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Utilizing time-frequency amplitude and phase synchrony measure to assess feedback processing in a gambling task☆

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ABSTRACT

The neurophysiological mechanisms involved in the evaluation of performance feedback have been widely studied in the ERP literature over the past twenty years, but understanding has been limited by the use of traditional time-domain amplitude analytic approaches. Gambling outcome valence has been identified as an important factor modulating event-related potential (ERP) components, most notably the feedback negativity (FN). Recent work employing time-frequency analysis has shown that processes indexed by the FN are confounded in the time-domain and can be better represented as separable feedback-related processes in the theta (3–7 Hz) and delta (0–3 Hz) frequency bands. In addition to time-frequency amplitude analysis, phase synchrony measures have begun to further our understanding of performance evaluation by revealing how feedback information is processed within and between various brain regions. The current study aimed to provide an integrative assessment of time-frequency amplitude, inter-trial phase synchrony, and inter-channel phase synchrony changes following monetary feedback in a gambling task. Results revealed that time-frequency amplitude activity explained separable loss and gain processes confounded in the time-domain. Furthermore, phase synchrony measures explained unique variance above and beyond amplitude measures and demonstrated enhanced functional integration between medial prefrontal and bilateral frontal, motor, and occipital regions for loss relative to gain feedback. These findings demonstrate the utility of assessing time-frequency amplitude, inter-trial phase synchrony, and inter-channel phase synchrony together to better elucidate the neurophysiology of feedback processing.

1. Introduction

A growing body of research has used gambling tasks to examine the neurophysiological mechanisms involved in the evaluation of performance feedback. Gambling outcome valence (i.e. monetary gains and losses), in particular, has been widely identified as an important factor modulating time-domain event-related potential (ERP) components, specifically the feedback negativity (FN) and reward positivity (RewP). Recent work employing time-frequency analysis has revealed that the FN and RewP, along with other time-domain ERP components, can be understood as a mixture of delta (0–3 Hz) and theta (3–7 Hz) activity which overlap in time but index separable processes (Bernat et al., 2015; Bernat et al., 2011; Harper et al., 2016; Harper et al., 2014; Watts et al., 2017). Alongside amplitude effects, ERP phase synchrony dynamics have been used to investigate the consistency of engagement within, and connectivity between, neural network nodes that have been found to underpin feedback processing. Despite the insights that have been gained using amplitude and phase measures, there is a growing need for a comprehensive assessment of how amplitude and phase indices relate to each other and provide unique understanding of feedback processing. Additionally, without a comparative evaluation of the various feedback processing measures used in the field, it can be difficult to determine if adding particular measures might expand the predictive power of current models and which combination of analytic techniques provides the most valid and powerful model of feedback processing. The current study aimed to contribute toward filling this gap by closely examining time-domain amplitude, time-frequency amplitude, inter-trial phase synchrony (ITPS), and inter-channel phase synchrony (ICPS) changes following monetary feedback in a gambling task.

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1.1. Time-domain ERP components of feedback processing

The FN has been widely examined as a marker of outcome valence, differentiating negative from positive feedback (Gehring and Willoughby, 2002; Miltner et al., 1997). The FN component can be observed as a negative deflection at medial-frontal electrodes, which occurs in the range of 180–350 ms after negative feedback. Early research posited that the FN demonstrated differential activity to negatively- and positively-valenced outcomes, with the FN being relatively diminished or non-existent to positive outcomes (Miltner et al., 1997). Further work demonstrated that the FN indexes key processes underlying reinforcement learning, where the FN is monotonically related to the size of the reward prediction error (RPE) and largest for a negative RPE (i.e., when an outcome is worse than expected; Holroyd and Coles, 2002; Nieuwenhuis et al., 2004). However, inconsistencies in the literature have led to a number of studies focused on improving quantification approaches and attempting to isolate separable feedback-related activity occurring in the FN time window.

One such line of work has advanced understanding of the diminished FN to positive feedback. This work has demonstrated that a slow positive deflection in response to rewarding stimuli, often referred to as the reward positivity (RewP), is a core constituent process occurring during the FN time window (Bernat et al., 2008; Cavanagh, 2015; Foti et al., 2015; Foti et al., 2011; Holroyd et al., 2011; Holroyd et al., 2008; Potts et al., 2006; Proudfit, 2015). The superposition of the RewP component over the FN partially explains the smaller negative amplitude to rewarding feedback observed during the FN time window. Along with being enhanced to positive relative to negative feedback, the activity underlying the RewP has also been found to be modulated by outcome expectancy, where unexpected feedback produces a larger RewP than expected feedback, as well as other complex secondary characteristics like relative outcome and outcome magnitude (Bernat et al., 2015; Holroyd et al., 2011, 2008; Watts et al., 2017), suggesting that slow-wave activity during feedback ERPs may be sensitive to a variety of processes, depending on the task. To disentangle these complex feedback-processing interactions apparent in the FN time window, new measurement approaches, like time-frequency decomposition, have been fruitful.

1.2. Time-frequency amplitude measures of feedback processing

Time-frequency analysis of the FN has proven effective in disentangling the effects of gain and loss feedback that are methodologically difficult to isolate in the time domain. Past work has demonstrated that the FN component can be separated into independent processing in theta and delta frequencies (Bernat et al., 2015, 2008, 2011; Foti et al., 2015; Nelson et al., 2011; Watts et al., 2017). Theta and delta activity explain unique variance when considered in a regression model predicting the time-domain FN, where increased theta activity reflects loss feedback and increased delta activity reflects gain feedback (Bernat et al., 2015, 2008, 2011; Nelson et al., 2011). Thus, for activity within the FN time window, time-frequency analysis can detect modulations of separable brain systems engaged differentially by positive and negative feedback, suggesting that theta and delta activity are robust metrics for the proposed functional roles of the FN and RewP components, respectively. To identify the neural sources of separable feedback activity indexed by delta and theta, Foti et al. (2015) applied source localization to these time-frequency measures of the FN. Separable generators were identified: loss-related theta localized to the ACC and gain-related delta to possible sources in the striatum. Taken together, these results support the view that discrepancies in time-domain feedback components can be clarified with time-frequency analytic approaches, and that using only time-domain measures may be insufficient in many contexts.

1.3. Reduced Interference Distribution: Time-frequency transform

A majority of work using time-frequency applications with ERP data utilizes wavelet approaches; however, the work from our group has focused on the reduced interference distribution (RID). Most analytic approaches can be implemented using either class of transforms. Indeed, we have shown that the principal component analysis (PCA) approach we use here can work similarly in both domains (Bernat et al., 2005). The RID has a number of properties that are desirable relative to wavelets, but perhaps the most useful is the uniform time-frequency resolution produced. Wavelets have non-uniform resolution, which exhibits itself as poor temporal resolution at low frequencies and poor frequency resolution at high frequencies. The RID, on the other hand, does not suffer from this trade-off (Aviyente et al., 2011; Bernat et al., 2005). This can have utility for analyzing low-frequency activity, such as delta, to parse this activity more carefully in time, but also in theta, where such resolution can support close investigation into the timing of theta-band activity associated with conventional P2, FN/N2, and P3 components. For a more complete discussion of important differences between the RID and wavelets with regard to amplitude, please see Bernat et al. (2005), and with regard to phase dynamics, see Aviyente et al. (2011) and Aviyente et al. (2017).

1.4. Phase dynamics and feedback processing: ITPS and ICPS

Although ERP amplitude effects have been widely studied and successfully linked to specific cognitive and affective processes, there is growing evidence that phase dynamics play a key role in neural communication and information processing (Fries, 2005; Varela et al., 2001). In order to link findings from single cell recordings, neural network analyses, computational modeling, and experimental psychology, investigating neural communication beyond simple amplitude effects is essential. Taking advantage of underutilized ERP phase measures, in addition to time-frequency amplitude measures, can provide more comprehensive assessments of feedback processing.

By examining neural activity time-locked to a specific event (e.g., feedback stimuli), phase dynamics can be measured within and between neural populations. Intertrial phase synchrony (ITPS) is calculated as the amount of phase alignment of frequency-specific event-locked neural activity from trial to trial, and is typically operationalized as a measure of the consistency of neural responding to a given stimulus condition. Across a variety of tasks, evidence now suggests that ITPS is closely linked to ERP amplitude changes and may be an important aspect of coordinating interactions between distant brain areas (Burwell et al., 2014; Cavanagh et al., 2009; Sauseng et al., 2007). Studies have found higher ITPS, particularly within the medial prefrontal cortex (mPFC), to be associated with increased ERP amplitude and more adaptive behavioral responses to task demands (Cavanagh et al., 2009; Marco-Pallares et al., 2008; Cohen and Cavanagh, 2011; Burwell et al., 2014).

A predominant view suggests ITPS promotes behavioral adaptation through enhanced encoding of new task information and the integration of the current stimulus and context with prior knowledge and associations (Fries, 2005). Within this view, ITPS represents a state of neural readiness, as more phase synchronization within a particular area will facilitate efficient information capture and integration through improved connectivity with linked network nodes. Empirical results showing an association between ITPS and learning rates supports this hypothesis (Van de Vijver et al., 2011). Indeed, trials that contain information valuable for learning (e.g., error trials) elicit increases in phase-locking (Cavanagh et al., 2009; Cohen and Cavanagh, 2011), and more cognitively demanding blocks of trials have been found to produce higher ITPS (Papenberg et al., 2013).

Findings of enhanced theta power and ITPS within reinforcement learning paradigms have been consistent, illustrating the role of ITPS in learning and performance monitoring. Enhanced mPFC theta power