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Research report

Medial frontal theta dissociates unsuccessful from successful avoidance and is modulated by lack of perseverance

Stefon J.R. van Noordt[a], Jia Wu[a], Caleb Thomas[b], Michael W. Schlund[c,d], Linda C. Mayes[a], Michael J. Crowley[a,*]

[a] Yale Child Study Center, Yale School of Medicine, New Haven, CT, United States
[b] Brown University, Providence, RI, United States
[c] Department of Psychology, Georgia State University, Atlanta GA, United States
[d] Department of Psychiatry, University of Pittsburgh, Pittsburgh, PA, United States

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ABSTRACT

Medial frontal activity in the EEG is enhanced following negative feedback and varies in relation to dimensions of impulsivity. In 22 undergraduate students (M_{age} = 18.92 years, range 18–22 years), we employed a probabilistic negative reinforcement learning paradigm in which choices to avoid were followed by cues indicating successful or unsuccessful avoidance of an impending aversive noise. Our results showed that medial frontal theta power was enhanced following a cue that signaled avoidance was unsuccessful. In addition, self-reported lack of perseverance, a dimension of impulsivity characterized by an inability to maintain focus and determination during a challenging task, was negatively correlated with medial frontal theta elicited to an unsuccessful avoidance cue. We also observed robust differences in alpha attenuation and beta modulation following unsuccessful avoidance cue presentation. To our knowledge, this is the first study in humans to show a functional relation between medial frontal theta modulation and avoidance success. We discuss our findings in the context of frontal theta and self-regulation, negative reinforcement, and anxiety.

1. Introduction

Aversive or harmful outcomes similarly motivate avoidance in both humans and non-humans. Reinforcement learning involves incorporating feedback such that unsuccessful outcomes facilitate the avoidance of similar future negative consequences (Carey et al., 2014; Cavanagh et al., 2010; Cohen and Ranganath, 2007; Ullsperger et al., 2014). These avoidance behaviors are negatively reinforced when the probability of contacting the aversive outcome is reduced, which can provide a measure of relief from aversive states, such as anxiety and distress. The impact of negative reinforcement on avoidance is also thought to vary with individual differences in impulsivity and response strategies (Berg et al., 2015; Keough et al., 2016; Koob, 2013). A large body of empirical evidence from animal studies indicates that theta rhythms are perturbed during negative reinforcement learning and avoidance of aversive stimuli in anxiety provoking contexts (Adhikari et al., 2010; Calhoon and Tye, 2015; Gordon, 2011; Stark et al., 2007). Although work in humans broadly links theta oscillations to self-regulation (Cohen and Cavanagh, 2011; Cohen and Donner, 2013; van Noordt et al., 2016; van Noordt et al., 2017; van Noordt et al., 2015a,b), few, if any studies, examine theta dynamics for successful vs. unsuccessful avoidance of aversive outcomes during reinforcement learning in humans, or how these relate to individual differences in affective impulsivity.

1.1. Theta and aversive conditioning in animals

Theta refers to rhythms of neural activity that oscillate in the approximate range of 4–8 Hz. Animal work provides direct evidence that theta rhythms are modulated by aversive stimuli and enhanced during negative reinforcement learning. In particular, findings suggest that hippocampal and medial prefrontal theta interactions reflect neural mechanisms supporting behavioral learning and working memory (e.g., Berry and Seager, 2001; Calhoon and Tye, 2015; Gordon, 2011). For example, theta is enhanced during the learning/acquisition phase of aversive tone-shock conditioning (Stark et al., 2008) and increased synchrony between frontal and hippocampal theta is observed in stress inducing environments (Adhikari et al., 2010). As well, increased theta is

* Corresponding author at: Yale Child Study Center, 230 South Frontage Rd., New Haven, CT 06473, United States.
E-mail address: michael.crowley@yale.edu (M.J. Crowley).

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predictive of learning and successful avoidance of aversive/threatening stimuli (Adhikari et al., 2010; Stark et al., 2007). Findings converge on the idea that frontal theta dynamics are associated with motivation to avoid aversive stimuli. These animal models provide an excellent framework for translational neuroscience and understanding how theta dynamics may underlie avoidance and aversive outcome processing in humans.

1.2. Frontal midline theta in humans

Similar to the animal literature, human work also shows that the medial frontal cortex generates theta rhythms (Asada et al., 1999; Cristofori et al., 2013; Ishii et al., 1999) and several event-related potentials (ERPs) that oscillate in the theta range (van Noordt et al., 2016). These ERPs and their theta signature are found across various paradigms that exploit cognitive control, emotional reactivity, and feedback processing (McNaughton et al., 2013; Neo and McNaughton, 2011). Relevant to outcome processing and reinforcement learning is the feedback-related negativity (FRN), an ERP component emerging approximately 200–400 ms following feedback stimuli that is characterized by enhanced theta-band activity. The FRN is typically larger for negative, undesirable, or unexpected outcomes (Cohen et al., 2007; van der Molen et al., 2017). The FRN and theta have also been linked to distress during the anticipation of threats (e.g., preparing a public speech; Osinsky et al., 2017), state and trait negative affect (Riepl et al., 2016; Santesso et al., 2011), and the proclivity to avoid aversive or risky outcomes (Cavanagh and Shackman, 2014; Chen and Wallraven, 2017). Taken together, the FRN and its theta signature are markers of reinforcement learning processes. Despite a strong conceptual basis, there is little work to date linking theta to unsuccessful avoidance and individual differences in the tendency avoid negative affect in the face of aversive outcomes (e.g., rash impulsivity).

1.3. Impulsivity, negative reinforcement, and FRN/theta

Emerging work highlights associations between impulsivity and individual differences in the proclivity to avoid aversive stimuli, which may be viewed as a bias toward negative reinforcement. Impulsivity has been defined as behavior without adequate thought, the tendency to act with less forethought than do most individuals of equal ability and knowledge, or a predisposition toward rapid, unplanned reactions to internal or external stimuli without regard to the negative consequences of these reactions (International Society for Research on Impulsivity). Several studies document that facets of impulsivity contribute to decision-making under stress. Impulsivity can have a range of cognitive and affective psychological correlates within the aversive impulsive domain, including negative urgency (tendency to act rashly when distressed), lack of perseverance (inability to remain focused on task), and lack of premeditation (tendency to act rashly without regards to consequences). These aspects of impulsivity are linked to real-world addictive and impulsive behaviors including smoking, alcohol consumption (Keough et al., 2016), and non-suicidal self-injury. In particular, negative affect following smoking cue exposure has been linked to negative urgency and sensation seeking (Doran et al., 2008), with smokers demonstrating greater expectations about the negative reinforcing properties of smoking (Guillot et al., 2014). Similarly, negative urgency and lack of premeditation predict group membership in daily and non-daily smokers, respectively (Lee et al., 2015). In another line of work, negative urgency and lack of perseverance predict the onset and maintenance, respectively, of non-suicidal self-injury in college women (Riley et al., 2015). Both of these types of real-world impulsive behavior are thought to reflect strong affect reduction motives (i.e., negative reinforcement; (Baker et al., 2004; Nock, 2010). Thus, the interplay between impulsivity and negative reinforcement has direct implications for real world decision-making, yet brain correlates of these processes, particularly at the level of EEG dynamics, have yet to be fully delineated.

Some recent work attempts to tease apart the associations between reinforcement, impulsivity, and FRN/theta EEG dynamics. In the context of reinforcement learning, several researchers report that FRN amplitude and theta-band activity predict the adjustment of behavior following undesirable/incorrect feedback (Cavanagh et al., 2010; Cohen et al., 2007; Luft et al., 2013; Ma et al., 2015; Ullsperger et al., 2014; Walsh and Anderson, 2012) (see also Li et al., 2016). Individuals who are highly impulsive typically have difficulty controlling their behavior and show different reinforcement learning and feedback processing compared to those lower in impulsivity. For example, individuals scoring high on risk-taking (Massar et al., 2012), non-planning impulsivity (Onoda et al., 2010; Yamaguchi et al., 2011), and trait surgency (Segalowitz et al., 2012) show FRN amplitude attenuation to feedback. Other work shows that frontal theta during the FRN is attenuated in persons with, or at risk of, impulsive control problems (e.g., alcoholics; Kamarajan et al., 2015). This reduced medial frontal activation suggests that individuals scoring high on dimensions of impulsivity are less sensitive to punishment (Potts et al., 2006) and less capable of adjusting behavior in the face of variable reward contingencies (Franken et al., 2008). Similar patterns have been reported for medial frontal theta, such that theta power is attenuated during response inhibition in persons with trait impulsivity (Pandey et al., 2016). In addition, converging EEG and fMRI data show that frontal theta to loss outcomes engages medial frontal circuitry (Andreou et al., 2017) and is negatively correlated with motor impulsivity (Leicht et al., 2013), suggesting that loss/punishment-related theta plays a role in reinforcement learning (De Pascalis et al., 2012).

1.4. Current study

The goal of the current study was to examine the role of frontal theta dynamics in relation to successful and unsuccessful avoidance of outcomes in the Annoying Noise Task (ANT), and whether frontal theta dynamics relate to dimensions of impulsivity. This report follows up on our previous analysis that focused on the time-domain activation associated with the FRN (Crowley et al., 2009). In our previous study we found that the FRN and frontal slow-wave activity was enhanced following unsuccessful avoidance cues (i.e., aversive) compared to successful avoidances cues (i.e., escape). The current study aims to extend our previous findings by considering the spectral properties of feedback processing, specifically focusing on event-related spectral perturbations (ERSPs) of theta following successful and unsuccessful avoidance. We expected to find that cues signaling unsuccessful avoidance of an impending aversive stimulus would elicit greater medial frontal theta power compared to cues indicating successful avoidance. In addition, we expected that theta modulation would vary as a function of self-control reflected in dimensions of impulsivity (i.e., negative urgency, lack of perseverance, lack of premeditation, and sensation seeking, defined earlier).

2. Results

2.1. ERSP

Fig. 1 shows that condition differences in spectral power were in line with our prediction that medial frontal theta would be enhanced following unsuccessful (left, middle) compared to successful avoidance (left, top) cues.