Reward feedback processing in children and adolescents: Medial frontal theta oscillations

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ABSTRACT

We examined event-related electroencephalography (EEG) oscillations, including event-related spectral perturbations (ERSP) and intertrial coherence (ITC), to compare feedback processing during a chance-based reward vs. non-reward task in groups of 10–12-year-old ($n = 42$), 13–14-year-old ($n = 34$) and 15–17-year-olds ($n = 32$). Because few, if any studies have applied these analytic methods to examine feedback processing in children or adolescents, we used a fine-grained approach that explored one half hertz by 16 ms increments during feedback (*no win* vs. *win* events) in the theta (4–8 Hz) frequency band. Complex wavelet frequency decomposition revealed that *no win* feedback was associated with enhanced theta power and phase coherence. We observed condition and age-based differences for both ERSP and ITC, with stronger effects for ITC. The transition from childhood to early adolescence (13–14 yrs.) was a point of increased differentiation of ITC favoring *no win* vs. *wins* feedback and also compared to children or older adolescents, a point of heightened ITC for *no win* feedback (quadratic effect).

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1. Introduction

The adolescent developmental period paradoxically reflects a time of rapid increases in physical strength and decision-making capacity, yet is also a time of vulnerability related to increased risk-taking and novelty seeking behavior (Arnett, 1992; Dahl, 2004; DiClemente, Hansen, & Ponton, 1996). An influential neurobiological model of adolescent development suggests an imbalance between early developing emotion/reward-related brain regions and slower-to-mature cognitive control/decision-making regions (Casey, Getz, & Galvan, 2008; Yurgelun-Todd, 2007).

Contemporary decision making models propose that choices are guided by the respective value assigned to available options (Kahneman & Tversky, 1979), with the relative value computed in a system supported by the medial prefrontal cortex (mPFC) (Frank & Claus, 2006; O'Doherty, Dayan, Friston, Critchley, & Dolan, 2003; Pagnoni, Zink, Montague, & Berns, 2002; Pasupathy & Miller, 2005). As such, the interplay between expectancy, action and outcome-related feedback is central to reward learning models (Holroyd & Coles, 2002; Schultz & Dickinson, 2000). Such reinforcement learning relies on the use of both positive and negative performance feedback to adaptively guide behavior (Sutton & Barto, 1998). Phasic changes within the mesolimbic dopamine system are thought to encode reward prediction error signals that reflect the difference between actual and expected outcomes. Research has begun to specifically examine the role of prediction error signals in adolescent decision-making (Cohen et al., 2010). In particular, some recent work suggests increased functional connectivity of the ventral striatum and the mPFC from childhood through adolescence to adulthood, accompanied by a decrease in learning rate for negative prediction errors (van den Bos, Cohen, Kahnt, & Crone, 2012).

Electroencephalography (EEG) studies of reward processing and reinforcement learning mainly focus on the feedback related negativity (FRN), a mid-frontal event related potential (ERP) component peaking approximately 200–300 ms post-stimulus. Holroyd and Coles' (2002) reinforcement learning model postulates that the stimulus-locked FRN, and also the response locked error-related negativity (ERN), reflect activity emerging from a generic error processing system. According to a prevailing reinforcement learning

model, FRN/ERN responses reflect a reward prediction error generated when transient dips in midbrain dopamine levels signal activation of disinhibitory neurons in the ACC (Holroyd & Coles, 2002). With regard to the FRN, both dipole and distributed source modeling studies indicate that the ACC and medial frontal cortical region are the main neural generators of the FRN (Gehring & Willoughby, 2002; Luu, Tucker, Derryberry, Reed, & Poulsen, 2003).

1.1. Developmental EEG studies of reward feedback

To date, the results of ERP studies on age-related feedback effects suggest that FRNs are generally greater in magnitude in younger groups (10–12 vs. 19–24 years, Eppinger, Mock, & Kray, 2009; 9–11 vs. 13–14, 30–40, 65–75 years, Hämmerer, Li, Müller, & Lindenberger, 2011; 10–12, 13–14 vs. 15–17 years, Crowley et al., 2013; 14–17 vs. 22–26 years, Zottoli & Grose-Fifer, 2012). Some studies suggest greater differentiation of ERP responses for positive vs. negative outcomes across development (Hämmerer et al., 2011; Zottoli & Grose-Fifer, 2012). There is also some evidence that FRN latency decreases from childhood through adolescence (Crowley et al., 2013; Zottoli & Grose-Fifer, 2012). However, ERP studies have not documented any adolescent-specific reward processing changes at the level of the FRN.

An important issue that can affect the magnitude of the FRN across a task is whether or not the task involves learning. Müller and colleagues (Müller, Möller, Rodriguez-Fornells, & Münte, 2005) observed that as participants learn the mapping of choices and outcomes, they come to rely less on the external feedback and more on internal error awareness. In their age-based studies, Eppinger et al. (2009) and Hämmerer et al. (2011) speculate that in learning tasks, children show larger FRNs than do older groups due to a greater reliance on external feedback cues as opposed to internal representations of feedback emerging from learning. However, in a chance-based (non-learning) reward feedback task, in a large sample ($n = 91$), Crowley et al. (2013) observed reductions in FRN magnitude across 10–17 years. Thus, age differences in FRN amplitude, which do seem to be reliable, are not necessarily a function of learning. More recently, investigators have begun to look to EEG oscillations associated with reward feedback processing (Cavanagh, Frank, Klein, & Allen, 2010; Cavanagh, Zambrano-Vazquez, & Allen, 2012; Cohen, Elger, & Ranganath, 2007), but only in adult samples.

1.2. EEG oscillatory dynamics and reward processing

One important consideration regarding ERPs such as the FRN is that they are computed as the average signal across time-locked trials. Hence, ERPs inevitably only capture the stimulus- or response-driven partial phase alignment and power increases in the ongoing EEG brought about by the event (Le Van Quyen & Bragin, 2007; Sauseng et al., 2007). While this fixed-latency average amplitude approach has utility, it discards important information about task-relevant EEG oscillatory dynamics that may be important for interrogating the neurophysiology of reward processing (see Cohen, 2011). Using an approach broadly conceived as event-related brain dynamics (Makeig, Debener, Onton, & Delorme, 2004), advanced signal processing techniques such as short-time Fourier and wavelet transform can investigate the EEG signal in terms of frequency, power and phase. Importantly, characterizing oscillatory dynamics in this way probably more closely reflects the activity of underlying neuronal assemblies (Buzsáki, 2006).

Event time-locked frequency analyses of EEG allows for the measurement changes in EEG power and phase synchrony, across trials, on a millisecond time scale. In particular, event-related spectral perturbation (ERSP) is a temporally sensitive index of the relative change of mean EEG power from baseline associated with

stimulus presentation or response execution. Unlike ERPs, ERSPs capture changes in spontaneous EEG activity that occurs across several frequency spectra and are sensitive to fluctuations that are temporally stable, but not coherent in phase angle (Makeig, 1993; Makeig et al., 2004). Although ERSPs are able to capture induced power changes, which are not revealed in typically averaged ERPs, they do not reveal details about the coherence in phase angle of the event-related EEG signals.

Inter-trial coherence (ITC) can be used to assess the extent to which EEG oscillations become phase aligned following feedback. Thus, ITC reflects the extent to which a specific task event (e.g., stimulus or response) generates changes in phase synchrony (or induces phase re-setting) of ongoing oscillations across frequency spectra. Analogous to a correlation coefficient, ITC values refer to the degree of association across trials, ranging from zero to one. ITC allows for the assessment of millisecond-to-millisecond fluctuations in partial phase synchrony induced by experimental events, independent of changes in EEG power (Makeig et al., 2004). ITC is assessed at a single location or region and thus reflects "temporal coherence," to be distinguished from "spatial coherence" assessed across brain regions.

Converging evidence suggests that performance monitoring processes associated with activation of the medial frontal cortex are reflected in a common oscillatory substrate in the theta rhythm (4–8 Hz) (Cavanagh et al., 2010; Cavanagh, Zambrano-Vazquez, et al., 2012; Cohen et al., 2007). For instance, several groups have now documented greater theta power and phase coherence for loss feedback compared to gain feedback (Cavanagh, Zambrano-Vazquez, et al., 2012; Cohen, Elger, & Fell, 2009; Cohen et al., 2007; Marco-Pallares et al., 2008). Despite a growing body of work on the family of frontal oscillations, reward/feedback processing studies have only focused on adult samples.

1.3. The present study

Here we examine age differences in theta oscillations for reward vs. non-reward feedback from middle childhood through adolescence across three groups of children, 10–12 years, 13–14 years, and 15–17 years. To our knowledge there are no published studies examining oscillatory aspects of reward feedback processing in children or adolescents. In reward feedback studies with adults, researchers typically average across the 4–8 Hz frequency range relying on a preselected temporal window reflecting visual inspection of a time/frequency plot or the peak amplitude of the ERP. Importantly, these decisions regarding a preselected frequency range and time window in averaged data may obscure the actual frequencies, timing and potential markers of subcomponent processes that reflect age differences in reward processing. We address this issue directly with a fine-grained examination of the theta band, moment by moment over the course of reward feedback processing. To this end we examined EEG oscillatory activity at 0.5 Hz increments and 16 ms time windows, relying on false discovery rate (FDR) methods to control for multiple comparisons. We draw on work in the field of functional magnetic resonance imaging (fMRI), where high-dimensional data create the potential for many statistical comparisons to be made and investigators have increasingly relied on FDR procedures (Benjamini & Hochberg, 1995; Benjamini, Krieger, & Yekutieli, 2006; Benjamini & Yekutieli, 2001) to control type I error rates. These approaches are just beginning to take hold in EEG research (Crowley, Wu, McCreary, Miller, & Mayes, 2012; Groppe, Urbach, & Kutas, 2011; Lage-Castellanos, Martinez-Montes, Hernandez-Cabrera, & Galan, 2010).

We hypothesized that complex wavelet frequency decomposition would show that EEG responses to non-rewards vs. rewards would be associated with enhanced power and phase coherence