Separating Cognitive Processes with Principal Components Analysis of EEG Time-Frequency Distributions

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ABSTRACT

Measurement of EEG event-related potential (ERP) data has been most commonly undertaken in the time-domain, which can be complicated to interpret when separable activity overlaps in time. When the overlapping activity has distinct frequency characteristics, however, time-frequency (TF) signal processing techniques can be useful. The current report utilized ERP data from a cognitive task producing typical feedback-related negativity (FRN) and P300 ERP components which overlap in time. TF transforms were computed using the binomial reduced interference distribution (RID), and the resulting TF activity was then characterized using principal components analysis (PCA). Consistent with previous work, results indicate that the FRN was more related to theta activity (3-7 Hz) and P300 more to delta activity (below 3 Hz). At the same time, both time-domain measures were shown to be mixtures of TF theta and delta activity, highlighting the difficulties with overlapping activity. The TF theta and delta measures, on the other hand, were largely independent from each other, but also independently indexed the feedback stimulus parameters investigated. Results support the view that TF decomposition can greatly improve separation of overlapping EEG/ERP activity relevant to cognitive models of performance monitoring.

1. INTRODUCTION

Measurement of EEG event-related potential (ERP) data has been most commonly undertaken in the time-domain. In cognitive psychology, the concept of transient 'components', such as the P300 and error-related negativity (ERN), has dominated measurement. Ideally such components contain either a single source or a small related network of sources, and represent a single or small related set of cognitive process. Time-domain measures can be particularly problematic for separating ERP components when they overlap in time. When overlapping components have distinct frequency characteristics, however, time-frequency (TF) signal processing techniques can be useful for separating the activity underlying the components. Such TF component measures may correspond more closely to distinguishable cognitive processes underlying event-related brain activity. Recently, TF methods have yielded important advances in the analysis of EEG/ERP signals. However, applications of TF approaches so far have tended to emphasize high-frequency activity or trial-level data, rather than the condition averages that serve as the basis for classical time-domain ERP components. Still, much is known about the TF representation of both the ERN and P300, with the ERN more so related to theta activity (3-7 Hz[1]) and P300 more so to delta activity (below 3 H[2,3]). In the current study, we present a time-frequency decomposition of condition average ERP data from a simulated gambling feedback task demonstrated to produce typical overlapping feedback-ERN and P300 components.[4,5] Results demonstrate that techniques of TF decomposition can contribute to cognitive psychology models of performance monitoring.

1.1 Performance Monitoring and Brain Response

Performance monitoring refers to the online monitoring and adjustment of one's behavior in relation to goals. Researchers in this area have primarily focused on two types of self-monitoring: endogenous self-monitoring (i.e., monitoring and identification of one's own errors in performance) and exogenous monitoring (i.e., monitoring external cues regarding one's performance). Endogenous monitoring has been indexed with response-locked ERPs to performance errors in a speeded response task (response-ERN[6,7]), and exogenous monitoring has been indexed in terms of ERPs to negative feedback stimuli such as errors or loss of money (feedback-ERN[4,8,9]). These alternative ERN measures entail a similar negative polarity deflection in medial-frontal brain regions, and are understood to emanate from a primary source in the anterior cingulate cortex (ACC). The focus of the current report is the feedback-ERN, also

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referred to as the feedback-related negativity (FRN). Prior research has suggested that the FRN reflects the evaluation function of a neural system that determines whether an outcome was good or bad relative to one's expectations.[5,8,10,11]

The FRN to a negative feedback stimulus is accompanied by a stimulus-locked P300 response, resulting in component overlap. The P300, a positive-going component that peaks slightly after the FRN, is thought to reflect a separate and more complex evaluative process than the FRN. Indeed, performance monitoring researchers have been wary of this overlapping P300 component[9], but the time-domain approach to measurement limits the ability of researchers had to parse these two components. Further, known distinctions exist between the cognitive processes underlying the FRN and P300, making it all the more important to separate them appropriately. For example, Yeung & Sanfey[12] found a double dissociation between the FRN and P300, such that the FRN responded to the valence of the feedback in a gambling task (i.e., whether it was good or bad) whereas the P300 responded to the magnitude of the reward.

Importantly, the FRN and P300 appear to occur in distinct frequency bands, such that the P300 occurs primarily in the delta (below 3 Hz) range whereas the FRN occurs primarily in the theta (3-7 Hz) range. Because they overlap in time but have distinct frequency characteristics, these components are ideal candidates for separation using time-frequency techniques. Below we show how we can parse the two components and demonstrate clearly how, in doing so, we may better represent the distinct cognitive processes they reflect.

1.2 Models of Performance Monitoring

Among tasks that generate the FRN (i.e. tasks that provide performance feedback), there has been debate about the cognitive parameters involved in FRN amplitude modulation. In one gambling task design, participants select from two monetary options and subsequently receive feedback as to whether they gained or lost the amount that they chose as well as learning what the alternative outcome would have been had they made the other choice. Thus, in addition to showing how much one gained or lost, one can infer whether the outcome was better or worse compared with the alternative (i.e. whether it was the correct or erroneous choice in the context of all possible outcomes), a process which presumably requires more attention and time. An early study using this task design[4] reported that the FRN was sensitive solely to the Loss/Gain information in the feedback. Subsequent research, however, demonstrated that this was the case only when Loss/Gain was the most prominent element of the feedback stimulus, when Error/Correct information was emphasized over Loss/Gain, the FRN responded to errors rather than to monetary losses.[13]

These results are explainable in terms of a model that suggests that the FRN occurs to feedback stimuli indicating that outcomes were 'worse than expected'.[8] According to work that has stemmed from this model, the FRN reflects a generalized, context dependent evaluative process that determines good and bad outcomes from the individual task demands of a specific task. Further research has suggested that the FRN makes a binary evaluation of whether or not a goal was satisfied, such that when three possible outcomes exist, the FRN amplitude is typically equivalent for the worst and middle outcomes.[5,10,11] Taken together, these findings point to the idea that the FRN reflects a simpler cognitive process than the P300, which has been found to scale to reward magnitude and to show relationships to more contextual, secondary feedback information.[12] It is worth noting that there have been some inconsistencies in findings related to the 'worse than expected theory' such that the FRN has not consistently been found to be related to violations of expectancies[14], and some FRN findings have been incongruent with the ERN findings.[15,16]

1.3 Time-Frequency and EEG Signals

Time-frequency signal processing techniques have yielded important advances in the analysis of EEG event-related potential (ERP) signals. One area of advance has been in high-frequency activity (e.g. gamma, > 30 Hz), where new high-frequency time-dependent findings are now routinely measured using time-frequency. Additionally, time-frequency approaches have provided advances in decomposing lower-frequency ERP activity that overlaps in time but is distinguishable in frequency – e.g. 'standard' ERP components, such as P300. However, there has not yet been a broad shift towards characterizing ERPs in terms of time-frequency, in part because the degree of overlap in common time-domain ERP component measures has been underappreciated.

While TF distributions are rich signal representations, they create increased complexity due to the extra dimensionality. This complexity has slowed efforts to utilize TF methods with ERP signals. A recently developed approach uses principal components analysis (PCA) to reduce the dimensionality of the data for analysis. In the method employed in this report[17], PCA is used to generate TF component measures across subjects, conditions, and electrodes. As described earlier, such an approach can be helpful for separating overlapping components. The TF-PCA approach has already been used to better separate the response-ERN[17,18] and P300 activity[2,3] from other co-occurring activity.

1.4 Current Study

The current study has two main goals. The first is to demonstrate how time-frequency measures can offer a more parsimonious and useful decomposition of the data. The second is to evaluate whether feedback properties beyond the primary 'worse than expected' outcome can be detected in the larger sample employed in the current study, and whether the time-frequency signal representations improve detection or separation of the processes relevant to these feedback dimensions.

2. METHODS

2.1 Participants

Participants were 166 undergraduate students were recruited from an introductory psychology course at the University of Minnesota who received either monetary compensation or course credit. Eighteen of these were excluded as follows: eight participants because of incomplete questionnaire data, three due to equipment problems during collection, four due to excessive artifacts, and two who could not complete the task due to physical problems (one had a cold-like illness and one due to irritation with one eye making it difficult to focus). Thus, the final sample for the study consisted of 149 participants.

2.2 Feedback Task Procedure

Testing was conducted in a dimly lit, sound-attenuated room. Experimental stimuli were presented centrally on a 21-inch Dell high-definition CRT color monitor, as a viewing distance of 100 cm, using E-Prime version 1.1 software (Psychology Software Tools, Inc.). Behavioral responses were made using a serial response box. The experimental task was a modified version of a simulated gambling task[4] in which the participant chose between two monetary options on each trial and then received feedback indicating whether the choice resulted in winning or losing money on that trial. The modification was that feedback was presented 100ms after the button press to have the feedback more immediately follow the choice. The target stimuli consisted of two adjacent squares, each enclosing a number (5 or 25) representing a monetary value (in cents). Participants chose one of the two squares (left or right), and a subsequent feedback stimulus displayed the outcome of their decision. That is, the choice boxes turn either green or red for the feedback stimulus, resulting in four possibilities (Gain-Gain, Gain-Loss, Loss-Gain, Loss-Loss). Similarly, all four possible combinations of 5 and 25 (i.e., 5-5, 5-25, 25-5, and 25-25) were presented as choices, with each combination presented an equal number of times in a randomized sequence. Thus, there are 16 possible feedback stimuli (four monetary value pairings by four color combinations). The target stimulus remained on the screen until a choice was made, after which a blank screen appeared for 100 ms. Next, a feedback stimulus appeared for 1,000 ms, followed by a blank screen for 1,500 ms, preceding the onset of the next trial. Participants completed 12 blocks of 32 trials.

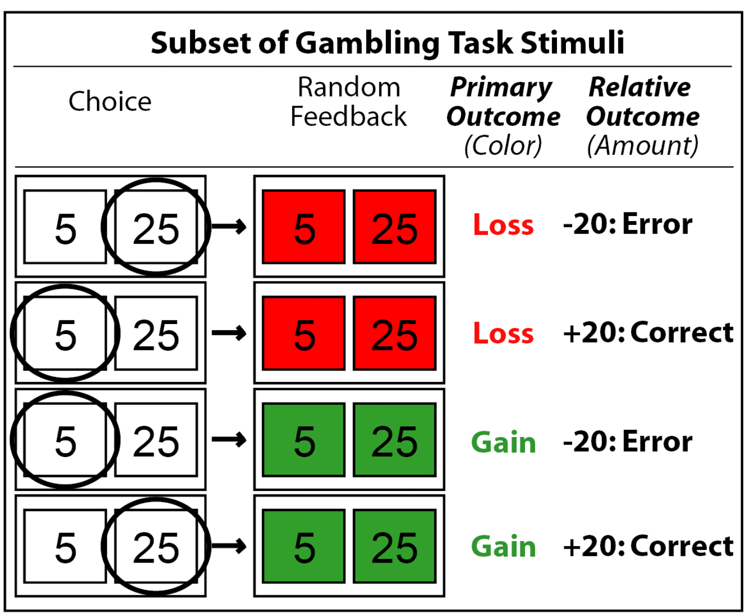

Fig. 1. Depiction of the subset of four stimuli (from 16) in which either choice resulted in the same primary outcome (monetary gain or loss). However, these stimuli represent special cases in the possible array of outcomes, where it is possible to gain (Primary outcome), but still have the worse of the two choices compared to the alternative (Relative outcome).

Four trials from the overall 16 possible outcomes were of particular interest, based on a secondary analysis performed in the previous report.[4] In particular, for the majority of feedback stimuli (12), when one choice is a Gain, the other is a loss. That is, the unchosen alternative is opposite. The remaining four types of outcome stimuli, however, represent an interesting case where both sides result the same outcome, either both gain or both loss (Fig. 1.). Within these four gain or loss outcomes, there is also a relative comparison with the side that was not chosen. For example, one can gain money, but gain less than the unchosen alternative – which can be considered an error (row three in Fig. 1.). Similarly, for these loss trials, one can lose, but avoid having lost a greater amount – which can be considered the more correct choice (row one in Fig. 1.). In the original report[4], loss trials evidenced increased FRN relative to Gain, but the Error versus Correct difference did not. Holroyd, et al.[13] demonstrated that this is governed by what stimulus comparisons are given the primary emphasis in the task – e.g. if the Error/Correct dimension had somehow been the primary distinction it would have shown significant FRN differences and the Gain/Loss would not have. In the current report, the Gain/Loss dimension is referred to as the Primary outcome, and the secondary Error/Correct dimension as the Relative outcome. The goal in the current report is to evaluate whether differences for the secondary Relative outcome comparison can be detected with the larger sample (sample size in the original report was 12, versus 149 in this report), and whether the time-frequency approach can help separate activity relevant to these feedback stimulus dimensions.

2.3 Electroencephalographic Recording

Data collection was conducted in two waves, using 64-channel Neuroscan bioamplifiers (Neuroscan, Inc.). Wave 1 (N=42) was collected using a Synamps unit. Wave 2 was a Synamps2 unit. All EEG activity was recorded using 64-channel Quick-caps containing sintered Ag-AgCl electrodes positions in accordance with the International 10-20 System. Fewer EEG sites were recorded in wave 1, and only the shared electrodes were retained for the current dataset. Additionally, problems with the FP1 and FP2 leads in wave one necessitated dropping these from both waves. Thus, 51 electrodes are included in the reported data, as follows: AF3, AF4, F7, F5, F3, F1, Fz, F2, F4, F6, F8, FT7, FC3, FC1, FCz, FC2, FC4, FT8, T7, C5, C3, C1, Cz, C2, C4, C6, T8, TP7, CP3, CP1, CPz, CP2, CP4, TP8, P7, P5, P3, P1, Pz, P2, P4, P6, P8, PO5, PO3, POz, PO4, PO6, O1, Oz, O2. Ocular activity was monitored using electrodes positioned on the outer canthus of each eye(Horizontal EOG) as well as above and below the left eye (Vertical EOG). Impedances were kept below 10 kΩ. All EEG signals were referenced to CPz and digitized on-line at 1000 Hz. The signals were then epoched off-line from 1,000 ms before to 2,000 ms after feedback onset, re-referenced to linked mastoids. Trial-level EEG data were corrected for ocular and movement artifacts using an algorithm developed by Semlitsch, Anderer, Schuster, & Presslich, (1986), as implemented in the Neuroscan Edit software, version 4.3. Finally, data were resampled to 128 Hz.

2.4 Time-Frequency Decomposition

Principal components analysis (PCA) of time-frequency transforms of the ERPs (see Bernat, et al., 2005) was applied to the current brain response data in an effort to better separate FERN and P300 components. These components, although presumed to reflect distinctive psychological processes, overlap with each other in time and thus need to be disentangled quantitatively. One approach to separating overlapping components has been to compute differences between time-domain ERP waveforms across differing trial conditions. A newer approach is to identify distinctive frequency elements of the ERP signal associated with one component versus another, using time-frequency principal components analysis (TF-PCA). The TF-PCA approach has proven effective in separating out overlapping ERP components in prior published studies of the response-ERN[17,18] and the P300.[3] Findings of these TF-PCA studies, together with simpler frequency-domain analyses in other published work, have indicated that both the ERN and FRN are primarily associated with brain activity in the theta frequency range (3-7 Hz[1]), whereas the P300 is more associated with activity in the delta range (< 3 Hz[2,3]).

To isolate these distinctive components in the current study, brain response activity in the window of -1000 to +2000 ms relative to feedback stimulus onset were filtered in two ways: 1) using a 3-9 Hz high- and low-pass 3rd order Butterworth filter to isolate theta activity, and 2) using 3 Hz, lowpass 3rd order Butterworth filter to isolate delta activity. These filtered signals were then transformed into time-frequency energy distributions (surfaces), using the binomial reduced interference distribution (RID) member of Cohen's class of time-frequency transforms as previously.[3,17] For each of these theta and delta TF distributions separately, PCA was then applied to an area corresponding to the zero to 750 ms time range and zero to 10 Hz frequency range. This yielded equivalent windows for decomposition, but with aforementioned filters having narrowed the frequency activity within the window to either theta or delta.

To identify the primary activation component within the theta and delta frequency bands, the shared covariance across all TF points was computed separately for each band by extracting the largest principal component in each (using PCA methods described previously[3,17], but opting to retain only the most dominant component. In both analyses the variance accounted for by the first component (theta, 39.25%; delta, 71.09%) substantially exceeded that accounted for by the next component (theta: 10.97% and delta: 9.37%), indicating that retention of a single principal component (PC) was reasonable in each case. These TF-based theta and delta PCs (depicted in Figure 2, TF-PCA Decomposition) served as the primary dependent measures in the analyses of brain reactivity to feedback stimuli reported here. Electrodes FCz and Cz were most proximal topographically to the maximum of the observed theta and delta PCs, respectively, across all trials (see Fig. 2), and Gain-Loss and Correct-Error condition differences (see Fig. 3). Data from these electrode sites were thus employed in the statistical analyses of TF component scores reported below

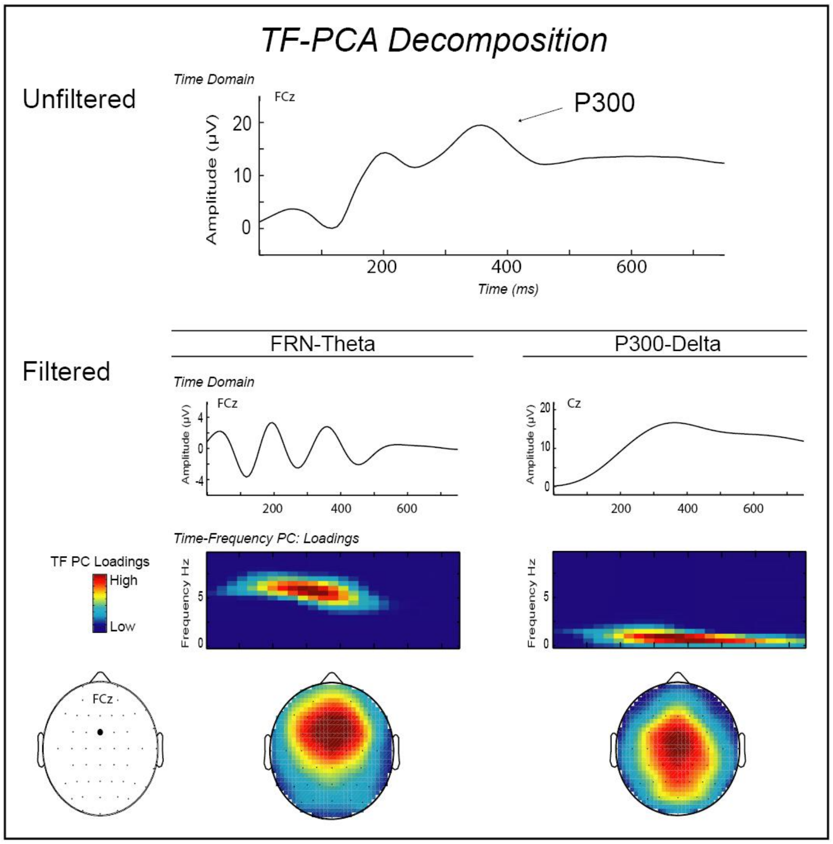

Fig. 2. Time-frequency PCA decomposition of theta and delta feedback ERP activity.

2.5 Data Analysis

Based on the data reduction strategy detailed in the previous section, TF theta and delta PCs served as the primary measures in the analysis of the brain response data. Initial omnibus analyses were conducted using a 3-way repeated-measures general linear model (GLM) with 2-level Frequency Band (delta, theta), 2-level Primary outcome (Gain, Loss), and 2-level Relative outcome (Correct, Error) conditions as within-subjects factors. This analysis permitted an evaluation of whether the Relative outcome was related to the brain measures overall, and whether this relationship differed in relation to the Primary Gain and Loss conditions and theta and delta frequency ranges. Follow-up repeated-measures GLM analyses assessed effects of Primary and Relative outcome conditions in theta and delta response components separately. Correlations and simple effects analyses are also presented to clarify the direction and relative magnitude of effects.

3. RESULTS

Main effects for Primary and Relative outcomes are presented in Figure 3. In the left panel, the previously investigated Gain/Loss Primary outcome is presented unfiltered in the upper plot. Here the FRN and P300 are apparent in the unfiltered time-domain waveforms, with an expectable pronounced FRN negativity in response to Loss feedback relative to Gain. Below this, time-domain signals filtered for theta and delta are presented, with Loss-Gain difference TF theta and delta surfaces below that. Topographical maps at the bottom depict Loss-Gain amplitude differences and statistical evaluation of those differences. Here it becomes apparent that Gain and Loss show inverse relationships with the theta and delta TF component measures. Specifically, theta is increased for Loss feedback (as suggested by previous work), but now it becomes apparent that delta is increased for Gain feedback. In the right panel, results from the Relative Error and Correct outcomes are presented. First, results for both theta and delta are robustly significant, supporting the idea that this secondary aspect of the feedback stimulus was differentially processed along with the primary Gain/Loss aspect. Interestingly, the relationships are strikingly similar to the Primary outcome, with Error trials related to increases in theta and Correct trials related to increases in delta. Further analyses (described below) demonstrated that the responses to the Primary and Relative aspects of the feedback stimuli were non-significantly related – i.e. independent. The results also indicate that theta and delta represent independent indices, sensitive to Loss and Gain or Error and Correct respectively. Together, our findings indicate that the TF decomposition of the data, relative to the time-domain approach, offers more specific indices of independent processes operating in response to the feedback stimuli.

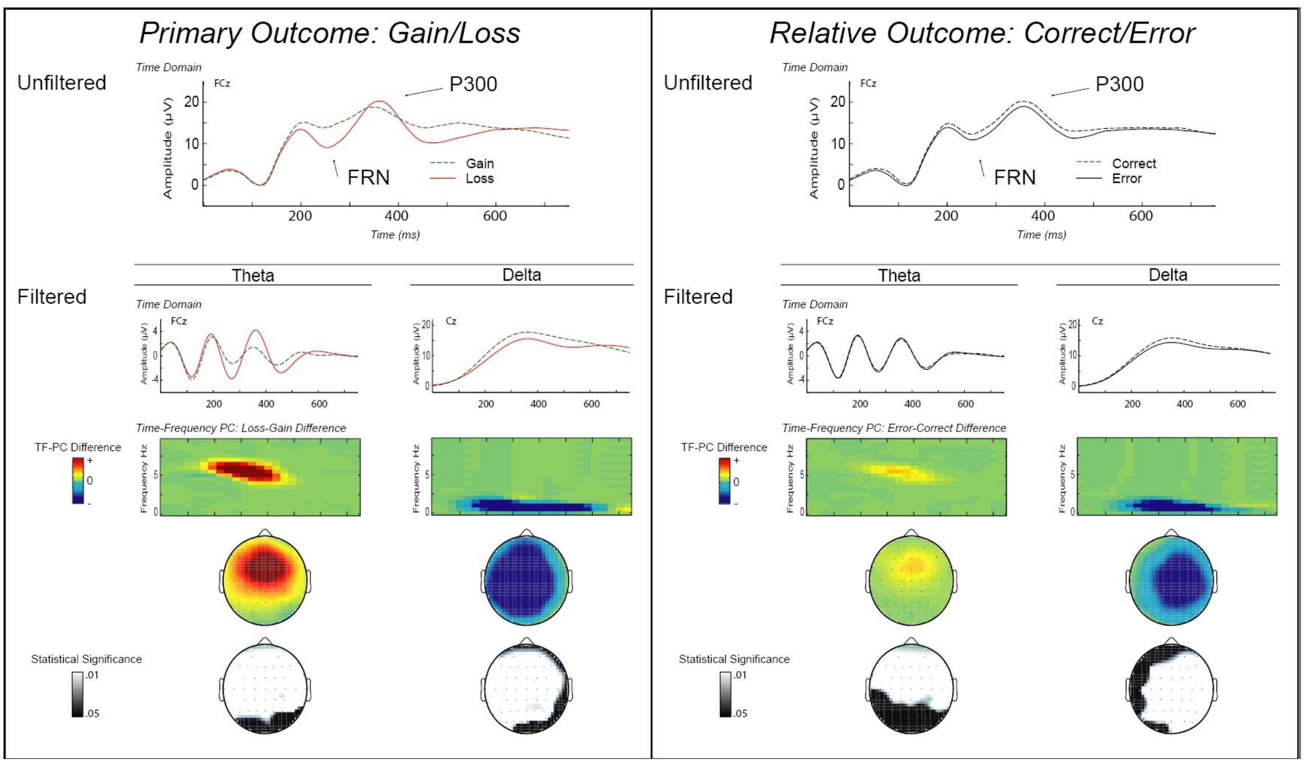

Fig. 3. The left panel depicts comparisons of the differences between the Primary Gain and Loss outcome averages. The right panel depicts comparisons of the Relative Correct and Error outcome averages. Results indicate increases in theta to Loss and Error trials, and increases in delta to Gain and Correct trials. White color on topographical maps in the bottom row indicates uncorrected t-test significance of p<.01.

An omnibus general linear model (GLM) was conducted with Band (delta, theta), Primary outcome (Gain, Loss), and Relative outcome (Error, Correct) as predictors of the TF signal representations. A large main effect for Band ($F(1,147)=133.90$, $p<.001$, $eta^2=.48$) was observed, due to the larger amplitude in delta than theta. The main effects for Primary and Relative outcomes were superseded by strong interactions with Band for each (Band X Primary, $F(1,147)=138.60$, $p<.001$, $eta^2=.49$; Band X Relative, $F(1,147)=46.09$, p<001, $eta^2=.239$). The interaction between Primary and Relative outcomes was not significant ($F(1,147)<1$, ns), nor was the three-way interaction ($F(1,147)=3.37$, $p<.07$), suggesting that Primary and Relative outcomes were not strongly related to each other. The same GLMs were conducted separately within theta and delta bands to follow up on the omnibus analysis indicating significant differences by Band, presented in Table 1. Results indicate robust main effects for both Primary and Relative outcomes. The nonsignificant interaction for both theta and delta suggests independent processing of these properties of the feedback.

Table.1. *F*, *p*, and eta^2 values from separate theta and delta repeated-measures GLMs. .

Band	Effect	*F(1,147)*	*p*	eta^2
Theta				
	Primary (Gain/Loss)	113.40	<.001	.435
	Relative Outcome (Correct/Error)	13.84	<.001	.086
	Primary x Relative	1.29	.258	.009
Delta				
	Primary (Gain/Loss)	60.85	<.001	.293
	Relative (Correct/Error)	33.89	<.001	.187
	Primary x Relative	1.95	.164	.013

3.1 FRN and TF-Theta

Previous work has demonstrated that the FRN involves increased activity in the theta range.[1] Consistent with the idea, both Loss and Error trials (the 'worse' trials) are associated with increases in TF theta activity, suggesting that TF-theta best represents the cognitive processes that have been associated with the FRN Following this logic, the Relative outcome theta response would be predicted to be decreased relative to the Primary outcome theta response, because the FRN has been shown to be most sensitive to the primary or emphasized stimulus dimension.[13] This comparison was significant in this data (t(148)=-6.64). Theta activity in the Relative outcome comparison was also significantly smaller than delta activity in both in the Primary (t(148)=-7.76) and Relative outcomes (t(148)=-4.06). It is worth noting that in these comparisons, difference scores were created using Loss-Gain and Error-Correct for theta and Gain-Loss and Correct-Error for delta, to express all increased differences as greater positive numbers for appropriate comparison. Finally, as noted in Fig. 4, the Relative outcome theta was also significantly lower than the mean of the other three difference scores. These results further support the idea that theta represents expected cognitive functions previously demonstrated to be associated with the time-domain FRN. The independent increases in Gain and Correct trials for delta potentially represents a novel index requiring further investigation.

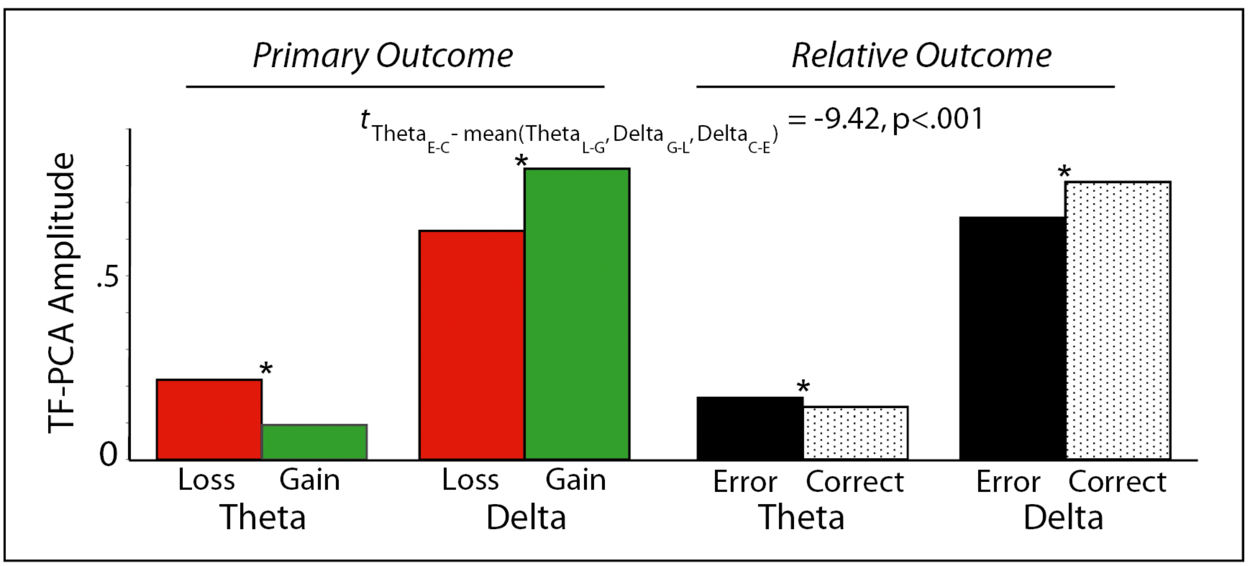

Fig. 4.Bar chart of mean for Primary (Gain, Loss) and Relative (Error, Correct) outcomes, for the TF theta and delta measures. All paired bars significantly differed (*=p<.001). Significant t-test indicates that theta in the Relative outcome had lower activity than all other pairs combined.

3.2 Comparing Time and Time-Frequency Signal Representations

Comparisons between time-domain (TD) and TF signal representations (analyses presented below, this section) revealed that the theta and delta TF-PCA measures together accounted for a majority of the variance in both the time-domain FRN and P300. This suggests that relevant variance in the time-domain measures was represented in the TF measures. Importantly, theta and delta shared only a small percentage of their variance, supporting the idea that these are separable processes. Additionally, when alternatively comparing the Primary and Relative feedback outcomes (Gain-Loss or Correct-Error difference scores), the variance shared between theta and delta dropped from small but significant, to non-significant, indicating that theta and delta are independent processes within Primary and Relative outcome conditions. Despite this, theta and delta showed robust and opposite relationships to the feedback outcomes (theta, Loss > Gain and Error > Correct; delta, Gain > Loss and Correct > Error). Thus, delta and theta provided parsimonious and largely independent indices of the Primary Gain and Loss and the Relative Correct and Error outcomes, respectively.

Time-domain FRN and P300 measures, on the other hand, were each characterized by mixtures of the TF theta and delta. This mixture was complicated by the phase of the faster theta oscillation (i.e. positive versus negative polarity). Specifically, there is a negative polarity peak in theta corresponding to the FRN, and the following positive peak in the oscillation occurs during the time of the P300 (see Figs. 2 and 3). This is in contrast to delta, which is a positive polarity slow-wave contributing positive values to time domain measures in both the FRN and P300 windows. Because activity at the same time but different frequencies is additive, this differing polarity has a direct impact on summed theta and delta activity when they are measured together unfiltered in the time domain as with the FRN and P300. For the FRN, delta increases for Gain (increased positive polarity amplitude) and theta increases for Loss (increased negative polarity amplitude) combine to create a bigger Gain-Loss difference (t(148)=12.03, this and all statistics reported below are p<.001, unless otherwise specified) than either TF measure alone (theta, t(148)=-10.65; delta, t(148)=7.82). Conversely, for the P300, both theta increases for Loss and delta increases for Gain translate into increased positive numbers, reducing Gain-Loss differences (t(148)=1.49, ns; see also Figure 3). For the Relative outcome (Correct-Error differences), results were somewhat different, and both time and TF measures showed a similar level of significance (theta, t(148)=-3.75; delta, t(148)=5.85; FRN, t(148)=5.01; P300, t(148)=5.07). A likely reason for this difference is the decreased theta difference for the Relative outcome (as noted in the previous section), which changes the mixture of theta and delta differences summed together in the time-domain FRN. This highlights how not only phase, but also relative activity levels in these independent theta and delta measures, can complicate time-domain FRN and P300 measures. The reported TF energy measures do not have this complication, because all increases are represented as more positive numbers (i.e. there is no polarity).

Analysis across all trials. Theta and delta TF measures have a moderate relationship when averaging across all Primary and Relative outcome trials (r=.24), indicating that while they do share some variance, they are not simply yoked expressions of the same underlying process in the data. Next, these theta and delta TF measures were entered as independent variables in two regression models in which TD FRN and P300 alternatively served as the dependent variable. For the FRN, theta and delta together accounted for a substantial amount of the TD variance (R=.72), with each accounting for significant unique variance (delta, t(147)=12.64; theta, t(147)=-2.70, p<.008). The stronger relationship for delta than theta with the TD FRN underscores the problem of overlapping processes in the time-domain, where FRN has been localized to the theta range. For the P300, theta and delta together accounted for nearly all of the variance (R=.94) with both delta (t(147)=29.12) and theta (t(147)=7.37) accounting for unique variance. These results support the view that these TD FRN and P300 measures can be understood as mixtures of TF theta and delta.

Analysis for Gain-Loss and Correct-Error differences. TF theta and delta Primary and Relative outcome differences were not significantly related to each other (Gain/Loss, r=.03, ns; Correct/Error, r=.004, ns), suggesting these are independent processes in response to the feedback. Regression models with Gain-Loss differences for both TD dependent and TF independent measures, indicated that TD FRN and P300 Gain-Loss differences were confounded in a similar way as when these TD measures are considered across trials – a mixture of theta and delta Gain-Loss differences. For the TD FRN dependent measure, TF theta and delta independent measures accounted for significant variance in the model (R=.55), and within that, each predicted unique variance (theta, t(147)=-5.35; delta, t(147)=5.58). The TD P300 Gain-Loss difference evidenced a similar mixture of theta and delta when it served as the dependent measure (R=.66; theta, t=5.14; delta, t=9.41). A similar pattern was true for Correct-Error differences (FRN: R^2=.67; theta, t=-2.36, delta, 5.61, and P300: R=.77; theta, t=4.03; delta, t=13.90).

4. CONCLUSIONS

These findings contribute to the existing performance monitoring literature in several ways. First, prior studies have failed to detect an effect of secondary feedback characteristics (termed Relative Outcomes here) on the FRN, and a growing number of studies have posited that the FRN responds in a binary way solely to the Primary outcome in a feedback task.[5,10,11,13] By using a larger sample size and the TF-PCA method to disentangle the processes represented by theta and delta, we were able to show that the Primary and Relative outcomes in such a feedback task can exercise both the FRN (as represented by theta) and the P300 (as represented by delta). In addition, by parsing these two processes, we demonstrated that the two independent TF processes differentially responded to both Primary and Relative outcomes, such that theta had more activity for Loss and Error trials, and delta had more activity for Gain and Correct trials. Our work demonstrates how, owing to the overlap of these components and their summation in the time-domain, important time-domain effects can be both exaggerated (as for the FRN Gain-Loss difference score) or attenuated (as for the P300 Gain-Loss difference) depending on the relative contributions of theta and delta to activity associated with the task parameters.

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