



Published in final edited form as:

Psychophysiology. 2018 October ; 55(10): e13208. doi:10.1111/psyp.13208.

Time-frequency approaches to investigating changes in feedback processing during childhood and adolescence

M.E. Bowers¹, G.A. Buzzell², E.M. Bernat^{1,3}, N.A. Fox^{1,2}, and T.V. Barker⁴

¹Neuroscience & Cognitive Science Program, University of Maryland, College Park, MD, USA

²Department of Human Development & Quantitative Methodology, University of Maryland, College Park, MD, USA

³Department of Psychology, University of Maryland, College Park, MD, USA

⁴Prevention Science Institute, University of Oregon, Eugene, OR, USA

Abstract

Processing feedback from the environment is an essential function during development to adapt behavior in advantageous ways. One measure of feedback processing, the feedback negativity (FN), is an event-related potential (ERP) observed following the presentation of feedback. Findings detailing developmental changes in the FN have been mixed, possibly due to limitations in traditional ERP measurement methods. Recent work shows that both theta and delta frequency activity contribute to the FN; utilizing time-frequency methods to measure change in power and phase in these frequency bands may provide more accurate representation of feedback processing development in childhood and adolescence. Here, we employ time-frequency (TF) power and inter-trial phase synchrony measures, in addition to conventional time-domain ERP methods, to examine the development of feedback processing in the theta (4-7 Hz) and delta (.1-3 Hz) bands throughout adolescence. A sample of 54 females (8-17 years old) completed a gambling task while electroencephalogram (EEG) was recorded. As expected, time-domain ERP amplitudes showed no association with age. In contrast, significant effects were observed for the time-frequency measures, with theta power decreasing with age and delta power increasing with age. For inter-trial phase synchrony, delta synchrony increased with age, while age-related changes in theta synchrony differed for gains and losses. Collectively, these findings highlight the importance of considering time-frequency dynamics when exploring how the processing of feedback develops through late childhood and adolescence. In particular, the role of delta band activity and theta synchrony appear central to understanding age-related changes in the neural response to feedback.

1 Introduction

The ability to process and learn from feedback, both reward and loss, is a central feature of cognition and undergoes substantial changes throughout development, particularly in adolescence (Peters et al., 2014; van Duijvenvoorde, Zanolie, Rombouts, Raijmakers, & Crone, 2008). An improved understanding of the neural development of feedback processing

is critical given that impairment in feedback processing during adolescence can lead to poor decision-making (Cauffman et al., 2010; Figner, Mackinlay, Wilkening, & Weber, 2009) or psychopathology (Bress, Foti, Kotov, Klein, & Hajcak, 2013). Understanding neural changes in the processing of rewards and losses during adolescence can lead to an improved understanding of adolescent decision-making, inform the development of future interventions, and aid in the identification of children at high risk for certain disorders.

One psychophysiological measure of feedback, the feedback negativity (FN; also known as the feedback-related negativity, or FRN), is an event-related potential (ERP) that occurs approximately 250-350 ms after feedback presentation, is maximal over fronto-central scalp regions, and has been localized to the anterior cingulate cortex (ACC; Gehring & Willoughby, 2002; Luu, Tucker, Derryberry, Reed, & Poulsen, 2003). The FN traditionally is thought to index loss-related activity, as it is more negative to losses compared to rewards, and typically quantified with a loss minus gain difference score (Holroyd & Coles, 2002; Miltner, Braun, & Coles, 1997). Though we incorporate the traditional FN naming convention here, it is important to note that recent work suggests that, instead of a loss-related negativity, the FN might be better characterized as the absence of a reward-related positivity (Proudfit, 2015). Thus, neural activity observed in response to rewards, compared to losses (a gain minus loss difference score), has been referred to as the reward positivity (RewP; Foti & Hajcak, 2009; Holroyd, Pakzad-Vaezi, & Krigolson, 2008; Proudfit, 2015). Within this theoretical conceptualization, the RewP has been suggested to originate from midbrain structures such as the ventral striatum (Carlson, Foti, Harmon-Jones, & Proudfit, 2015; Foti, Weinberg, Dien, & Hajcak, 2011). Although such difference score approaches can often be useful, the dissociability of loss- and gain-related activity suggests the importance of separately exploring the development of neural responses to losses and rewards, as opposed to only employing a difference wave (subtraction) approach. In this study, feedback processing to both rewards and losses will be examined individually and referred to as “FN-gain” and “FN-loss” in order to avoid assumptions undertaken with the difference score approach; although, difference scores will also be reported, for comparison with prior research.

Studies examining developmental patterns of the FN have been mixed. Some have found that, compared to adults and older adolescents, children exhibit a larger (i.e. more negative) FN (Arbel, McCarty, Goldman, Donchin, & Brumback, 2018; Crowley et al., 2013; Eppinger, Mock, & Kray, 2009; Hämmerer, Li, Müller, & Lindenberger, 2011; Zottoli & Grose-Fifer, 2012), or smaller differentiation between rewards and losses (Hämmerer et al., 2011). However, other studies have found no relation between age and the FN (Larson, South, Krauskopf, Clawson, & Crowley, 2011; Lukie, Montazer-Hojat, & Holroyd, 2014) and no developmental changes in the differentiation between the feedback types (Lukie et al., 2014). Given these contradictory findings about the development of feedback-related ERPs, it is important to explore alternative methods to measure these components that may provide more information about the development of feedback processing.

One potential explanation for a lack of consistency across electrophysiological investigations of feedback processing is the reliance on time-domain analyses of the EEG signal (i.e. ERP analyses). Traditional analyses of feedback ERPs compute amplitude by averaging neural

activity to individual gain and loss trials, which isolates neural activity time-locked to feedback presentation and assumes that the component of interest is temporally synchronous across trials (Luck, 2005). However, it has been demonstrated that both power and inter-trial phase synchrony (ITPS) can influence the observed ERP component (Makeig, Debener, Onton, & Delorme, 2004). Developmental changes in power and phase synchrony can amplify or mask observed changes in the magnitude of an ERP component (DuPuis et al., 2015).

Recent work has suggested that activity in both the theta band (4-7 Hz) and the delta band (.1-3Hz) differentially contribute to the FN-gain and FN-loss (Bernat, Nelson, & Baskin-Sommers, 2015; Bernat, Nelson, Steele, Gehring, & Patrick, 2011; Foti, Weinberg, Bernat, & Proudfit, 2015). Theta power is typically increased for losses compared to gains; whereas, delta power is typically increased for gains compared to losses (Bernat et al., 2011; Cohen, 2007; Foti et al., 2015; Nelson et al., 2017; van de Vijver, Ridderinkhof, & Cohen, 2011; Webb et al., 2017). Theories of the functional significance of loss-related theta suggest that theta acts as a signal that recruits subsequent increased attention or top-down control following salient events like errors, novel stimuli, or negative feedback (Aviyente, Tootell, & Bernat, 2017; Cavanagh & Frank, 2014; Cavanagh, Zambrano-Vazquez, & Allen, 2012; Van Noordt, Campopiano, & Segalowitz, 2016; van Noordt, Desjardins, Gogo, Tekok-Kilic, & Segalowitz, 2017). On the other hand, increased delta power following rewards is thought to reflect more nuanced processing of secondary feedback characteristics like outcome magnitude or relative outcomes (Bernat et al., 2015). The fact that the theta and delta frequency bands index different processes, but both contribute to the FN, further complicates the interpretation of traditional FN measures.

Another related measure contributing to the amplitude of averaged feedback ERPs is inter-trial phase synchrony (ITPS). Similar to theta power, ITPS within the theta band is increased for loss as compared to gain feedback in adults (Aviyente et al., 2017; Cavanagh, Frank, Klein, & Allen, 2010; Cohen, Elger, & Ranganath, 2007; Crowley et al., 2014). Isolating theta and delta activity following feedback allows for the investigation of both power and phase synchrony changes, which could provide more insight into how feedback processing develops throughout childhood and adolescence.

The objective of the current study was to further explore how the neural response to reward and loss changes throughout adolescence by employing a variety of electrophysiological analytic approaches. Mirroring the majority of prior work, we first assessed whether the time-domain FN-gain and FN-loss changed in magnitude across later childhood and adolescence. In order to improve upon a traditional ERP-based approach, we also analyzed theta and delta band activity in response to feedback using time-frequency principal components analysis (TF-PCA) methods to measure both power and ITPS (Bernat, Williams, & Gehring, 2005). Of note, this is the first study to apply TF-PCA to examine these measures in a developmental sample spanning late childhood to late adolescence. We hypothesized that, although both traditional ERP measurement and time-frequency analyses would accurately capture differences between gain and feedback, the FN-gain and the FN-loss would be unrelated to age, but both delta and theta power and ITPS would exhibit developmental changes to reward and losses across adolescence. Second, we investigated

how much variance in the time-domain FN is explained by these four TF measures (theta power, theta ITPS, delta power, and delta ITPS) in adolescents. Based on prior work in adults (Bernat et al., 2015, 2011; Foti et al., 2015), we hypothesized that both theta and delta power would significantly contribute to the amplitude of the FN. Collectively, these measures allow for a more comprehensive analysis of how the neural dynamics of feedback processing change as a function of age.

2 Method

2.1 Participants

Participants were 61 adolescent females (Mean age = 11.88, $SD = 2.24$) who were part of a larger study examining social and cognitive development across adolescence (Barker et al., in press). Adolescents were excluded due to excessive EEG artifact resulting in fewer than four good trials for either feedback type ($n = 7$; bootstrapping was applied to all analyses; see Electrophysiology Recording and Preprocessing). Thus, EEG analyses included 54 adolescents (Mean age = 12.1, $SD = 2.28$, range 8 - 17). The Institutional Review Board of the University of Maryland approved all measures and tasks, and parents provided informed consent and participants provided assent at the study visit.

2.2 Gambling Task

Participants completed a gambling task variant referred to as the doors task (Foti et al., 2011; Proudfit, 2015). This task has been shown to reliably elicit an FN in adults and adolescents (Bress, Smith, Foti, Klein, & Hajcak, 2012; Levinson, Speed, Infantolino, & Hajcak, 2017). The task was presented in EPrime 2.0.8.74 (Psychology Software Tools, Pittsburgh, PA). During the task, images of two doors were presented side-by-side and adolescents were instructed to choose one of the two doors. Adolescents were instructed to press the left side of a button box to choose the left door and the right side of a button box to choose the right door. Following the response, a gain of 50 points was denoted by an upward green arrow and a loss of 25 points was denoted by a downward red arrow. Gains and losses were presented at random for a total of 60 trials (30 gains and 30 losses). Door stimuli remained on the screen until the participant made a choice. A 1000 ms ISI was presented between door choice and feedback, followed by a 2000 ms presentation of feedback stimuli, and an inter-trial interval of 1500 ms.

2.3 Procedure

Adolescents were seated in a soundproof and electrically shielded room about 70 cm in front of the presentation computer. The gambling task was introduced and participants completed 2 practice trials. In order to keep the adolescents engaged, they were informed that they should try their best to discern a rule/pattern about which door was going to award them the most points (although gains and losses were presented at random). They were also told that they needed to accrue as many points as possible because their performance was going to be compared to other adolescents who played the gambling game. After the task, adolescents were told that their performance would not be compared and were allowed to choose a prize from a prize basket that included a variety of age-appropriate prizes with a similar monetary

value. It is important to note that the points accumulated by the participant did not translate into actual monetary reward.

2.4 Electrophysiology Recording and Preprocessing

EEG was recorded using a 128-channel HydroCel Geodesic Sensor Net and sampled at 250 Hz using a NetAmp 300 amplifier and Netstation 4 software (Electrical Geodesic, Inc, Eugene, OR). All electrode impedances were reduced below 50 k Ω prior to data collection and used Cz as an online reference. EEG analysis was conducted off-line using MATLAB 2014b (MathWorks, Inc., Natick, MA), the EEGLab Toolbox (Delorme & Makeig, 2004), and custom MATLAB scripts. Data were high-pass filtered at 0.3 Hz and low-pass filtered at 49 Hz. A 36 ms delay intrinsic to the EGI system and 14 ms delay specific to the experimental task were accounted for by shifting the data a total of 50 ms earlier. The FASTER plugin for EEGLab (Nolan, Whelan, & Reilly, 2010) was used to identify bad channels. To identify artifacts in the data, independent components analysis (ICA) was performed on a copy of the dataset that was filtered with a 1 Hz high-pass filter. Prior to ICA decomposition, the copied data was epoched into arbitrary 1 s epochs for the purpose of detecting and removing portions of the EEG data contaminated with significant artifact. An initial rejection of noisy EEG data was performed using a combined voltage threshold rejection of ± 1000 μV to remove disconnected channels and spectral threshold rejection using a 30 dB threshold within the 20–40 Hz band to remove EMG-like activity (EEGLAB `pop_rejspec` function; Delorme & Makeig, 2004). If artifact rejection led to > 20% of epochs being rejected for a given channel, the channel was removed from both the 1 Hz high-pass dataset and the 0.1 Hz high-pass ERP dataset. ICA weights from the ICA run on the copied (1Hz) dataset were then copied back to the continuous 0.3 Hz high-passed data. ICA artifact identification was guided by the ADJUST Matlab plug-in (Mognon, Jovicich, Bruzzone, & Buiatti, 2011) and supplemented by manual identification of artifacts. Artifactual ICA components were removed from the data. Stimulus-locked FN trials were segmented 1500 ms before the presentation of the feedback to 2000 ms after feedback. All waveforms were baseline corrected from -200 ms to 0 ms (feedback presentation). Following the removal of ICA artifacts, a rejection threshold of ± 125 μV based on ocular electrodes (electrode numbers on 128 ch. geodesic net: 8, 25, 127, 126) was utilized to identify and reject any ocular artifacts that may have been missed during previous processing steps. After rejection of epochs containing residual ocular artifacts, epochs containing channels with voltage ± 125 μV were interpolated at the channel level unless more than 10% of channels exceeded this threshold within a given epoch, in which case the epoch was instead rejected. Channels that exceeded the ± 125 μV threshold for greater than 20% of epochs were instead removed from the dataset. Finally, any missing or removed channels were interpolated using a spherical spline interpolation and data were re-referenced to the average of all electrodes. Participants had an average of 38.9 artifact-free trials ($SD = 16.4$), with 21.3 artifact-free gain trials ($SD = 7.6$) and 19.5 artifact-free loss trials ($SD = 8.1$). To provide a more reliable approximation of average amplitudes (Di Nocera & Ferlazzo, 2000), a bootstrapping procedure was used with four trials subsampled without replacement from the total number of trials 25 times to create an average ERP; these samples were bootstrapped 100 times to create the bootstrapped EEG signal that was utilized for all analyses and plotting.

2.5 Time-Domain Analysis

Preprocessed data were down-sampled to 128Hz to improve processing speed and conserve storage space without any loss of signal quality. The FN analysis window was centered on the sample point closest to the peak difference between gain and loss trials over fronto-central electrodes for each individual; the latency of the peak difference between gain and loss trials for each individual was not associated with age, $r(52) = -.11$, $p = .42$. Given the sampling rate, the analysis window was 62.5 ms, encompassing 8 time bins at 128Hz. The FN-gain was evaluated as the mean amplitude on loss trials in this time window, and the FN-loss was quantified as the mean amplitude on gain trials in this time window. Data were extracted from an average of nine fronto-central electrodes surrounding FCz (electrode numbers on 128 ch. geodesic net: 11,12, 5, 6, 13, 7, 112, 106, 128).

2.6 Time-Frequency Principal Components Analysis

Time-frequency (TF) decompositions were conducted in MATLAB 2014b using custom MATLAB scripts (Bernat et al., 2005). Pre-processed data were down-sampled to 32 Hz for TF analyses to further reduce file size and increase processing speed while maintaining the ability to investigate the frequency bands of interest. To isolate the theta band frequency, a 2 Hz high-pass filter and 8 Hz low-pass filter were applied. To isolate the delta band frequency, a 4Hz lowpass filter was applied. Pre-filtering maximizes the division between the stronger delta frequency that often overlaps with theta activity (Bernat, Nelson, Holroyd, Gehring, & Patrick, 2008; Foti et al., 2015). A binomial reduced interference distribution (RID) variant of Cohen's class of time-frequency transforms was used to convert the filtered condition average waveforms into time-frequency energy distributions. RID transforms allow for consistent resolution across both time and frequency domains and provide a more precise characterization in the time domain at low frequencies and in the frequency domain in high frequencies (Bernat et al., 2005). Then, we performed a time-frequency principal components analysis (TF-PCA) on the filtered TF surfaces. A one-factor solution was chosen for the theta-filtered TF distribution based on the scree plot. The TF-PCA factor accounted for approximately 32% of the variance. This factor exhibited maximal weightings for theta power during the FN time range, was most pronounced over fronto-central electrodes, and significantly differentiated gain and loss trials. Theta loadings were extracted from an average of nine fronto-central electrodes surrounding FCz (electrode numbers on 128 ch. geodesic net: 11,12, 5, 6, 13, 7, 112, 106, 128). For the delta-filtered TF distribution, a five-factor solution was chosen based on the scree plot. The TF-PCA factor chosen accounted for approximately 3.5% of variance, was maximal over central electrodes, and significantly differentiated gain and loss trials in the time range of the FN. Delta activity was extracted from an average of six central electrodes surrounding Cz (electrode numbers on 128 ch. geodesic net: 6, 13, 7, 112, 106, 128).

2.7 Inter-Trial Phase Synchrony (ITPS)

ITPS of the time frequency distributions was computed for each trial type using custom MATLAB scripts (Aviyente, Bernat, Evans, & Sponheim, 2011). ITPS measures the consistency of the phase oscillations within a given frequency band across trials, contributing to more stable ERPs. ITPS was calculated by examining each time point in the

TF distribution over all trials, yielding an ITPS surface for all time points and frequency bands. ITPS values range from 0, indicating random phase at that TF time-point, to 1, representing perfect phase alignment at that TF time-point. Next, the PCA weights of the one-factor solution of the theta TF-PCA were applied to the theta ITPS surface in order to analyze ITPS values using the same TF-PCA weightings as the analysis of the theta amplitude data (i.e. fronto-central theta during the FN time range). Similarly, the PCA weights of the five-factor solution of the delta TF-PCA were applied to the delta ITPS surface in order to match the TF-PCA weightings of the delta amplitude data (i.e. central delta during the FN time range).

2.8 Analysis Approach

To evaluate the effects of feedback valence and age on the electrophysiological measures, a 2-phase analysis was employed. First, a repeated measures general linear model (GLM) was employed to investigate the within-subject effect of feedback type (gain vs loss) on the neural measures. Second, mean-centered age was added as a between-subject variable in the analysis to examine the effect of age (as a continuous variable) and the interaction feedback type (Thomas et al., 2009). This approach allows for a more accurate assessment of the main effect of feedback. While, the addition of the between-subject variable should not change the within-subject effect of feedback, Delaney and Maxwell (1981) show that a between-subject variable can make the main effect of the repeated measure weaker because the between-subject variable is taken to explain variance in the difference between the repeated measures. Nonetheless our results of the 2-phase analysis revealed that the main effect of feedback type was qualitatively the same across both phases of the analysis, so only the repeated measures GLM results including age are presented below. Greenhouse-Geisser corrections were applied where appropriate and Cohen's *d* for repeated measures was computed to compare effect sizes.

Next, in order to understand how the TF measures contribute to the time-domain ERPs, all TF measures (theta TF-PCA, theta ITPS, delta TF-PCA, and delta ITPS) were entered as predictors in a multiple regression with the time-domain FN as the dependent variable. A multiple regression was conducted separately for gain trials and loss trials, both with and without age entered as a covariate. For comparison with prior research, we also examined correlations between all variables of interest, to include the calculation of loss-minus-gain difference scores for the time-frequency and time-domain measures.

3 Results

3.1 Time Domain

Table 1 summarizes the associations between age and all neural measures of interest as well as the relations between each neural measure; moreover, this table also includes correlations with loss-minus-gain difference scores. As expected, there was a negative deflection in the waveform about 300ms following feedback presentation that was maximal over fronto-central electrodes (Fig 1).

The FN-loss was larger (more negative) than the FN-gain, $F(1,52) = 20.43, p < .001, \eta^2_p = .28$. There were no effects of age on the FN-loss or the FN-gain, $F(1,52) = 1.83, p = .18, \eta^2_p = .03$. There was no significant interaction between age and feedback type, $F(1,52) = .30, p = .59, \eta^2_p = .006$.

3.2 Theta Band

3.2.1 Theta Time-Frequency PCA—Theta TF-PCA-loss was significantly larger than theta TF-PCA-gain, $F(1,52) = 14.04, p < .001, \eta^2_p = .21$ (Fig 2). Overall, theta TF-PCA significantly decreased with age, $F(1,52) = 4.23, p = .045, \eta^2_p = .08$. Follow-up correlation tests showed that theta TF-PCA-gain decreased with age, $r(52) = -.41, p = .002$. However, the relation between theta TF-PCA-loss and age failed to reach significance, $r(52) = -.14, p = .29$. The interaction between feedback type and age was not significant for theta TF-PCA, $F(1,52) = 1.62, p = .21, \eta^2_p = .03$.

3.2.2 Theta Inter-trial phase synchrony (ITPS)—Theta ITPS-loss was significantly greater than theta ITPS-gain, $F(1,52) = 21.13, p < .001, \eta^2_p = .29$ (Fig 3). There were no main effects of age for theta ITPS, $F(1,52) = .13, p = .72, \eta^2_p = .003$. However, there was a significant interaction between age and feedback type for theta ITPS, $F(1,52) = 5.51, p = .023, \eta^2_p = .10$. The nature of the interaction between age and feedback type was such that increasing age was associated with decreased theta ITPS-gain, whereas increasing age was associated with increased theta-ITPS-loss. However, despite the significant interaction effect, it should be noted that follow-up correlation tests did not reach significance for either age and theta ITPS-gain, $r(52) = -.14, p = .32$, or theta ITPS-loss, $r(52) = .20, p = .15$.

3.3 Delta Band

3.3.1 Delta Time-Frequency PCA—Delta TF-PCA was significantly larger for gains relative to losses, $F(1,52) = 12.23, p = .001, \eta^2_p = .19$ (Fig 2). Overall, delta TF-PCA significantly increased with age, $F(1,52) = 4.63, p = .04, \eta^2_p = .08$. Follow-up correlation tests show that delta TF-PCA-loss marginally increased with age, $r(52) = .24, p = .08$. Similarly, delta TF-PCA-gain marginally increased with age, $r(52) = .27, p = .05$. The interaction between feedback type and age was not significant for delta TF-PCA, $F(1,52) = 1.42, p = .24, \eta^2_p = .03$.

3.3.2 Delta Inter-trial phase synchrony (ITPS)—Delta ITPS-gain was significantly larger than delta ITPS-loss, $F(1,52) = 12.77, p = .001, \eta^2_p = .20$ (Fig 3). Additionally, delta ITPS significantly increased with increasing age, $F(1,52) = 13.74, p = .001, \eta^2_p = .21$. Follow-up correlation tests demonstrated a positive relationship between both delta ITPS-loss and age, $r(52) = .39, p = .003$, as well as delta ITPS-gain and age, $r(52) = .44, p = .001$. The interaction between feedback type and age failed to reach significance for delta ITPS, $F(1,52) = .39, p = .53, \eta^2_p = .007$.

3.4 Time-Frequency Measures Predicting Time-Domain Measures

The model predicting FN-gain using the four TF measures on gain trials was significant, $R^2 = .31, F(4,53) = 5.39, p = .001$. Delta TF-PCA to gain was the only significant predictor of FN to gain, when controlling for the remaining TF measures, $\beta = 10.55, SE = 3.18, t(53) =$

3.32, $p = .002$, showing that increases in delta TF-PCA to gain is associated with a more positive FN to gain. The results were not qualitatively different when also controlling for age.

The four TF measures to loss also explained a significant amount of variance in the FN to loss, $R^2 = .44$, $F(4,53) = 9.79$, $p < .001$. Again, delta TF-PCA to loss was the only significant predictor of FN to loss, when controlling for the other TF measures, $\beta = 21.93$, $SE = 3.81$, $t(53) = 5.75$, $p < .001$, indicating that increases in delta TF-PCA to loss is associated with a more positive FN to loss. The results were not qualitatively different when also controlling for age. Whereas the theta band measures did not predict the FN to gains or losses, over and beyond the variance explained by delta TF-PCA, it is important to note the loss-minus-gain difference score for theta TF-PCA did significantly predict the loss-minus-gain FN difference score (see Table 1).

4 Discussion

The purpose of this study was to provide a comprehensive understanding of how the neural dynamics of feedback processing develop throughout late childhood and adolescence. To this end, we investigated changes in the electrophysiological responses to feedback (gains and losses) in a sample of adolescent females using both time-domain and time-frequency approaches. The traditional analysis of the feedback negativity (FN) replicated the feedback valence effect, such that the FN to loss was more negative than the FN to gain. However, consistent with conflicting reports on the relation between the FN and age (Crowley et al., 2013; Eppinger et al., 2009; Hämmerer et al., 2011; Larson et al., 2011; Lukie et al., 2014; Zottoli & Grose-Fifer, 2012), the FN-gain and the FN-loss did not exhibit any significant developmental changes. By using a time-frequency (TF) approach, we again observed expected effects of feedback type, but were also able to detect developmental changes within the theta and delta bands for both power and ITPS. Of particular interest, we found that theta power decreased with age, whereas delta power increased with age. For inter-trial phase synchrony, delta synchrony increased with age, while age-related changes in theta synchrony differed for gains and losses. Finally, we observed that the strongest predictor of the time-domain FN ERP in adolescents was delta power; although a theta power difference score also predicted the time-domain FN difference score. Collectively, these results emphasize the importance of using TF measures when probing nuanced developmental changes in feedback processing throughout childhood and adolescence.

In our sample age range of late childhood and adolescence, the time-frequency approach revealed effects of feedback type consistent with previous electrophysiological measures of feedback processing in both adults and other adolescent samples. First, we observed the traditional time-domain FN effect, such that the FN to loss was more negative than the FN to gain (Gehring & Willoughby, 2002; Hajcak, Moser, Holroyd, & Simons, 2006; Proudfit, 2015). Next, within the time-frequency domain, we observed that theta power was increased for losses compared to gains, and delta power was increased for gains compared to losses. These time-frequency effects for feedback are consistent with previous adolescent (Nelson et al., 2017; Webb et al., 2017) and adult (Bernat et al., 2011; Foti et al., 2015) samples. Similarly, inter-trial phase synchrony (ITPS) within theta was increased for losses compared

to gains, while delta ITPS was increased for gains relative to losses. The theta ITPS effect after feedback is consistent with previous adolescent (Crowley et al., 2014) and adult (Cavanagh et al., 2010; Cohen, 2007) results, but less work has focused on delta ITPS after feedback. Our sample of 8 to 17 year olds show valence effects for feedback that are consistent with previous adolescent and adult work, demonstrating that time-frequency measures are a valid measurement alternative to event-related potentials (ERPs) in samples as young as 8 years old.

Traditional time-based measurement of ERPs are highly sensitive to broadband artifact and noise (Luck, 2005), and developmental ERP studies tend to have a lower signal-to-noise ratio due to typical issues associated with child and adolescent participants (e.g., movement and physiological artifacts), which can increase error variance and obfuscate effects (DeBoer, Scott, & Nelson, 2005). However, filtered TF approaches allow for extraction of power and phase synchrony in specific frequency ranges, reducing the effects of high or low frequency artifacts (Bernat et al., 2005). While time-frequency approaches are widely used in adult samples, their utility is largely underappreciated in developmental work. Our findings suggest that these TF approaches are useful and should be increasingly employed for developmental samples.

Beyond establishing the utility of employing time-frequency domain analyses within a developmental sample encompassing childhood and adolescence, we also observed differential developmental changes in both power and ITPS within the theta and delta bands. In the theta band, we observed that theta power decreases with increasing age. However, delta power increased with age. These developmental patterns may be explained by the development of the underlying neural structures associated with theta and delta activity, such as the anterior cingulate cortex (ACC) and striatal structures, respectively (Asada, Fukuda, Tsunoda, Yamaguchi, & Tonoike, 1999; Debener et al., 2005; Foti et al., 2015). Developmentally, both ACC cortical thickness and the fMRI BOLD response within the ACC (in response to feedback) decrease linearly with age (Peters et al., 2014; Peters, Van Duijvenvoorde, Koolschijn, & Crone, 2016), consistent with the observed decreases in theta activity. On the other hand, adolescents exhibit greater activation in the ventral striatum in anticipation of reward compared to both children and adults (Galvan et al., 2006; Galvan, 2010; Van Leijenhorst et al., 2010), consistent with the increases in delta activity presented here. Future work should examine changes to the localization of these frequency bands in response to feedback in adolescence.

Similarly, the developmental patterns of ITPS within the theta and delta bands were distinct. There were clear age effects within the delta band, with older adolescents exhibiting greater phase synchrony. However, within the theta band, there was a significant interaction between feedback type and age. Nominally, theta ITPS to losses increased with age, while theta ITPS to gains decreased with age (though, this finding should be interpreted with caution as only the interaction term was significant, and the follow-up comparisons did not reach statistical significance). However, this result is consistent with prior work that found a relative increase in coherence for a no-win condition in 13-14 year olds compared to 11-12 year olds (Crowley et al., 2014). Previous research has shown that a fronto-parietal network in children aged 11-13 and of adults aged 18-25 respond to negative feedback more strongly,

while this fronto-parietal network in younger children aged 8-11 years has greater activation following positive feedback (van Duijvenvoorde et al., 2008).

Both delta power and ITPS displayed age-related increases, suggesting that delta activity is important to consider when examining the development of feedback processing and reward-related activity. One potential explanation is that adolescence is a time period with a heightened sensitivity to reward (Galvan et al., 2006; Somerville, Jones, & Casey, 2010; Urošević, Collins, Muetzel, Lim, & Luciana, 2012). Consistent with this interpretation, increasing delta power has previously been associated with reward processing (Foti et al., 2015; Nelson et al., 2017). Thus, the observed increase in delta across ages 8 to 17 could reflect the known increase in reward sensitivity that emerges during the teenage years (Smith, Xiao, & Bechara, 2012; Steinberg et al., 2009). Moreover, the fact that increased delta power contributes to a more positive FN could explain previous reports that younger children exhibit a more negative FN compared to older adolescents and adults (Arbel et al., 2018; Crowley et al., 2013; Eppinger, Mock, & Kray, 2009; Hämmerer et al., 2011; Zottoli & Grose-Fifer, 2012). One unexpected finding presented here is that delta power had the strongest influence on the time-domain FN in adolescent females, whereas theta power predicted no unique variance in the time-domain FN after accounting for delta effects. In adult samples, both theta and delta have been shown to predict unique variance in terms of FN amplitude (Bernat et al., 2015, 2011; Foti et al., 2015); although consistent with adult reports, a theta power difference score indeed predicted the time-domain FN difference score in the current sample. Taken altogether, these findings suggest that both delta power and phase synchrony need to be considered, in addition to theta dynamics, when considering the neural development of feedback processing.

Individual differences in ERP amplitude are widely examined in adolescence as potential biomarkers that could represent risk factors for certain psychopathologies or developmental disorders. For instance, reductions in the FN have been associated with a wide variety of maladaptive outcomes including depression (Bress et al., 2013; Bress, Meyer, & Hajcak, 2015; Bress, Meyer, & Proudfit, 2015) and problematic internet use (Yau, Potenza, Mayes, & Crowley, 2015). Utilizing time-frequency methods to better dissociate underlying theta and delta power and phase synchrony measures may provide evidence for more specific mechanisms that contribute to the development of these disorders and problem behaviors. Indeed, blunted delta power in particular has been related to the onset of depression in adolescence (Nelson et al., 2017).

In conclusion, the current study provides evidence of the utility of time-frequency approaches in understanding developmental changes in feedback processing. Time-frequency methods revealed developmental changes within both the theta and delta bands that were unable to be detected using ERPs alone. Adolescents exhibited different developmental patterns within theta and delta bands for both power and phase synchrony. These findings further support the notion that theta and delta activity reflect different neurological mechanisms during feedback processing. Moreover, the increase in delta power and phase synchrony throughout late childhood and adolescence suggests that activity within the delta band may be an especially influential part of feedback processing that needs to be considered throughout development.

References

- Arbel Y, McCarty KN, Goldman M, Donchin E, Brumback T. Developmental changes in the feedback related negativity from 8 to 14years. *International Journal of Psychophysiology*. 2018.
- Asada H, Fukuda Y, Tsunoda S, Yamaguchi M, Tonoike M. Frontal midline theta rhythms reflect alternative activation of prefrontal cortex and anterior cingulate cortex in humans. *Neuroscience Letters*. 1999; 274(1):29–32. DOI: 10.1016/S0304-3940(99)00679-5 [PubMed: 10530512]
- Aviyente S, Bernat EM, Evans WS, Sponheim SR. A phase synchrony measure for quantifying dynamic functional integration in the brain. *Human Brain Mapping*. 2011; 32(1):80–93. DOI: 10.1002/hbm.21000 [PubMed: 20336687]
- Aviyente S, Tootell A, Bernat EM. Time-frequency phase-synchrony approaches with ERPs. *International Journal of Psychophysiology*. 2017; 111:88–97. DOI: 10.1016/j.ijpsycho.2016.11.006 [PubMed: 27864029]
- Barker TV, Troller-Renfree S, Bowman LC, Pine DS, Fox NA. Social influences of error monitoring in adolescent girls. *Psychophysiology*. (in press).
- Bernat EM, Nelson LD, Baskin-Sommers AR. Time-frequency theta and delta measures index separable components of feedback processing in a gambling task. *Psychophysiology*. 2015; 52(5): 626–637. DOI: 10.1111/psyp.12390 [PubMed: 25581491]
- Bernat EM, Nelson LD, Holroyd CB, Gehring WJ, Patrick CJ, Luk FT, editor Separating cognitive processes with principal components analysis of EEG time-frequency distributions. 2008. 70740S
- Bernat EM, Nelson LD, Steele VR, Gehring WJ, Patrick CJ. Externalizing psychopathology and gain-loss feedback in a simulated gambling task: dissociable components of brain response revealed by time-frequency analysis. *Journal of Abnormal Psychology*. 2011; 120(2):352–64. DOI: 10.1037/a0022124 [PubMed: 21319875]
- Bernat EM, Williams WJ, Gehring WJ. Decomposing ERP time-frequency energy using PCA. *Clinical Neurophysiology*. 2005; 116(6):1314–1334. DOI: 10.1016/j.clinph.2005.01.019 [PubMed: 15978494]
- Bress JN, Foti D, Kotov R, Klein DN, Hajcak G. Blunted neural response to rewards prospectively predicts depression in adolescent girls. *Psychophysiology*. 2013; 50(1):74–81. DOI: 10.1111/j.1469-8986.2012.01485.x [PubMed: 23252717]
- Bress JN, Meyer A, Hajcak G. Differentiating Anxiety and Depression in Children and Adolescents: Evidence From Event-Related Brain Potentials. *Journal of Clinical Child & Adolescent Psychology*. 2015; 44(2):238–249. DOI: 10.1080/15374416.2013.814544 [PubMed: 23879474]
- Bress JN, Meyer A, Proudfit GH. The stability of the feedback negativity and its relationship with depression during childhood and adolescence. 2015.
- Bress JN, Smith E, Foti D, Klein DN, Hajcak G. Neural response to reward and depressive symptoms in late childhood to early adolescence. *Biological Psychology*. 2012; 89(1):156–162. DOI: 10.1016/j.biopsycho.2011.10.004 [PubMed: 22015709]
- Carlson JM, Foti D, Harmon-Jones E, Proudfit GH. Midbrain volume predicts fMRI and ERP measures of reward reactivity. *Brain Structure and Function*. 2015; 220(3):1861–1866. DOI: 10.1007/s00429-014-0725-9 [PubMed: 24549705]
- Cauffman E, Shulman EP, Steinberg L, Claus E, Banich MT, Graham S, Woolard J. Age Differences in Affective Decision Making as Indexed by Performance on the Iowa Gambling Task. 2010.
- Cavanagh JF, Frank MJ. Frontal theta as a mechanism for cognitive control. *Trends in Cognitive Sciences*. 2014; 18(8):414–421. DOI: 10.1016/j.tics.2014.04.012 [PubMed: 24835663]
- Cavanagh JF, Frank MJ, Klein TJ, Allen JJB. Frontal theta links prediction errors to behavioral adaptation in reinforcement learning. *NeuroImage*. 2010; 49(4):3198–3209. DOI: 10.1016/j.neuroimage.2009.11.080 [PubMed: 19969093]
- Cavanagh JF, Zambrano-Vazquez L, Allen JJB. Theta lingua franca: A common mid-frontal substrate for action monitoring processes. *Psychophysiology*. 2012; 49(2):220–238. DOI: 10.1111/j.1469-8986.2011.01293.x [PubMed: 22091878]
- Cohen MX. Individual differences and the neural representations of reward expectation and reward prediction error. *Social Cognitive and Affective Neuroscience*. 2007; 2(1):20–30. DOI: 10.1093/scan/nsi021 [PubMed: 17710118]

- Cohen MX, Elger CE, Ranganath C. Reward expectation modulates feedback-related negativity and EEG spectra. *NeuroImage*. 2007; 35(2):968–978. DOI: 10.1016/j.neuroimage.2006.11.056 [PubMed: 17257860]
- Crowley MJ, van Noordt SJR, Wu J, Hommer RE, South M, Fearon RMP, Mayes LC. Reward feedback processing in children and adolescents: medial frontal theta oscillations. *Brain and Cognition*. 2014; 89:79–89. DOI: 10.1016/j.bandc.2013.11.011 [PubMed: 24360036]
- Crowley MJ, Wu J, Hommer RE, South M, Molfese PJ, Fearon RMP, Mayes LC. A Developmental Study of the Feedback-Related Negativity From 10–17 Years: Age and Sex Effects for Reward Versus Non-Reward. *Developmental Neuropsychology*. 2013; 38(8):595–612. DOI: 10.1080/87565641.2012.694512 [PubMed: 24219697]
- Debener S, Ullsperger M, Siegel M, Fiehler K, von Cramon DY, Engel AK. Trial-by-trial coupling of concurrent electroencephalogram and functional magnetic resonance imaging identifies the dynamics of performance monitoring. *The Journal of Neuroscience: The Official Journal of the Society for Neuroscience*. 2005; 25(50):11730–7. DOI: 10.1523/JNEUROSCI.3286-05.2005 [PubMed: 16354931]
- DeBoer T, Scott LS, Nelson CA. ERPs in developmental populations. In: Handy TC, editor *Event-Related Potentials: A Methods Handbook*. Cambridge, Massachusetts: MIT Press; 2005. 263–97.
- Delaney HD, Maxwell SE. On Using Analysis Of Covariance In Repeated Measures Designs. *Multivariate Behavioral Research*. 1981; 16(1):105–123. DOI: 10.1207/s15327906mbr1601_6 [PubMed: 26800630]
- Delorme A, Makeig S. EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*. 2004; 134:9–21. DOI: 10.1016/j.jneumeth.2003.10.009 [PubMed: 15102499]
- Di Nocera F, Ferlazzo F. Resampling approach to statistical inference: bootstrapping from event-related potentials data. *Behavior Research Methods, Instruments, & Computers: A Journal of the Psychonomic Society, Inc.* 2000; 32(1):111–9. DOI: 10.3758/BF03200793
- DuPuis D, Ram N, Willner CJ, Karalunas S, Segalowitz SJ, Gatzke-Kopp LM. Implications of ongoing neural development for the measurement of the error-related negativity in childhood. *Developmental Science*. 2015; 18(3):452–68. DOI: 10.1111/desc.12229 [PubMed: 25209462]
- Eppinger B, Mock B, Kray J. Developmental differences in learning and error processing: Evidence from ERPs. *Psychophysiology*. 2009; 46(5):1043–1053. DOI: 10.1111/j.1469-8986.2009.00838.x [PubMed: 19497006]
- Figner B, Mackinlay RJ, Wilkening F, Weber EU. Affective and deliberative processes in risky choice: Age differences in risk taking in the Columbia Card Task. *Journal of Experimental Psychology: Learning, Memory, and Cognition*. 2009; 35(3):709–730. DOI: 10.1037/a0014983
- Foti D, Hajcak G. Depression and reduced sensitivity to non-rewards versus rewards: Evidence from event-related potentials. *Biological Psychology*. 2009; 81(1):1–8. DOI: 10.1016/j.biopsycho.2008.12.004 [PubMed: 19162124]
- Foti D, Weinberg A, Bernat EM, Proudfit GH. Anterior cingulate activity to monetary loss and basal ganglia activity to monetary gain uniquely contribute to the feedback negativity. *Clinical Neurophysiology*. 2015; 126(7):1338–1347. DOI: 10.1016/j.clinph.2014.08.025 [PubMed: 25454338]
- Foti D, Weinberg A, Dien J, Hajcak G. Event-related potential activity in the basal ganglia differentiates rewards from nonrewards: Temporospatial principal components analysis and source localization of the feedback negativity. *Human Brain Mapping*. 2011; 32(12):2207–2216. DOI: 10.1002/hbm.21182 [PubMed: 21305664]
- Galvan A. Adolescent development of the reward system. *Frontiers in Human Neuroscience*. 2010; 4:6.doi: 10.3389/neuro.09.006.2010 [PubMed: 20179786]
- Galvan A, Hare TA, Parra CE, Penn J, Voss H, Glover G, Casey BJ. Earlier Development of the Accumbens Relative to Orbitofrontal Cortex Might Underlie Risk-Taking Behavior in Adolescents. *Journal of Neuroscience*. 2006; 26(25):6885–6892. DOI: 10.1523/JNEUROSCI.1062-06.2006 [PubMed: 16793895]

- Gehring WJ, Willoughby AR. The Medial Frontal Cortex and the Rapid Processing of Monetary Gains and Losses. *Science*. 2002; 295(5563):2279–2282. DOI: 10.1126/science.1066893 [PubMed: 11910116]
- Goddings AL, Mills KL, Clasen LS, Giedd JN, Viner RM, Blakemore SJ. The influence of puberty on subcortical brain development. *NeuroImage*. 2014; 88:242–251. DOI: 10.1016/j.neuroimage.2013.09.073 [PubMed: 24121203]
- Hajcak G, Moser JS, Holroyd CB, Simons RF. The feedback-related negativity reflects the binary evaluation of good versus bad outcomes. *Biological Psychology*. 2006; 71(2):148–154. DOI: 10.1016/j.biopsycho.2005.04.001 [PubMed: 16005561]
- Hämmerer D, Li SC, Müller V, Lindenberger U. Life Span Differences in Electrophysiological Correlates of Monitoring Gains and Losses during Probabilistic Reinforcement Learning. *Journal of Cognitive Neuroscience*. 2011; 23(3):579–592. DOI: 10.1162/jocn.2010.21475 [PubMed: 20377358]
- Holroyd CB, Coles MGH. The neural basis of human error processing: Reinforcement learning, dopamine, and the error-related negativity. *Psychological Review*. 2002; 109(4):679–709. DOI: 10.1037/0033-295X.109.4.679 [PubMed: 12374324]
- Holroyd CB, Pakzad-Vaezi KL, Krigolson OE. The feedback correct-related positivity: Sensitivity of the event-related brain potential to unexpected positive feedback. *Psychophysiology*. 2008; 45(5): 688–697. DOI: 10.1111/j.1469-8986.2008.00668.x [PubMed: 18513364]
- Larson MJ, South M, Krauskopf E, Clawson A, Crowley MJ. Feedback and reward processing in high-functioning autism. *Psychiatry Research*. 2011; 187(1):198–203. DOI: 10.1016/j.psychres.2010.11.006 [PubMed: 21122921]
- Levinson AR, Speed BC, Infantolino ZP, Hajcak G. Reliability of the electrocortical response to gains and losses in the doors task. *Psychophysiology*. 2017.
- Luck SJ. *An Introduction to the Event-Related Potential Technique*. Cambridge, Massachusetts: The MIT Press; 2005.
- Lukie CN, Montazer-Hojat S, Holroyd CB. Developmental changes in the reward positivity: An electrophysiological trajectory of reward processing. *Developmental Cognitive Neuroscience*. 2014; 9:191–199. DOI: 10.1016/j.dcn.2014.04.003 [PubMed: 24879113]
- Luu P, Tucker DM, Derryberry D, Reed M, Poulsen C. Electrophysiological Responses to Errors and Feedback in the Process of Action Regulation. *Psychological Science*. 2003; 14(1):47–53. DOI: 10.1111/1467-9280.01417 [PubMed: 12564753]
- Makeig S, Debener S, Onton J, Delorme A. Mining event-related brain dynamics. 2004.
- Miltner WHR, Braun CH, Coles MGH. Event-Related Brain Potentials Following Incorrect Feedback in a Time-Estimation Task: Evidence for a “Generic” Neural System for Error Detection. *Journal of Cognitive Neuroscience*. 1997; 9(6):788–798. DOI: 10.1162/jocn.1997.9.6.788 [PubMed: 23964600]
- Mognon A, Jovicich J, Bruzzone L, Buiatti M. ADJUST: An automatic EEG artifact detector based on the joint use of spatial and temporal features. *Psychophysiology*. 2011; 48(2):229–240. DOI: 10.1111/j.1469-8986.2010.01061.x [PubMed: 20636297]
- Nelson BD, Infantolino ZP, Klein DN, Perlman G, Kotov R, Hajcak G. Time-Frequency Reward-Related Delta Prospectively Predicts the Development of Adolescent-Onset Depression. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*. 2017.
- Nolan H, Whelan R, Reilly RB. FASTER: Fully Automated Statistical Thresholding for EEG artifact Rejection. *Journal of Neuroscience Methods*. 2010; 192(1):152–162. DOI: 10.1016/j.jneumeth.2010.07.015 [PubMed: 20654646]
- Perrin JS, Hervé PY, Leonard G, Perron M, Pike GB, Pitiot A, Paus T. Growth of White Matter in the Adolescent Brain: Role of Testosterone and Androgen Receptor. *Journal of Neuroscience*. 2008; 28(38)doi: 10.1523/JNEUROSCI
- Peters S, Braams BR, Raijmakers MEJ, Cédric P, Koolschijn MP, Crone EA. The Neural Coding of Feedback Learning across Child and Adolescent Development. 2014.
- Peters S, Van Duijvenvoorde ACK, Koolschijn PCMP, Crone EA. Longitudinal development of frontoparietal activity during feedback learning: Contributions of age, performance, working

- memory and cortical thickness. *Developmental Cognitive Neuroscience*. 2016; 19:211–222. DOI: 10.1016/j.dcn.2016.04.004 [PubMed: 27104668]
- Proudfit GH. The reward positivity: From basic research on reward to a biomarker for depression. *Psychophysiology*. 2015; 52(4):449–459. DOI: 10.1111/psyp.12370 [PubMed: 25327938]
- Smith DG, Xiao L, Bechara A. Decision making in children and adolescents: Impaired Iowa Gambling Task performance in early adolescence. *Developmental Psychology*. 2012; 48(4):1180–1187. DOI: 10.1037/a0026342 [PubMed: 22081879]
- Somerville LH, Jones RM, Casey BJ. A time of change: Behavioral and neural correlates of adolescent sensitivity to appetitive and aversive environmental cues. *Brain and Cognition*. 2010; 72(1):124–133. DOI: 10.1016/J.BANDC.2009.07.003 [PubMed: 19695759]
- Steinberg L, Graham S, O'Brien L, Woolard J, Cauffman E, Banich M. Age Differences in Future Orientation and Delay Discounting. *Child Development*. 2009; 80(1):28–44. DOI: 10.1111/j.1467-8624.2008.01244.x [PubMed: 19236391]
- Thomas MSC, Annaz D, Ansari D, Scerif G, Jarrold C, Karmiloff-Smith A. Using Developmental Trajectories to Understand Developmental Disorders. 2009.
- Urošević S, Collins P, Muetzel R, Lim K, Luciana M. Longitudinal changes in behavioral approach system sensitivity and brain structures involved in reward processing during adolescence. *Developmental Psychology*. 2012; 48(5):1488–1500. DOI: 10.1037/a0027502 [PubMed: 22390662]
- van de Vijver I, Ridderinkhof KR, Cohen MX. Frontal Oscillatory Dynamics Predict Feedback Learning and Action Adjustment. *Journal of Cognitive Neuroscience*. 2011; 23(12):4106–4121. DOI: 10.1162/jocn_a_00110 [PubMed: 21812570]
- van Duijvenvoorde ACK, Zanolie K, Rombouts SAR, Raijmakers MEJ, Crone EA. Evaluating the Negative or Valuing the Positive? Neural Mechanisms Supporting Feedback-Based Learning across Development. *Journal of Neuroscience*. 2008; 28(38)doi: 10.1523/JNEUROSCI.1485-08.2008
- van Leijenhorst L, Zanolie K, Van Meel CS, Westenberg PM, Rombouts SAR, Crone EA. What Motivates the Adolescent? Brain Regions Mediating Reward Sensitivity across Adolescence. *Cerebral Cortex*. 2010; 20(1):61–69. DOI: 10.1093/cercor/bhp078 [PubMed: 19406906]
- van Noordt SJR, Campopiano A, Segalowitz SJ. A functional classification of medial frontal negativity ERPs: Theta oscillations and single subject effects. *Psychophysiology*. 2016; 53(9)doi: 10.1111/psyp.12689
- van Noordt SJR, Desjardins JA, Gogo CET, Tekok-Kilic A, Segalowitz SJ. Cognitive control in the eye of the beholder: Electrocortical theta and alpha modulation during response preparation in a cued saccade task. *NeuroImage*. 2017; 145:82–95. DOI: 10.1016/J.NEUROIMAGE.2016.09.054 [PubMed: 27666384]
- Webb CA, Auerbach RP, Bondy E, Stanton CH, Foti D, Pizzagalli DA. Abnormal neural responses to feedback in depressed adolescents. *Journal of Abnormal Psychology*. 2017; 126(1):19–31. DOI: 10.1037/abn0000228 [PubMed: 27935729]
- Yau YHC, Potenza MN, Mayes LC, Crowley MJ. Blunted feedback processing during risk-taking in adolescents with features of problematic Internet use. *Addictive Behaviors*. 2015; 45:156–163. DOI: 10.1016/j.addbeh.2015.01.008 [PubMed: 25679363]
- Zottoli TM, Grose-Fifer J. The feedback-related negativity (FRN) in adolescents. *Psychophysiology*. 2012; 49(3):413–420. DOI: 10.1111/j.1469-8986.2011.01312.x [PubMed: 22091835]

Time-Domain FN

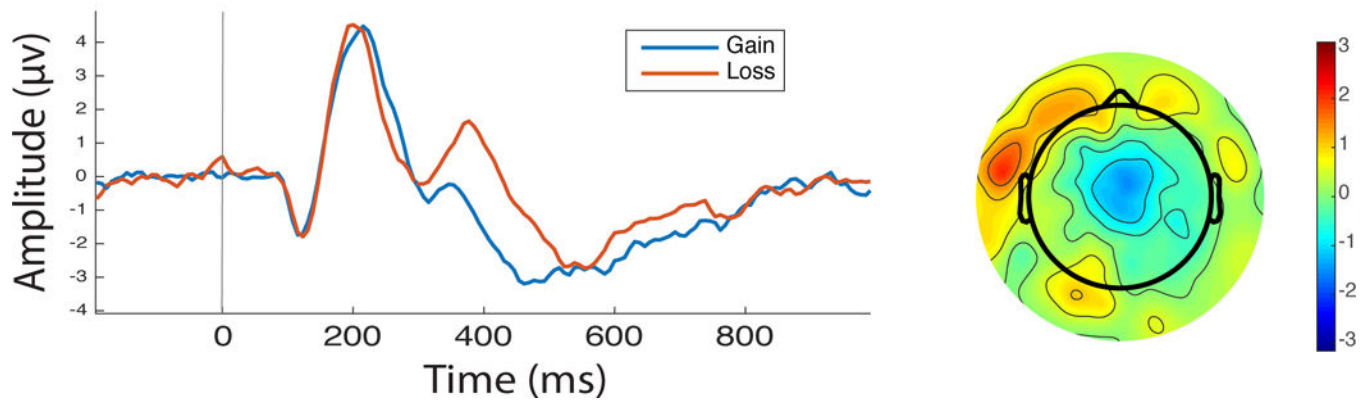


Figure 1. Unfiltered grand average ERP Waveform and topographic plot of the voltage difference between loss and gain between 213 ms and 273 ms. The line at 0 ms in the waveform represents feedback onset.

Time Frequency PCA (TF-PCA)

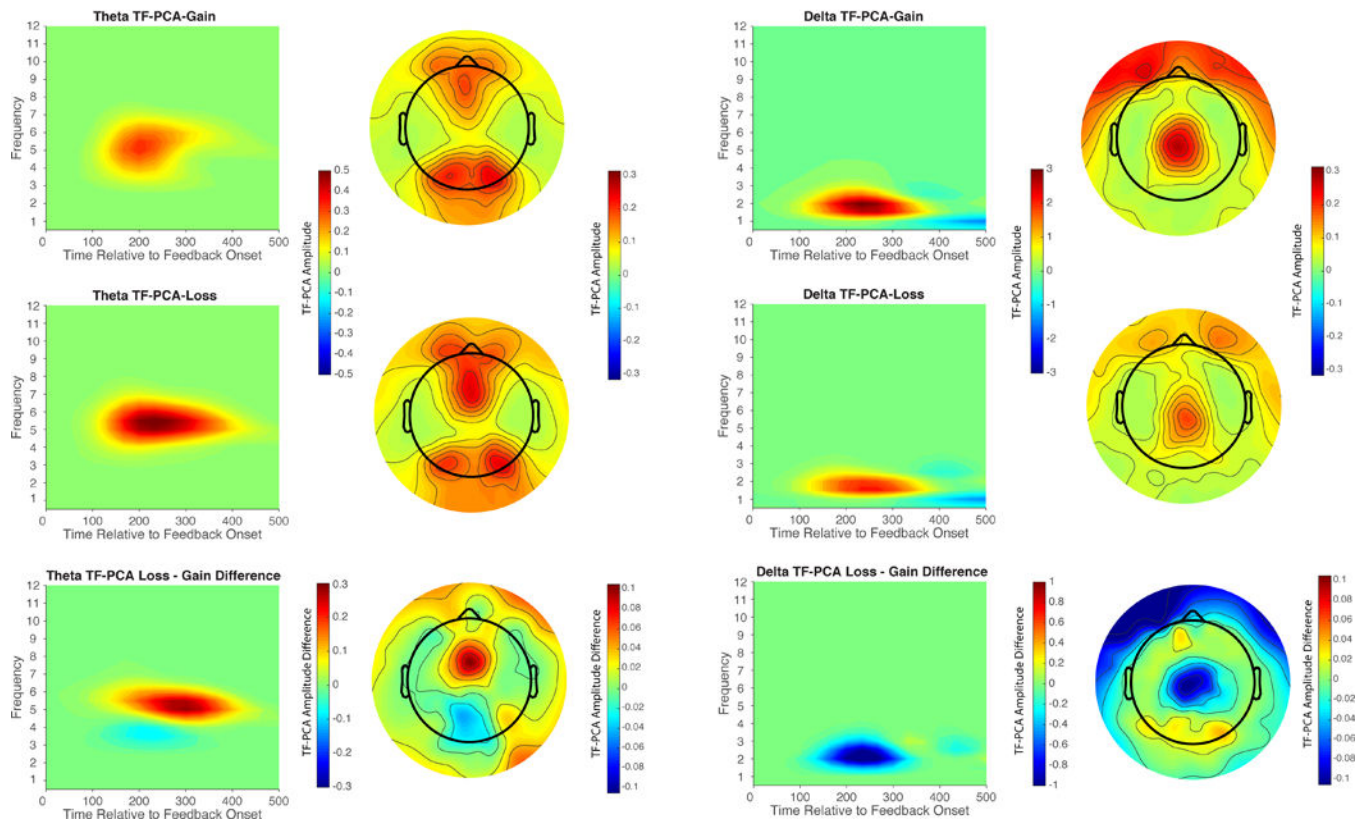


Figure 2. Time-Frequency Principal Components Analysis. TF energy distributions and topographic plots based on PCA weights for both theta and delta bands in response to gains, losses, and the difference between gains and losses.

Inter-Trial Phase Synchrony (ITPS)

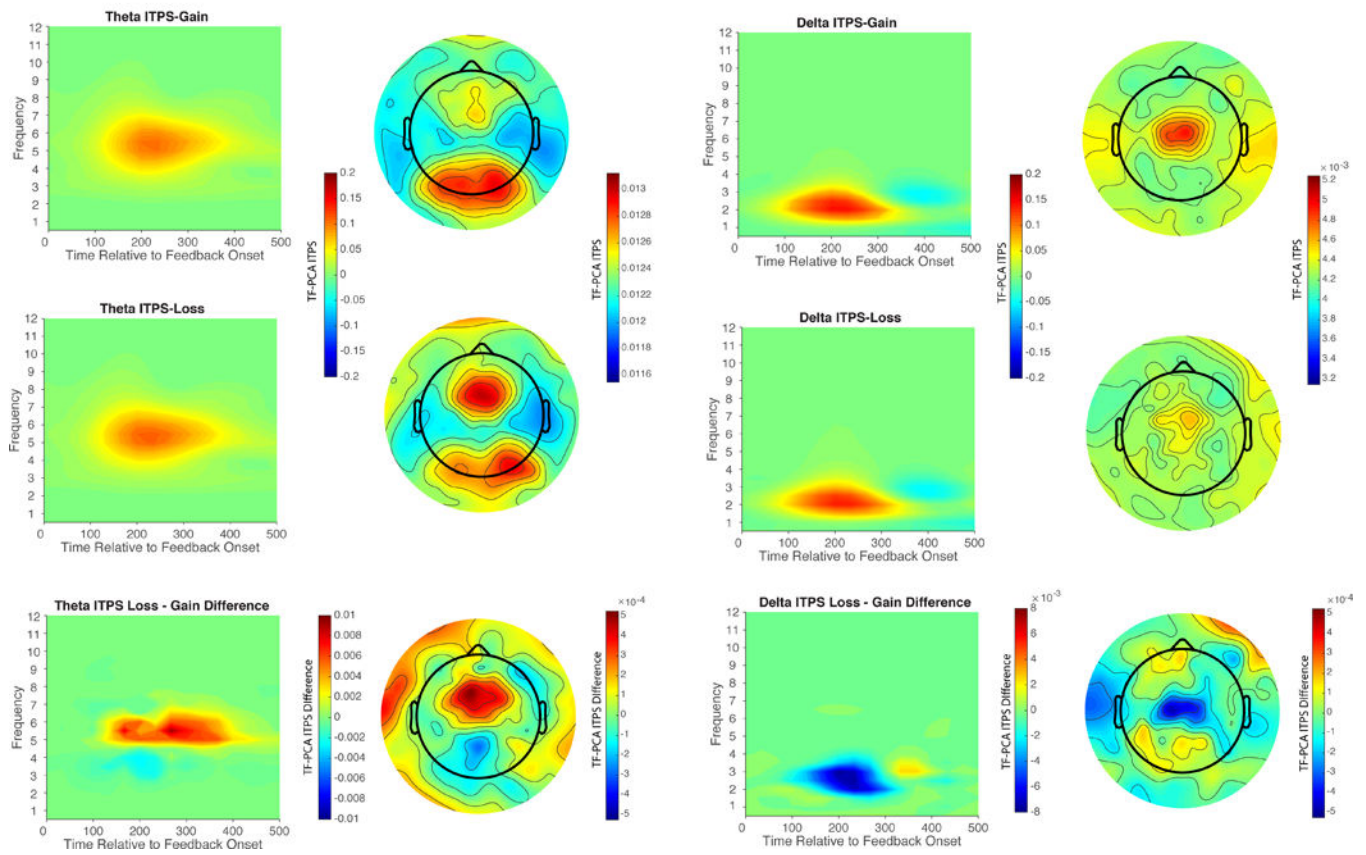


Figure 3. Inter-trial phase synchrony. TF energy distributions and topographic plots based on PCA weights for both theta and delta bands in response to gains, losses, and the difference between gains and losses.

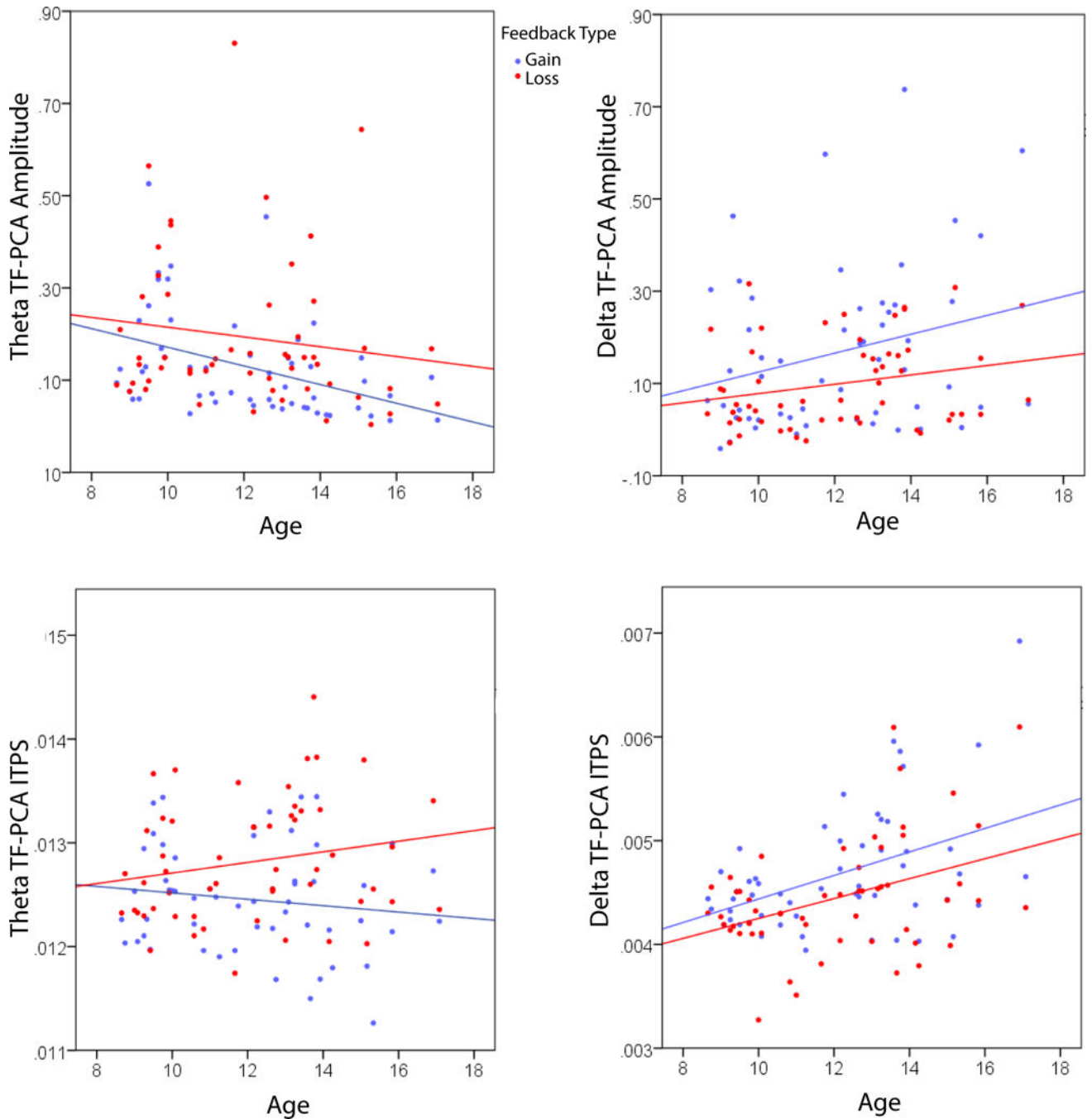


Figure 4. Relations between age and TF neural measures. Loss is presented in red, while gain is presented in blue. Both delta power and ITPS increase with age, while theta power decreases with age. Theta ITPS to loss showed a pattern of increasing with age, while theta ITPS to gain showed a pattern of decreasing with age.

Table 1

Correlations between Electrophysiological Measures and Age

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
1. Age															
2. FN-gain	.12														
3. FN-loss	.22	.65**													
4. FN	.08	-.61**	.20												
5. Theta TF-PCA-gain	-.41**	.10	-.04	-.17											
6. Theta TF-PCA-loss	-.14	.13	-.16	-.33*	.66**										
7. Theta TF-PCA	.18	.08	-.17	-.28*	-.01	.74**									
8. Theta ITPS-gain	-.14	.14	.04	-.14	.69**	.42**	-.06								
9. Theta ITPS-loss	.20	.06	-.03	-.11	.33*	.59**	.50**	.39**							
10. Theta ITPS	.31*	-.06	-.06	.02	-.27	.22	.53**	-.46**	.64**						
11. Delta TF-PCA-gain	.27	.55**	.27*	-.43**	.07	.37**	.43**	.24	.39**	.17					
12. Delta TF-PCA-loss	.24	.50**	.61**	-.01	.02	.11	.13	.09	.22	.15	.57**				
13. Delta TF-PCA	-.16	-.33*	.08	.51**	-.08	-.38**	-.43**	-.23	-.32*	-.12	-.84**	-.03			
14. Delta ITPS-gain	.44**	.36**	.24	-.22	-.06	.13	.22	.26	.51**	.27*	.64**	.44**	-.49**		
15. Delta ITPS-loss	.39**	.31*	.20	-.19	-.11	.05	.17	.13	.42**	.30*	.54**	.53**	-.30*	.68**	
16. Delta ITPS	-.09	-.09	-.06	.05	-.06	-.10	-.08	-.18	-.14	.02	-.16	.09	.25	-.45**	.35**

** p<.01,

* p<.05