanding of the neurocognitive mechanisms supporting coping with frustration and suggest this process may be less effective under heightened subjective frustration.

Keywords: frustrative nonreward, midfrontal theta, cognitive control, irritability, frustration.

1. INTRODUCTION

Irritability, defined as proneness to anger that may impair an individual's functioning (Leibenluft et al., 2024), is a common, impairing, and transdiagnostic symptom present across many psychiatric disorders (Stringaris et al., 2018). It is one of the most common reasons for youth mental health consultations (Evans et al., 2023) and remains prevalent in adults, affecting 50–60% of those with depression (Fava et al., 2010; Judd et al., 2013; Rizk et al., 2025). In this context, irritability is linked to more severe, longer-lasting depression, and higher risk of suicidality (Jha et al., 2020; Judd et al., 2013; Rizk et al., 2025). Severe irritability can also occur independently of mood or anxiety disorders, particularly in young adults, with a prevalence of 1.8% (Perlis et al., 2024). Its impairing nature and high prevalence highlight the need to better understand its underlying etiology and physiological mechanisms.

Irritability is conceptualized as a low threshold for experiencing frustration (Brotman et al., 2017; Leibenluft, 2017). Indeed, frustration has a central role in the clinical presentation of irritability (Tseng et al., 2023). Frustration is defined as the negative emotional and behavioral response that occurs when individuals face obstacles that impede their pursuit of a desired or expected goal or reward (Amsel, 1992; Berkowitz, 1989; Dollard et al., 1939). This phenomenon has been widely examined in animal research under the term *frustrative nonreward* (FNR), referring to the negative psychological state triggered by the unexpected omission, devaluation, or obstruction of an anticipated reward (Amsel, 1958; Papini et al., 2015). In human research, FNR paradigms that build reward expectations and then withhold the reward, provide a loss instead (e.g., through rigged feedback), or obstruct reward access have been used to investigate the pathophysiology of irritability (e.g., Brown et al., 2025; Harlé et al., 2023; Tseng et al., 2017). Building on FNR paradigms and neuroimaging findings, a prominent model (Brotman et al., 2017) proposes that individuals with irritability may present aberrant frontostriatal brain activity to FNR (Deveney et al., 2013; Perlman et al., 2015; Scheinost et al., 2021; Tseng et al., 2019), which may contribute to their increased negative affect (e.g., anger, annoyance, frustration) and behavioral responses (e.g., motor activity, aggression).

To investigate the physiological mechanisms underlying FNR, electroencephalography (EEG) has proven useful. Several EEG/event-related potential (ERP) studies in children and adolescents have used FNR paradigms to examine neural responses to frustration (Gatzke-Kopp et al., 2015; Lewis et al., 2006, 2008; Rich et al., 2007a, 2007b, 2011; Riek et al., 2023; Woltering et al., 2011). However, findings in adults remain relatively limited. In healthy young adults, irritability has been linked to smaller amplitudes of feedback-related negativity (i.e., an ERP component related to feedback processing) in response to FNR (Deveney, 2019). Additionally, greater self-reported state anger has been associated with increased P3b amplitudes (i.e., an ERP component associated with motivational salience) in response to FNR (Angus & Harmon-Jones, 2019).

While these ERP studies provided valuable insights, midfrontal theta power (4-8Hz) may also serve as a relevant marker to investigate neural responses to FNR. Midfrontal theta power is a well-established electrophysiological marker of expectancy violations that signal a need for increased cognitive control when outcomes are worse than expected or when conflict occurs (Cavanagh & Frank, 2014; Cavanagh & Shackman, 2015; Cohen et al., 2007; Glazer et al., 2018; Holroyd & Umemoto, 2016; Mas-Herrero & Marco-Pallarés, 2014). Indeed, previous studies have shown increased theta activity in response to unexpected negative outcomes (e.g., Gheza et al., 2018; Rawls et al., 2020), even in paradigms not explicitly designed to elicit FNR. Similarly, studies using slot-machine tasks have reported increased theta in response to near misses (i.e., loss outcomes that closely resemble wins but hold the same economic value as losses) compared to wins or complete losses (Alicart et al., 2019; Dymond et al., 2014; Fryer et al., 2021). Near misses may elicit FNR by creating a discrepancy between expected and actual outcomes, as they signal the omission of a reward despite cues suggesting a win is imminent (Fryer et al., 2021). To our knowledge, only one previous study has directly examined midfrontal theta activity using magnetoencephalography in a task specifically designed to induce FNR (Rich et al., 2010). In this study, compared to healthy controls (*n*=20), euthymic youth with bipolar disorder (*n*=20), where irritability is a common symptom (American Psychiatric Association, 2013), exhibited greater self-reported sadness, slower reaction times (RT), and increased theta power in the right anterior cingulate cortex (ACC) in response to FNR. Taken together, these findings point to midfrontal theta power as a strong candidate for capturing neural mechanisms underlying FNR.

Furthermore, most previous research using FNR paradigms has relied on cross-trial averaging, which assumes stable reward expectations, neural responses to feedback, and behavior across the task. However, in paradigms involving FNR, reward expectations are likely to change over trials, as the repeated omission of expected rewards may lead to extinction learning, gradually diminishing reward expectation and the surprise associated with its absence. These dynamic changes in expectations should be reflected in trial-by-trial fluctuations in midfrontal theta power. Moreover, such neural fluctuations are expected to correlate with behavioral adjustments, since FNR is theorized to drive adaptive behavior in response to changing reward contingencies (Amsel, 1992), and theta power has been shown to relate to trial-by-trial behavioral adjustment (Cavanagh et al., 2009; Cooper et al., 2019; van de Vijver et al., 2011). To capture this variability, we employed single-trial linear mixed-effects models (LMM; Frömer et al., 2018), which allowed us to examine how trial-level changes in midfrontal theta power relate to subsequent behavioral adjustments (i.e., RT) during frustration induction. This approach may provide a better understanding of the neural mechanisms associated with FNR and their impact on behavioral and affective responses.

Taken together, this study aimed, as an initial step, to replicate previous findings by Deveney (2019), which demonstrated the impact of FNR on the feedback-related negativity and its association with irritability. The main aims of the study were threefold: (1) to test whether midfrontal theta power indexes FNR by examining neural responses in a task explicitly designed and validated to elicit FNR (i.e., the Affective Posner Task; Tseng et al., 2017); (2) to investigate whether trial-by-trial fluctuations in midfrontal theta power in response to FNR relate to subsequent RT adjustment. We hypothesized that midfrontal theta power will increase in response to FNR and that these responses will predict subsequent trial-by-trial behavioral RT adjustments (i.e., response speeding). To this end, we used a data-driven multivariate spatial filtering method (Cohen, 2022), which applies generalized eigendecomposition to maximize the signal-to-noise ratio of single-trial EEG data; and (3) to explore whether individual differences in trait irritability and state frustration moderate the associations between FNR-related theta activity and behavioral adaptation, given the proposed mechanistic role of FNR in the pathophysiology of irritability (Brotman et al., 2017).

2. METHOD

2.1. Participants

In total, 91 young adults (ages 18–25 years, $M_{age=}$21.36 ± 2.26, 61.54% females; see **Table 1** for socio-demographic characteristics) were recruited in 2022 through flyers in New Haven, Connecticut. The study was approved by the Institutional Review Board of the Yale University. An initial phone survey determined eligibility (18–25 years old, no major medical illnesses, no loss of consciousness >5 min, and no psychiatric condition other than depression or anxiety) and the absence of PTSD, alcohol/substance dependence, and psychotic disorders was verified via the Mini International Neuropsychiatric Interview (Sheehan et al., 1998). In our sample, 13 participants (14.29%) scored above the clinical cutoff (≥14) on the depression subscale of the Depression Anxiety and Stress Scale, while 15 participants (16.48%) exceeded the clinical cutoff (≥10) on the anxiety subscale. Additionally, five participants (5.50%) self-reported an ADHD diagnosis. Self-reported medication use included Adderall (n=5; 5.50%) and antidepressants (n=9; 9.89%). Controlling for depression, anxiety, and medication use did not affect the main results (see Results S1).

Eligible participants who provided informed consent were then invited to the lab for an EEG session, which included completing online questionnaires and performing the Affective Posner Task. Participants were paid $15/hour and were informed that they could earn an additional $25 during the Affective Posner Task. They also completed the Doors task, the results of which are described in Bellaert et al. (2025a)

One participant was excluded due to sickness during the experimental session (*n*=1), yielding 90 participants for the behavioral analyses. For the ERP analyses, data from an additional 10 participants were excluded due to excessive EEG artifacts (*n*=4), EEG equipment being incompatible with participants' hair types or hairstyles (*n*=5), and hardware issue (*n*=1), yielding 80 participants (M_{age}=21.34±2.31, 58.75% females). For the time-frequency analyses, additional participants were excluded based on signal quality criteria (details provided below), resulting in a final sample of 71 participants (*M*=21.34±2.31, 64.79% females). We examined potential differences in demographic variables across the behavioral sample (*n*=90), ERP subsample (*n*=80), and the time-frequency subsample (*n*=71). Statistical tests indicated no significant differences between groups in age (ANOVA, p=0.997), gender, education level, occupation, race, ethnicity, family income, or individual income (all χ^2 or Fisher's exact tests, p>0.84), suggesting that the sociodemographic characteristics of the samples were comparable.

All data (including EEG data under BIDS format), MATLAB, and R scripts necessary to reproduce the subsequent analyses are available at https://doi.org/10.17605/OSF.IO/QSPBF

Table 1. Socio-demographic characteristics of the full sample (N=91).

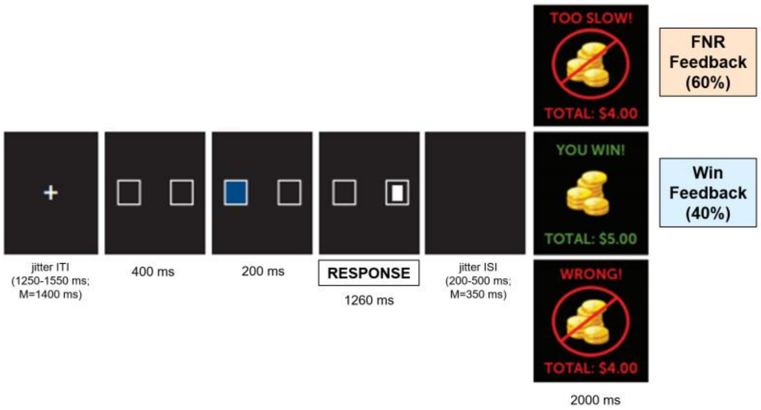
Variables		n (%)
Gender		
	Female	56 (61.54%)
	Male	34 (37.36%)
	Refuse to answer/Don't know	1 (1.10%)
Education		
	Partial High School Degree	1 (1.10%)
	High School Degree	27 (29.67%)
	Technical School Degree/Partial College	24 (26.37%)
	College/University Degree	33 (36.27%)
	Postgraduate Degree	6 (6.59%)
Occupation		
	Student	71 (78.02%)
	Professional	10 (10.99%)
	Laborer	1 (1.10%)
	Other	8 (8.79%)
	Self-employed	1 (1.10%)
Race		
	Asian	18 (19.78%)
	Black or African American	8 (8.79%)
	White or Caucasian	57 (62.64%)
	More than one race	7 (7.69%)

Refuse to answer	1 (1.10%)
Ethnicity	
Hispanic/Latinx	16 (17.58%)
Not Hispanic/Latinx	75 (82.42%)
Family Annual Income	
Less than $14.999	6 (6.59%)
$15,000 through $19,999	3 (3.30%)
$20,000 through $49,999	9 (9.89%)
$50,000 through $74,999	18 (19.78%)
$75,000 through $99,999	10 (10.99%)
$100,000 and greater	42 (46.15%)
Refuse to answer/Don't know	3 (3.30%)
Individual Annual Income	
Less than $14.999	63 (69.23%)
$15,000 through $19,999	3 (3.29%)
$20,000 through $24,999	2 (2.20%)
$25,000 through $49,999	18 (19.78%)
$50,000 through $74,999	3 (3.30%)
Refuse to answer/Don't know	2 (2.20%)

2.2. Materials

Affective Posner Task. Participants completed an adapted version of the Affective Posner Task (AP) used in prior research (Deveney, 2019; Tseng et al., 2019). In this task, participants were instructed to identify the location of a target following a cue by button press (left or right). On 75% of trials, the target appeared in the same location as the cue (valid trials), and on the remaining 25%, it appeared in the opposite location (invalid trials). Participants first completed four practice trials. A sample trial of the task is illustrated in **Figure 1**. The task included two blocks of a non-frustration condition (100 trials total) followed by two blocks of a frustration condition (100 trials total). During the non-frustration condition, participants were informed that they would win or lose 25¢ for every correct ("You Win!") or incorrect ("Wrong!") response, respectively, and received accurate feedback on their performance. During the frustration condition, participants were told that they needed to respond both accurately *and quickly* in order to win 25¢. They were informed that the speed requirement was determined by a "complicated formula" applied on a trial-by-trial basis. To induce frustration, feedback was rigged on 60% of correct trials: participants were told they were "Too Slow!" and lost 25¢ (i.e., FNR trials), regardless of their actual response time. On the remaining 40% of correct trials, they received positive feedback ("You Win!") and gained 25¢. At the end of each block, participants rated their levels of frustration and unhappiness using 9-point Likert scales (1="not at all frustrated" to 9="extremely frustrated"; 1="happy" to 9="sad"). At the end of the experimental session, a debriefing was done to assess participant deception about the task, and participants were given the maximum reward ($25) regardless of their actual performance.

Figure 1. Illustration of a sample trial from the Affective Posner Task. In the frustration condition (100 trials), correct responses were followed by frustrative nonreward (FNR) feedback ("TOO SLOW!") on 60% of trials and by win feedback ("YOU WIN!") on 40% of trials. All incorrect responses were followed by negative feedback ("WRONG!"). ISI=interstimulus interval; ITI=intertrial interval.



Brief Irritability Test (BITe). Before completing the AP, participants completed an online version of the BITe (Holtzman et al., 2015), a 5-item self-report questionnaire rated on a 6-point Likert type scale (1=never, 2=rarely, 3=sometimes, 4=often, 5=very often, 6=always) designed to assess irritability over the past two weeks. The total score is calculated by summing the score of each item, with a higher total score corresponding to a higher level of irritability. The BITe is thought to be the most precise and reliable tool for measuring irritability in adults (Saatchi et al., 2023; Toohey & DiGiuseppe, 2017) and in the current sample, demonstrated excellent internal consistency (α=.89).

2.3. Overview of the analytic approach

Our analytic approach began with manipulation checks on the behavioral sample (*n*=90) to ensure that the frustration induction effectively impacted self-reported ratings, RT, and accuracy data.

We then performed time-domain ERP analyses (*n*=80) to replicate findings from Deveney, (2019), examining the impact of FNR on the feedback-related negativity and its associations with irritability as measured by the BITe.

For our primary analyses on midfrontal theta power to FNR (*n*=71), we extracted single-trial theta activity using generalized eigendecomposition (GED). These analyses were limited to trials from the frustration condition, as this condition includes the FNR trials. To test whether theta power was sensitive to FNR, we ran a LMM assessing the within-subject effect of Feedback Type (Win vs. FNR) on theta power. To examine whether theta power in response to FNR predicted subsequent behavioral adjustments, we conducted a single-trial LMM testing whether trial-by-trial theta power and Feedback Type predicted RT on the next trial. Finally, to explore whether these brain-behavior associations were moderated by individual differences, we included interaction terms with trait irritability and state frustration (separately) in the mixed-effects models, assessing whether these measures influenced the coupling between FNR-related theta activity and behavioral adaptation.

2.4. Manipulation check

Self-reported ratings

The two frustration ratings from the non-frustration blocks and the two ratings from the frustration blocks were averaged separately to create summary scores for each condition. This self-reported measure has been used extensively to index state frustration (Bellaert et al., 2025b; Deveney, 2019; Ghosn et al., 2023; Scheinost et al., 2021; Tseng et al., 2019), and has good test-retest reliability (Tseng et al., 2017). The same procedure was applied to the unhappiness ratings. Frustration and unhappiness ratings were analyzed using LMMs with Condition (non-frustration, frustration) as fixed effect and a random intercept for subject to account for within-subject variability.

Behavioral data

Incorrect trials and trials with RTs below 150ms were excluded from the analyses, following previous work (Deveney, 2019). Following Frömer et al. (2018), outliers (>3 median absolute deviation [MAD] above each participant's median RT) were excluded on a per-subject basis. RTs and accuracy were analyzed using LMMs, with Condition (non-frustration, frustration) and Trial Type (valid, invalid) as fixed effects, and a random intercept for subject.

2.5. EEG recording and preprocessing.

EEG data were collected using a 128-channel HydroCel Geodesic Sensor Net with Ag/AgCl electrodes (Electrical Geodesics, Inc. [EGI], Eugene, OR) and a Net Amps 200 amplifier, via Net

Station 4.2.2 software. The reference electrode was positioned at Cz, and electrode placement followed the 10–20 system. Signals were sampled at 500Hz, with a 100Hz low-pass filter applied during recording (cut-off at the half-power point, −3 dB, with standard roll-off). Electrode impedances were kept below 50 kΩ duing acquisition. EEG preprocessing and analyses were performed using custom MATLAB 2022b scripts (MathWorks, Inc., Natick, MA) and the EEGLAB Toolbox (Delorme & Makeig, 2004). Our preprocessing pipeline was adapted from previous work (Bowers et al., 2018) that used similar EEG equipment as in the current study. Data were downsampled to 200Hz to improve processing speed. Data were high-pass filtered at 0.3Hz and low-pass filtered at 49Hz. Noisy channels were identified via visual inspection and removed (*M*=1.55, *SD*=1.38, range 0–6). Channels were marked as "noisy" if they showed persistent excessive high-frequency noise, flatlining, or poor signal quality across the recording. Trials were epoched from -200 to 1000ms relative to feedback onset. Epochs were inspected visually, and segments showing motion artifacts, muscle activity, or sudden voltage changes beyond physiological limits were excluded. This manual artifact rejection approach was employed because it is generally more effective and less prone to bias than automatic methods (Cohen, 2017). To identify artifacts in the data, independent components analysis (ICA) was performed on a copy of the data set that was filtered with a 1Hz high-pass filter, as this enhances the quality of the decomposition. ICA weights from the ICA run on the copied (1Hz) data set were then copied back to the 0.3Hz high-passed data. ICA artifact identification was guided by the ICLabel MATLAB plug-in (Pion-Tonachini et al., 2019), and components with clearly identifiable nonbrain artifacts (e.g., eye-blinks or heartbeats) were removed from the data (*M*=4.11, *SD*=1.49, range 1–8). Missing or removed channels were interpolated using a spherical spline interpolation, and data were re-referenced to the average of all electrodes. ERP amplitudes were baseline-corrected using the –200 to 0ms pre-stimulus window. Participants had an average of 95.44 non-frustration win trials (*SD*=8.14, range 51–100), 35.15 frustration win trials (*SD*=3.86, range 24–40), and 52.18 FNR trials (*SD*=5.17, range 38–59).

2.6. Time-domain analysis.

The feedback-related negativity was operationalized as the mean amplitude between 225–325ms after feedback presentation, in line with Deveney (2019). Visual inspection of grand-average waveforms and topographies indicated that the feedback-related negativity peaked at FCz, and thus ERP analyses were conducted at this site. Three feedback-related negativity components were calculated: non-frustration win, frustration win, and FNR. The non-frustration loss feedback-related negativity was not calculated due to insufficient number of incorrect responses in the non-frustration condition (*M*=2.14, *SD*=1.88). Finally, the Reward Positivity (RewP) was calculated by subtracting the feedback-related negativity to FNR from the feedback-related negativity to frustration win (Proudfit, 2015). We conducted a LMM to investigate the effect of condition on feedback-related negativity amplitudes in response to wins, with Condition (Non-frustration vs. Frustration) as a fixed effect and random intercepts for each subject to account for within-subject variability. A second model assessed the impact of Feedback Type within the frustration condition (frustration win vs. FNR), using the same structure.

Associations between ERP and irritability

To replicate prior ERP findings linking feedback-related negativity in response to FNR with irritability (Deveney, 2019), linear regressions were conducted to evaluate whether irritability, as measured by the BITe, was associated with the feedback-related negativity to (1) non-frustration win, (2) frustration win, (3) FNR, and with the RewP during frustration.

2.7. Time-frequency analysis.

To address our first main aim – testing whether midfrontal theta power indexes FNR – we conducted time-frequency analyses focused on the feedback-locked neural responses. This analysis, as well as all subsequent analyses, was limited to trials from the frustration condition, as this condition includes the FNR trials. To test our hypothesis regarding theta-band activity, we created a spatial filter that maximize power in the theta band in response to feedback receipt using generalized eigendecomposition (GED), a hypothesis-driven multivariate source separation method (see Cohen, 2022 for details). GED was chosen because it offers several advantages: (1) as a hypothesis-driven approach based on a priori contrasts, it enables the extraction of neural components that most strongly capture task-related brain activity associated with the cognitive process of interest, (2) it accounts for interindividual differences in theta peak frequency and topography, therefore reducing the impact of individual variability on statistical power, and importantly (3) it enhances the signal-to-noise ratio at the single-trial level. This approach follows prior implementations in the literature (Duprez et al., 2020; Zuure et al., 2020).

A spatial filter is constructed by finding a set of weights for the data channels that emphasizes a desired contrast between two data features. This contrast is quantified using two covariance matrices: **S**, representing the signal of interest, and **R**, representing a reference. Both matrices encode all pairwise linear relationships across EEG channels. GED aims to find a set of channel weights contained in a vector **w** that maximizes the power ratio between **S** and **R**, expressed through the generalized Rayleigh quotient:

$$\lambda = \frac{\mathrm{w^T S w}}{\mathrm{w^T R w}} \qquad (1)$$

Here, λ is the generalized eigenvalue corresponding to the spatial filter w. In our study, the goal was to isolate theta-band activity from broadband activity. To do this, we computed the **S** matrix as channel*channel covariance derived from EEG data that had been narrowband filtered around each participant's individual theta peak frequency, to account for the high interindividual variability in theta peaks (Haegens et al., 2014; Williams et al., 2021). Individual peaks were identified by finding the maximum power based on the average of all trials across win and FNR trials in the frustration condition within the theta band (4–9Hz, 0–700ms) from a time-frequency decomposition at FCz. Time-frequency measures were obtained by multiplying the power spectrum of the epoched trials with a fast Fourier power spectrum of a set of complex Morlet wavelets spanning 1–20Hz in 100 logarithmically spaced steps. Wavelet width increased with frequency, ranging from 2/(2πf) to 10/(2πf). Then, the inverse fast Fourier transform was computed to recover the time series. For each feedback type, the power at each time point was calculated by averaging the squared absolute value of the amplitude. Power was then converted to decibel (dB) units relative to a baseline defined from –150 to –50ms before feedback onset. The analysis code was adapted from Cavanagh et al. (2021).

The identified theta peaks were used as center frequencies for Gaussian narrowband filters (full-width at half-maximum=3Hz) applied to the broadband data. The resulting theta-filtered data were then used to compute the **S** matrix, defined within an 800ms time window (defined to incorporate multiple theta cycles) centered on the power peak. We computed the R matrices as the channel*channel covariance matrices derived from the broadband unfiltered data from the same time window and regularized using 1% shrinkage (γ=0.01) to enhance matrix stability and separability.

The GED solution was obtained by solving the equation SW=RWΛ, yielding eigenvectors (W) and corresponding eigenvalues (Λ). Each eigenvector serves as a potential spatial filter, with higher eigenvalues indicating greater separation between signal and reference. From the 128 spatial filters generated by GED, the 15 filters with the highest eigenvalues were retained and applied to the unfiltered data to extract component time series and their associated activation patterns (topographies). To identify the best component for each participant, we followed a selection procedure inspired by Zuure et al., (2020). The topography of each component was compared to a predefined EEG template consisting of a Gaussian centered on midfrontal electrode FCz, where theta power is typically maximal. For each component, we computed the shared spatial variance (R^2) with this template. To ensure that the selected component not only matched the expected topography but also optimally separated theta activity from other signals, R^2 values were weighted by the normalized eigenvalue of each component using the formula:

$$Eigenvalue\ weighted\ correlation = \frac{Eigenvalue_{component}}{\sum Eigenvalues} * R^2_{component}$$

The component with the highest weighted score was selected as the best theta spatial filter. The selected theta components were time-frequency decomposed through complex Morlet wavelet convolution, as described previously. For single-trial power normalization, we applied the baseline normalization procedure proposed by Ciuparu & Mureşan (2016), in which baseline periods from all trials are fused to create a single, common baseline. For each frequency band and participant, power values from the baseline period were combined across trials in the frustration condition to form this unified baseline distribution. The resulting mean and standard deviation were then used to normalize power at each time point and trial via a z-scoring approach, yielding normalized EEG power expressed in z-score units. This method has been shown to reduce bias in single-trial normalization (Ciuparu & Mureşan, 2016). Four participants exhibiting low or no theta activation were excluded from further analysis. Another five participants showed prominent edge artifacts (i.e., high-amplitude broadband power artifacts that occur at the beginning and end of the signal) in the theta-band time-frequency decomposition, which distorted the spectral estimates within the analysis window, were excluded from further analysis, resulting in the final analytic time-frequency subsample (*n*=71).

Based on inspection of the grand average time-frequency representations, theta power values were extracted at the participant level within the 4–8Hz frequency range and the 0–600ms post-feedback time window for statistical analyses. Because single-trial power estimates can be relatively noisy (Ciuparu & Mureşan, 2016), theta values >3 MAD above each participant's mean were excluded. To test whether midfrontal theta power was sensitive to FNR, we conducted a LMM to investigate the within-subject effect of Feedback Type (Win vs. FNR) on theta power, with feedback type included as a fixed effect and subject-specific random intercepts.

Descriptive statistics and correlations between task measures

Means, standard deviations, and ranges of the BITe, frustration ratings, and theta power values separately averaged across win and FNR trials were computed, and bivariate, zero-order correlations between them were examined. To illustrate trial-wise trends, we plotted smoothed trajectories of mean theta power by feedback type (Win vs. FNR) and mean RT across trials using LOESS (Locally Estimated Scatterplot Smoothing), see Figure S1.

Single-trial LMM of theta power and RT adjustment

To address our second main aim – testing whether theta power to FNR is associated with subsequent RT adjustment – we conducted a single-trial LMM to examine whether trial-by-trial theta power and Feedback Type (Win vs. FNR) predicted RT on the following trial. In line with the behavioral analyses, outliers (>3 MAD above each participant's median RT) were excluded. We also excluded RT<150ms and incorrect trials, to ensure that the model captured meaningful cognitive adjustments post-FNR and not anticipatory responses. The model included a random intercept for subject and was fitted using restricted maximum likelihood (REML). Degrees of freedom and p-values were estimated using Satterthwaite's approximation. 95% confidence intervals were calculated using the profile likelihood method (Bates et al., 2015). To interpret the significant interaction between theta power and feedback type on subsequent RT, a simple slopes analysis was conducted using the probe_interaction() function from the jtools R package (Long, 2022). This procedure decomposes the interaction by estimating the conditional effect (slope) of theta power on the outcome (next-trial RT) at each level of the moderator variable (feedback type). The slope of theta power was examined separately for win and FNR feedback.

Moderation by irritability and state frustration

To address our third main aim – exploring whether the brain-behavior associations between theta power to FNR and subsequent RT were moderated by individual differences in trait irritability and state frustration – we conducted LMMs. Each model included theta power, feedback type (FNR vs win), ratings of frustration or irritability (in separate models), and their respective interaction terms as fixed effects, with subject included as a random factor to account for repeated measures. We examined the interactions using the Johnson-Neyman technique, a robust method for identifying regions of significance within an interaction (Bauer & Curran, 2005; Johnson & Neyman, 1936). Four outliers were identified on the BITe using a conservative outlier detection method (±3 MAD). The exclusion of these outliers did not substantially change the results. The moderation model excluding these cases are reported in Results S2.

2.8. Sample size justification and sensitivity power analysis

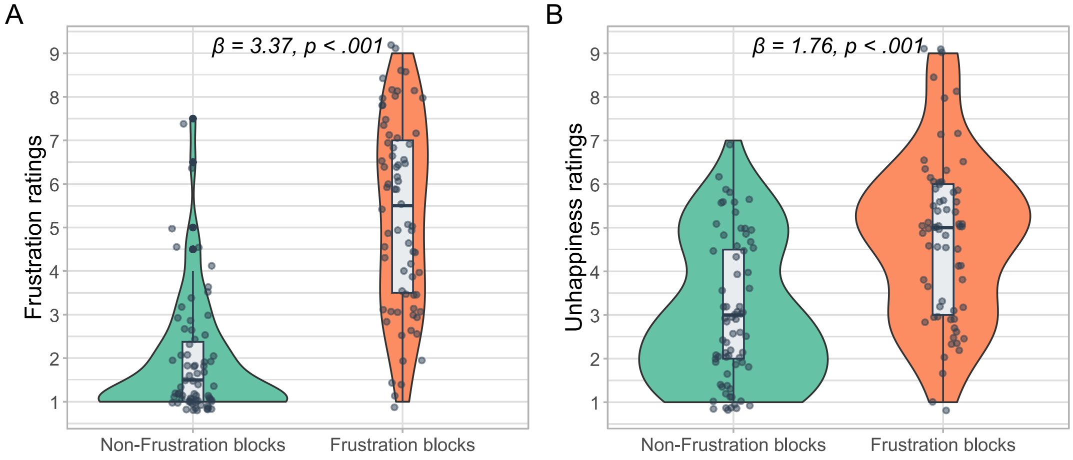
The planned sample size was informed by prior work by Deveney (2019), which indicated that 62 participants would be sufficient to detect significant effects of the feedback manipulation on the feedback-related negativity amplitudes to loss versus gain. Power calculations suggested that 65 participants would provide 80% power to detect a moderate effect size (f = 0.20). We aimed to collect approximately 70 participants with usable EEG data. For the present single-trial LMM, sensitivity power simulations indicated that the observed interaction between theta power and feedback type in predicting subsequent RT was detectable with 80% power ($\alpha = .05$), confirming that the study had sufficient power to detect this effect.

3. RESULTS

3.1. Manipulation checks: self-reported ratings and behavioral results

Relative to the non-frustration condition, the frustration manipulation increased self-reported ratings of frustration, β=3.37, p<.001 ($M_{non\text{-}frustration}$=1.90; *SD*=1.34; $M_{frustration}$=5.28; *SD*=2.18, see **Figure 2A**) and unhappiness, β=1.76, p<.001 ($M_{non\text{-}frustration}$=3.04; *SD*=1.64; $M_{frustration}$=4.79; *SD*=1.64, see **Figure 2B**).

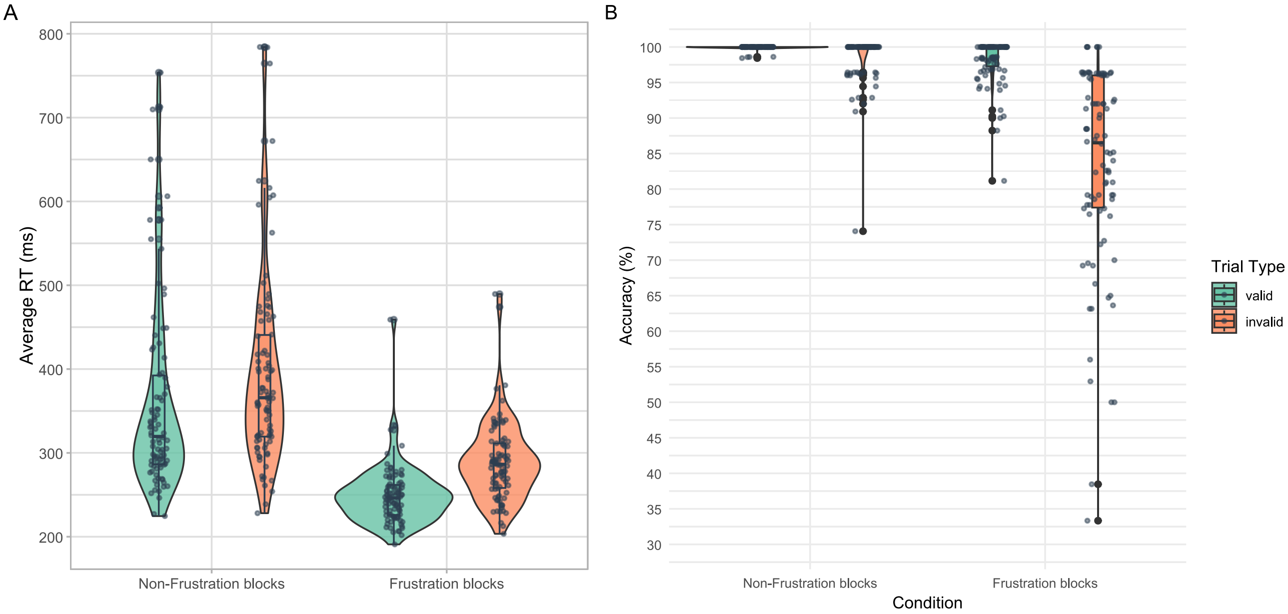
Figure 2. Mean self-reported ratings of frustration (**A**) and unhappiness (**B**) across non-frustration and frustration blocks.



The model for RT revealed significant main effects of Condition, β=112.26, *SE*=2.84, t(15491)=39.59, p<.001, and Trial Type, β=-37.10, *SE*=2.48, t(15489)=-14.98, p<.001, see **Figure 3A**. RTs were faster in the frustration block and on valid trials. There was no significant interaction between Condition and Trial Type, β=0.77, *SE*=3.29, t(15489)=0.23, p=.81.

The model for accuracy revealed significant main effects of Condition, β=2.80, *SE*=0.19, z=14.56, p<.001, and Trial Type, β=2.40, *SE*=0.12, z=19.22, p<.001, see **Figure 3B**. Accuracy was lower in the frustration block and on invalid trials. There was no interaction between Condition and Trial Type, β=0.63, *SE*=0.53, *z*=1.18, *p*=.24.

Figure 3. A. Mean RT Across Conditions and Trial Types. RTs were faster during frustration versus non-frustration condition and on valid versus invalid trials. **B.** Mean Accuracy Across Conditions and Trial Types. Accuracy was lower during frustration versus non-frustration and for invalid versus valid trials. No interaction between condition and trial type was observed. Error bars reflect standard errors.

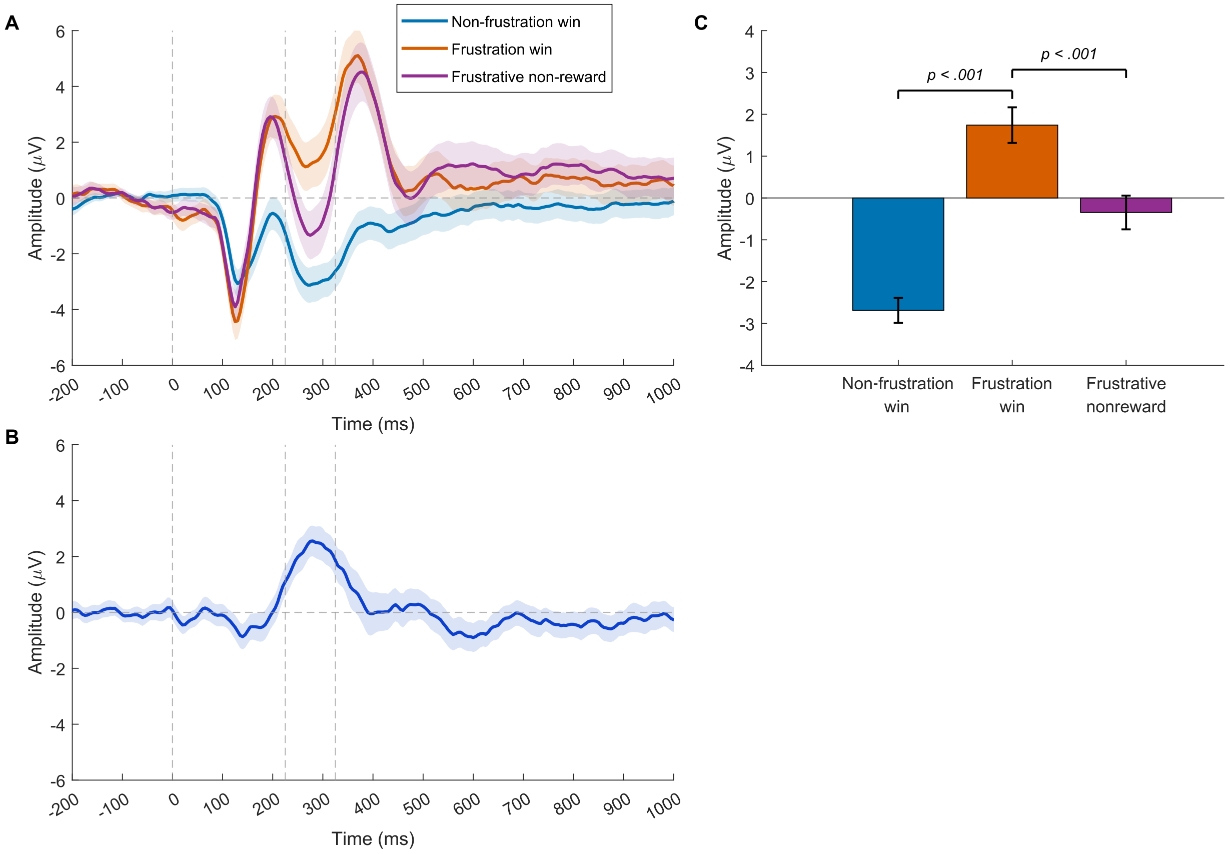


3.2. Time domain results

The grand average ERPs are shown in **Figure 4A**. A LMM revealed a significant effect of Condition on feedback-related negativity amplitudes in response to wins, with larger (i.e., more negative) amplitudes for non-frustration wins compared to frustration wins, β=−4.43, *SE*=0.31, *t*(79)=−14.22, *p*<.001.

The second LMM showed a significant effect of Feedback Type (Win vs FNR) on feedback-related negativity amplitude in the frustration condition, with larger (i.e., more negative) amplitudes for FNR compared to frustration wins, *β*=- 2.09, *SE*=0.24, *t*(79)=-8.63, *p*<.001.

Figure 4. A. Grand averaged ERPs per feedback type at FCz with 95% confidence intervals. Time=0ms corresponds to feedback presentation. **B.** Grand average difference waveform between frustrative nonreward (FNR) and frustration wins (computed by subtracting the feedback-related negativity to FNR from the feedback-related negativity to frustration win) with 95% confidence intervals. **C.** Mean amplitude between 225-325ms for each feedback type. Error bars reflect standard errors.



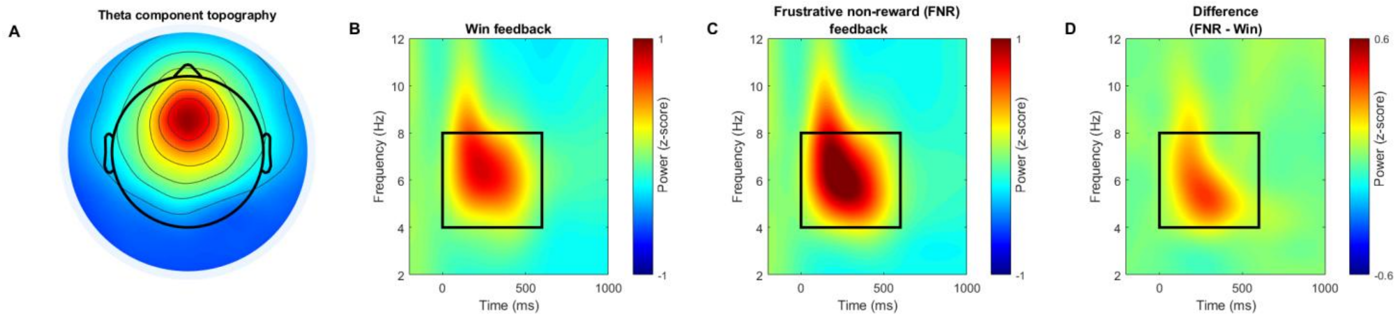
Association between irritability and ERP measures

No significant associations were found between irritability and (1) the feedback-related negativity to non-frustration win ($r=-0.14$, $p=.21$); (2) the feedback-related negativity to frustration win ($r=-0.11$, $p=.32$); (3) the feedback-related negativity to FNR ($r=-0.13$, $p=.26$); and (4) the RewP during frustration ($r=0.01$, $p=.91$).

3.3. Time-frequency results

We applied GED to find a spatial filter that best isolates theta activity from broadband activity. **Figure 5A** shows the topography of the activation pattern of the selected theta spatial filters averaged across participants, with a clear activation around midfrontal electrodes. Theta power extracted from the time-frequency decomposition of this component revealed that theta power to FNR (**Figure 5C**; $M=0.46$, $SD=0.98$) was significantly higher than theta power to frustration win (**Figure 5B**; $M=0.32$, $SD=0.81$), $\beta=0.13$, $SE=0.02$, $t(5879)=7.46$, $p<.001$. The corresponding time-frequency plot of the difference between FNR and frustration win trials is presented in **Figure 5D**, showing an increase in theta-band power following FNR.

Figure 5. A. Topographical map showing the activation pattern of the theta spatial filter defined by GED. Time-frequency power of the theta component defined by GED for frustration win trials (B), frustrative nonreward (FNR) trials (C), and the difference computed by subtracting the averaged power of frustration win trials from the averaged power of FNR trials (D). Black rectangles show the time-frequency windows used to extract theta power to feedback.



Descriptive statistics and correlations

Table 2 shows the means, standard deviations, ranges, and correlations between variables. Irritability was significantly associated with higher self-reported state frustration (*r*=.35, *p*=.01), and marginally with lower mean theta power in response to FNR (*r*=–.23, *p*=.06) but not in response to frustration win (*r*=-.19 *p*=.11). Self-reported frustration was significantly correlated with theta power to FNR (*r*=–.28 *p*=.03) and marginally associated with theta power to frustration win (*r*=–.26, *p*=.05). Theta power in response to FNR and to win were highly correlated (*r*=0.93, *p*<.01).

Table 2. Descriptive statistics (means, standard deviations, range) and correlations of study variables.

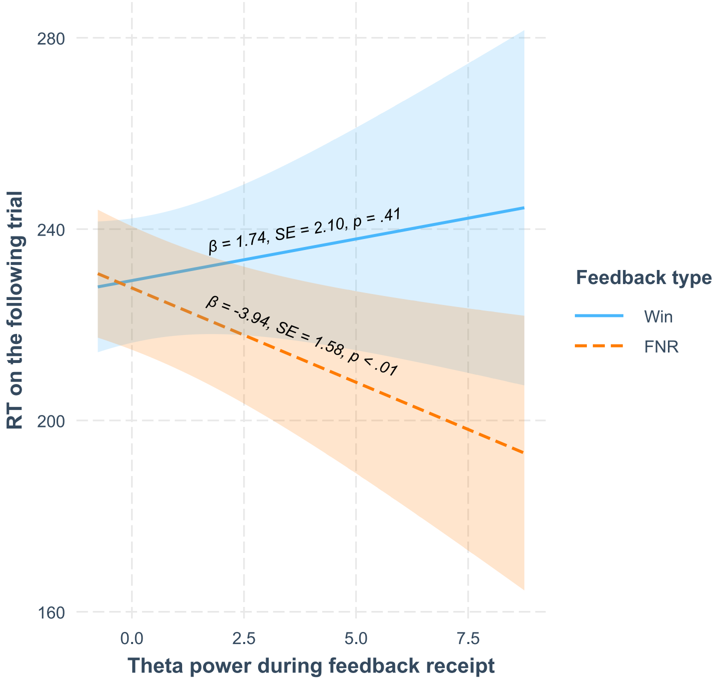
Variable	Descriptive Statistics			Correlations					
	Mean	*SD*	Range	1		2		3	
				r	*p*	*r*	*p*	*r*	*p*
1. BITe	11.39	4.02	5–25						
2. Self-reported frustration in the frustration condition	5.44	2.20	1–9	**.36**	**<.01**				
3. Mean theta power to FNR	0.44	0.69	-.24–2.98	-.23	.06	**-.28**	**.03**		
4. Mean theta power to frustration win	0.31	0.50	-.31–2.39	-.19	.11	-.26	.05	**.93**	**<.01**

Note. BITe=Brief Irritability Test. Significant correlations are bolded. Degrees of freedom = 69.

Results of the single-trial LMM of theta power and RT adjustment

The main effect of theta power was not significant, $\beta=1.74$ (95% CI [−2.38, 5.89]), $SE=2.10$, $t(5132)=0.83$, $p=.41$, nor was the main effect of feedback type, $\beta=-1.55$ (95% CI [−5.80, 2.69]), $SE=2.17$, $t(5074)=-0.72$, $p=.47$. The interaction between theta power and feedback type was significant, $\beta=-5.68$ (95% CI [−10.12, −1.24]), $SE=2.27$, $t(5075)=-2.51$, $p=.012$, indicating that the association between theta power and subsequent RT differed by feedback type. The simple slopes analysis revealed that theta power did not significantly predict RT following win feedback, $\beta=1.74$, $SE=2.10$, $t=0.83$, $p=.41$. In contrast, theta power significantly predicted faster RT following FNR feedback, $\beta=-3.94$, $SE=1.58$, $t=-2.50$, $p<.01$, see **Figure 6**.

Figure 6. Interaction between theta power during feedback receipt and feedback type on reaction time (RT) on the following trial. Higher theta power was associated with faster subsequent RTs following frustrative nonreward (FNR) feedback but not following win feedback. Shaded areas represent 95% confidence intervals. N=71.



Moderation by state frustration and irritability

To examine whether frustration or irritability moderated the relationship between theta power and subsequent RT, LMMs were conducted with feedback type, theta, and either frustration ratings or irritability as predictors, including all two- and three-way interactions. For the model including frustration, results indicated no significant main effects of feedback type, theta power, or frustration on subsequent RT (all *p*>.12). The interaction between feedback type and theta approached significance (*p*=.06), but none of the other two-way or three-way interactions reached significance (all *p*>.29). Similarly, for the model including irritability, there were no significant main effects or interactions, including the three-way interaction between feedback type, theta, and irritability (all $p > .12$).

Overall, these findings suggest that neither self-reported state frustration nor irritability moderated the effect of theta power on subsequent RT.

DISCUSSION

The current study had three primary aims. First, we evaluated whether midfrontal theta power indexes FNR in a task specifically designed to induce frustration by withholding an expected reward. Results showed that theta power was greater following FNR compared to win feedback within the frustration condition. Second, we investigated whether trial-by-trial variations in midfrontal theta power in response to FNR were associated with adjustment in subsequent RT. Findings indicated that higher theta power following FNR, but not following win feedback, was associated with faster RT on the next trial. These findings suggest that theta oscillations may support adaptive behavioral adjustments to frustrative outcomes. Reduced theta power in response to FNR was associated with higher self-reported frustration, suggesting a link between neural response to FNR and subjective experience. Lastly, we explored whether these brain-behavior associations between theta power to FNR and subsequent RT were moderated by individual differences in trait irritability and state frustration and found no significant moderation effects.

As an initial step, we examined the impact of our frustration induction on affective and behavioral responses. The frustration induction effectively increased self-reported ratings of frustration and unhappiness. Participants reported moderate levels of frustration during the frustration condition (*M*=5.38, *SD*=2.31 on the 9-point Likert scale), aligning with previous studies that used the same task in community samples of young adults (*M*=4.96, *SD*=2.30; Deveney, 2019) and youths aged 9–14 years (*M*=5.49, SD=2.66; Tseng et al., 2017). The Affective Posner Task used in these studies elicited frustration through reward omission, one form of FNR. However, FNR can also arise from reward devaluation or obstruction (Papini et al., 2015). Notably, paradigms involving reward obstruction (i.e., blocking access to an expected reward, for example by making the response button temporarily unresponsive) have been shown to elicit even higher levels of frustration in young adults, particularly when the obstruction occurs close to the anticipated reward delivery (M>8 on a 10-point Likert scale; Yu et al., 2014; replicated in Eben et al., 2024). Exploring such paradigms in future studies could help further evoke individual differences in irritability and frustration tolerance in healthy young adult samples. Consistent with prior findings using the Affective Posner Task (e.g., Deveney, 2019; Tseng et al., 2019), the frustration manipulation also resulted in reduced RT and accuracy. A previous study using drift-diffusion modeling revealed that these behavioral effects were driven by a reduced decision threshold, indicating a tendency to favor speed over accuracy during frustration (Bellaert et al., 2025b).

We also replicated earlier findings (Deveney, 2019) showing that the feedback-related negativity was significantly larger for FNR feedback compared to win feedback. However, we did not replicate previous reports of a positive association between feedback-related negativity responses to FNR and irritability. Given that the present study employed similar sample characteristics, the same task paradigm, and irritability measure as previous work, the lack of replication is unlikely to be due to methodological differences. One notable difference, however, is that our sample included both male and female participants, whereas Deveney (2019) studied an all-female sample. However, when we restricted our analyses to female participants, we found a negative correlation between feedback-related negativity responses and irritability (see Results S3). This suggests that gender differences do not fully explain the lack of replication of the previously reported positive association. Instead, the discrepancy may reflect sampling variability, individual differences in EEG responses to FNR, or limited power to detect subtle effects in our sample. This underscores the importance of future studies with larger samples to clarify the robustness and the direction of this association.

Our main findings indicate that midline frontal theta power was significantly greater following FNR compared to win feedback, further confirming the role of theta oscillations as a sensitive neural marker of discrepancies between expected and actual outcomes. This aligns with prior evidence demonstrating increased theta activity for worse-than-expected events (e.g., Dymond et al., 2014; Fryer et al., 2021; Rawls et al., 2020). Our study extends these observations by demonstrating that this effect was also evident in response to FNR, i.e., a frustration state induced by omission of an expected reward. Importantly, we also found that increased theta power following FNR was associated with faster responding on the subsequent trial. This could suggest that increased theta activity may reflect a mechanism for mobilizing attentional control processes to adapt behavior in response to frustration, supporting more efficient responding. We showed that higher midfrontal theta appears to facilitate quicker and more accurate responding, effectively meeting the heightened attentional demands induced by the rigged task feedback, without relying on anticipation. Notably, this RT adjustment mechanism was not found following positive feedback, highlighting the specificity of theta-related control processes to FNR. These findings fit within a broader literature linking frontal midline theta to cognitive control and attentional allocation under conditions of outcome uncertainty (Cavanagh & Frank, 2014; Cavanagh & Shackman, 2015). Theta oscillations are thought to arise from synchronous activity in medial frontal structures, particularly the ACC and medial prefrontal cortex (mPFC), which have been implicated in error monitoring, evaluating action outcomes, and guiding behavioral adjustments (Asada et al., 1999; Debener et al., 2005; Kawai et al., 2015; Luu et al., 2000; Ridderinkhof et al., 2004; Womelsdorf et al., 2010). Moreover, recent work in animal models has shown that dopamine neurons in the ventral tegmental area (VTA) exhibit increased firing to unexpected reward omissions, which correlates with behavioral adaptations aimed at coping with unexpected nonreward (Ishino et al., 2023). This may suggest a pathway between subcortical dopaminergic signaling and cortical theta dynamics in implementing adaptive responses to frustrative events.

The observed response speeding may not solely be a consequence of the rigged feedback explicitly instructing participants to respond faster. Similar post-error speeding effects have been documented even in tasks that provide no explicit feedback speed directives, specifically following uncontrollable outcomes (i.e., errors or gambling losses) compared to controllable ones (Dixon et al., 2013; Dyson et al., 2018; Eben et al., 2020, 2023; Verbruggen et al., 2017). It is highly probable that the rigged feedback used in our Affective Posner Task induced a feeling of uncontrollability over the outcomes, as participants may have realized that meeting the speed requirement was unattainable. This lack of perceived control could itself amplify feelings of frustration and negative affect (Burger, 1989; Lawrence, 2006). This pattern of post-FNR speeding observed in our sample appears to parallel the *frustration effect* described in the animal FNR literature, where the omission or devaluation of an expected reward leads to an initial increase in behavioral vigor (Amsel, 1992; Papini et al., 2015). Our study extends these findings by demonstrating that, in humans, this post-FNR behavioral invigoration may be supported by increased theta activity, reflecting an adaptive mechanism that enhances subsequent performance under frustration. Whether this effect is primarily driven by increased motivation, enhanced attentional control, or a combination of both remains a question for future research.

Our findings suggest that this adaptive mechanism may be weakened when higher levels of frustration are experienced during the task. Specifically, reduced mean theta power to FNR was associated with higher self-reported state frustration. This may imply that elevated frustration may interfere with the adaptive engagement of cognitive control mechanisms. According to theories of cognitive control, when motivationally relevant goals are not met, the resulting negative affect serves to signal the need for goal reprioritization and the mobilization of further goal-directed actions (Inzlicht et al., 2015). However, experiencing high level of negative affect may attenuate the engagement of processes associated with cognitive control, as observed in individuals with anxiety or depression (Bishop, 2009; West et al., 2010). Alternatively, increased frustration may promote disengagement from the task goal when continued pursuit is perceived as no longer worthwhile. In mammals, frustration has been proposed to facilitate disengagement from unproductive goal pursuit, redirecting effort toward the exploration of alternative and potentially more rewarding opportunities (Papini et al., 2022). In our study, the observed reduction in theta power may reflect a disruption of the neural processes underlying adaptive control, shifting from active goal maintenance toward withdrawal or reduced engagement under high levels of frustration.

Moreover, our study offers preliminary correlational evidence that this mechanism may also be attenuated in young adults with irritability. In the full sample, the association between irritability and mean theta power in response to FNR was marginal ($r=-0.23, p=0.06$) but reached significance after removing outliers ($r=-0.29$, $p=0.02$), indicating that irritability was associated with reduced theta activity. This might suggest that irritable individuals may be less able, or less motivated, to engage the cognitive resources needed to adjust their behavior following frustration. These findings align, to some extent, with results from a large fMRI study that examined the brain mechanisms of frustration in 195 youths with varying levels of irritability performing the Affective Posner Task (Tseng et al., 2019). That study found that age moderated the relationship between irritability and activation in the mPFC and ACC during attention orienting after FNR versus win feedback. Specifically, irritability was positively correlated with activation in these regions among younger children aged 8–11.5 years ($r=.61$), this association remained positive though weaker in early adolescents aged 11.5–14 years (*r*=.27), and shifted to a negative (albeit non-significant) association in older adolescents aged 14–18 years (*r*=–.13), suggesting a developmental trend toward reduced recruitment of these regions with increasing age. Our EEG findings extend this pattern into young adulthood (18–25 years), showing a negative correlation between irritability and theta power, a signal thought to originate from mPFC and ACC sources (Cavanagh & Frank, 2014), during frustration. Taken together, these results suggest that the association between irritability and neural engagement in response to FNR may change with age, potentially reflecting diminished recruitment of adaptive control processes over development. Further research, particularly in clinical samples of young adults, is needed to clarify this trajectory. It is possible that older adolescents and young adults with irritability are more prone to disengage following frustrative feedback, exhibiting reduced recruitment of neural regions such as the ACC and mPFC and diminished theta oscillatory activity. This could represent a neural mechanism underlying their lower tolerance to frustration, as insufficient engagement of these systems may impair the adjustment of behavior in response to unexpected reward omission.

These findings should be interpreted considering some limitations. Our sample was composed of non-clinical participants, therefore limiting representation of the higher end of the irritability spectrum. Additionally, our sample had a predominantly high socioeconomic status, further limiting the generalizability of our findings. Moreover, only modest correlations were found between irritability symptoms and self-reported frustration during the FNR task (*r*=.35), suggesting that not all individuals with elevated irritability experience frustration in this context. This indicates that our paradigm may be capturing just one aspect of irritability. Given that irritability is frequently experienced in interpersonal situations, there is a clear need to develop paradigms that elicit frustration in social contexts to increase ecological validity and to capture the interpersonal aspects of irritability. Finally, the short pre-feedback baseline period (i.e., -150 to -50 ms) may have reduced the reliability of time-frequency power estimates.

In summary, the present study demonstrates that midfrontal theta power is increased following FNR and predicts faster subsequent responding, highlighting its role in adaptive adjustments to unexpected reward omission. These findings advance our understanding of the neurocognitive mechanisms supporting behavioral adaptation under frustration by showing the role of theta oscillations in coping with frustrative events. Future studies probing the relative motivational and cognitive contributions to this process will be critical for further understanding these mechanisms. We also provide preliminary correlational evidence that this process may be less effective in individuals with higher irritability, although further research with larger, clinical samples is needed to clarify these associations and their developmental course.

Highlights:

- Midfrontal theta increases in response to frustrative nonreward (FNR).
- Trial-by-trial theta predicts faster responding after unexpected reward loss.
- Reduced theta to FNR is linked to higher self-reported frustration.
- Theta–behavior link is unaffected by irritability or state frustration.
- Midfrontal theta supports coping with frustrative outcomes.

Conflict of Interest: The authors have no relevant interests to disclose.

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