Bringing in the negative reinforcements: the avoidance feedback-related negativity

Michael J. Crowley, Jia Wu, Christopher A. Bailey and Linda C. Mayes

The feedback-related negativity (FRN) is an event-related potential thought to reflect a reward prediction error, when an outcome is worse than expected. Behavior motivated by the avoidance of negative outcomes is sustained through negative reinforcement processes. Escaping or avoiding a negative outcome may be successful or not, resulting in an analogous situation to that which elicits the FRN. We observed that when expected avoidance of an aversive outcome fails to occur, there occurs a negative deflection in the frontocentral event-related potential at approximately 350 ms, but with a slow wave following. We suggest that the FRN may be considered an index of a broader class of reward-based learning that also includes avoiding negative outcomes as well as expecting positive ones. ***NeuroReport*** **00:000–000 © 2009 Wolters Kluwer Health | Lippincott Williams & Wilkins.**

NeuroReport 2009, **00**:000–000

Keywords: avoidance learning, event-related potential, feedback negativity, negative reinforcement

Yale Child Study Center, Yale School of Medicine, New Haven, Connecticut, USA

Correspondence to Dr Michael J. Crowley, PhD, Yale Child Study Center, 230 South Frontage Road, New Haven, CT 06473, USA
Tel: +1 203 785 5786; fax: +1 203 785 7926;
e-mail: michael.crowley@yale.edu

Received 6 June 2009 **accepted** 22 June 2009

Introduction

Negative reinforcement refers to behaviors that are learned and maintained to minimize or eliminate the occurrence of aversive events. The range of behaviors maintained by avoiding aversive stimuli spans basic needs (predators), social threats (enemies), mundane external aversive events (fire alarms, nagging, an itch) and aversive internal emotional states (anxiety, negative affect). Common to positive reinforcement and negative reinforcement is the idea that an action will lead to an outcome, which may be a desired result, or worse than expected. Humans generally rely on feedback (internal or external) about outcomes to improve performance.

A considerable body of work with event-related potentials (ERPs) has recently focused on performance monitoring brain responses [1]. ERP studies find a negative deflection in response-locked ERP, the response error-related negativity (response ERN) occurring approximately 120 ms posterror in choice reaction time tasks [2,3]. A similar ERP, the feedback error-related negativity [feedback ERN or feedback-related negativity (FRN)] occurs at approximately 250–300 ms when feedback to the participant indicates that predicted or expected rewards will not occur [4]. Studies find a frontocentral scalp distribution for the ERN/FRN and source localization studies consistently show that the error-related brain activity for behavior feedback can be best accounted for by a neural generator in the anterior cingulate cortex (ACC) [5,6], converging with event-related functional MRI data [7].

Drawing on work documenting the role of the basal ganglia and the midbrain dopamine system in feedback-based learning [8], Holroyd and Coles [9] proposed a reinforcement learning theory (RLT) to account for both the ERN and the FRN. According to RLT, the mesencephalic dopamine system relays an error signal to the ACC, where it is used to improve performance. The ACC-associated neural electrical activity is detectible at the scalp. Specifically, the impact of dopamine signals on the ACC modulates the amplitude of the ERN – with outcomes worse than expected leading to phasic decreases in dopamine activity and large ERNs and outcomes better than expected producing the opposite effect.

Most ERP studies that focus on reward processing and feedback monitoring involve instrumental behaviors that lead to positive or negative feedback about rewards or positive outcomes. However, a substantial amount of human behavior is motivated not by obtaining positive outcomes, but by avoiding negative ones. In turn, an action to avoid a negative outcome may be successful or not, leading to a prediction error. Emerging neuroimaging work in humans suggests that both appetitive and aversive prediction errors are represented in the striatum, a key basal ganglia structure [10,11]. Thus, not only does the idea of 'outcome worse than expected' fit conceptually across positive and negative reinforcement processes, some common neural circuitry seems to underlie positive and negative prediction errors. Yet, the FRN for aversive outcomes has not been studied. Thus, in this report we compare ERPs for feedback indicating successful versus unsuccessful avoidance of an aversive noise, expecting that unsuccessful avoidance would produce an FRN.

0959-4965 © 2009 Wolters Kluwer Health | Lippincott Williams & Wilkins DOI: 10.1097/WNR.0b013e32832ff2f5

Copyright © Lippincott Williams & Wilkins. Unauthorized reproduction of this article is prohibited.

Methods

Participants

The sample consisted of 22 undergraduate students, aged 18–22 years (eight female) who participated for course credit. The mean age was 18.92 (SD = 1.10). The Edinburgh Handedness Inventory [12] identified one left-handed participant. Participant ethnic backgrounds were as follows: African-American ($n = 3$), Hispanic ($n = 1$), Asian ($n = 3$), Caucasian ($n = 15$). The Human Investigation Committee of the Yale University School of Medicine approved this research and written informed consent was provided by each participant. Two participants were excluded because of data artifact (one male).

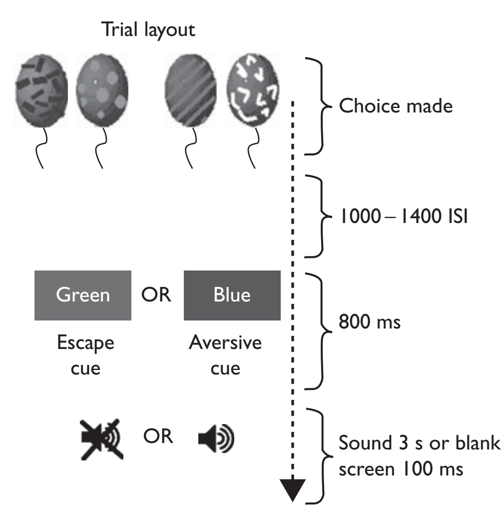
Procedure

Each participant sat 60 cm from a 19-inch LCD monitor in a dimly lit (60 w bulb) sound-attenuated room. They were instructed to minimize blinks while responding on a four-button response pad with both hands (left and right middle and index fingers).

Annoying Noise Task

The Annoying Noise Task is a negative reinforcement task for studying prediction errors in avoidance of aversive sounds. The task consists of 10 blocks of trials. Each block of trials begins with the aversive noise to be avoided for that block. Three types of 75 dB noises are played, (alarm × 3, white noise × 3, baby cry × 4; random order) from a speaker positioned 193 cm from the floor and 70 ± 5 cm above the participant. A row of four colored balloons appear randomly across a screen from trial to trial (Fig. 1). Balloons remain the same within block, changing across blocks (from a set of 16). Balloons stay on the screen until one is chosen. After a balloon is chosen, the screen is blank for 1000–1400 ms (ISI). Next, one of two cues is presented for 800 ms. An aversive cue (e.g. green) indicates a noise will occur; an escape cue (e.g. blue) indicates the noise will not occur. Cue color identity is counterbalanced across participants. Following the escape cue is a blank screen lasting 100 ms and following the aversive cue is a noise lasting 3 s.

Fig. 1



The Annoying Noise Task (ANT). The trial layout for the timing of each of the ANT trials.

Each block of trials consists of a Learning Phase and a Prediction Error Phase. During the Learning Phase, the participant discovers the 'correct balloon' for avoiding the noise. Initially, this balloon is 100% effective; other balloons are 100% ineffective. The Learning Phase continues until the 'correct balloon' has been chosen four times consecutively, at which point the Prediction Error Phase seamlessly begins. In this phase, the correct balloon becomes approximately 64% (range 59–71%) effective for avoiding the noise. An unsuccessful escape is defined as choosing the correct balloon, but receiving the aversive cue followed by the aversive sound; a successful escape is defined as choosing the correct balloon and receiving the escape cue (no sound). The number of unsuccessful escapes varies across the 10 blocks (range 5–7), 60 in total. The task consists of approximately 280 trials across all blocks (approximately 50 learning, approximately 170 escape, approximately 60 aversive), varying based on participant performance and chance. ERPs are derived only for trials on which the participant chose the correct balloon, time-locked to the escape cue or the aversive cue (60 possible aversive cue trials and 60 selected escape cue trials).

Electrophysiological methods

Each participant's head circumference was measured to determine the appropriate electroencephalogram net size and to mark Cz. Next, a high-density array Geodesic Sensor Net (GSN) of 128 Ag/AgCl electrodes (Electrical Geodesics Inc., Eugene, Oregon, USA) soaked in warm potassium chloride (KCl) electrolyte solution was placed on the participant's head using standard procedures. The filters were set at 1–30 Hz. Brain wave data were recorded through the Nestation v.4.0 software package (Electrical Geodesics Inc.) and EGI high impedance amplifiers, sampled at 250 Hz. All electrodes were referenced to Cz for recording. All impedances remained at or under 40 kΩ as indicated by impedance measures made immediately before and after the test session. EGIS v.4.2.1 (Electrical Geodesics Inc.) and E-prime v.1.2 (Psychology Software Tools, Pittsburgh, Pennsylvania, USA) software packages controlled the stimulus presentation.

Each ERP epoch included a 100-ms prestimulus baseline and an 800-ms poststimulus interval. Artifact rejection was carried out to eliminate ERPs contaminated by movement and eye artifacts. Rejection rates were comparable across stimulus conditions. Data from electrodes

Copyright © Lippincott Williams & Wilkins. Unauthorized reproduction of this article is prohibited.

identified with poor signal quality (50% or more of the trials) were replaced using spherical spline interpolation. For data to be included in the analyses, a total of no more than 20 channels could be interpolated. Averaged data were baseline-corrected by subtracting the average microvolt value across the 100-ms prestimulus interval from the post-stimulus segment. After artifact rejection, the single trial data were re-referenced from the vertex (Cz) to an average reference of all electrodes. The trial by trial data were then averaged separately for each of the 128 electrode sites and each of the two stimulus conditions (escape cue, aversive cue).

Results

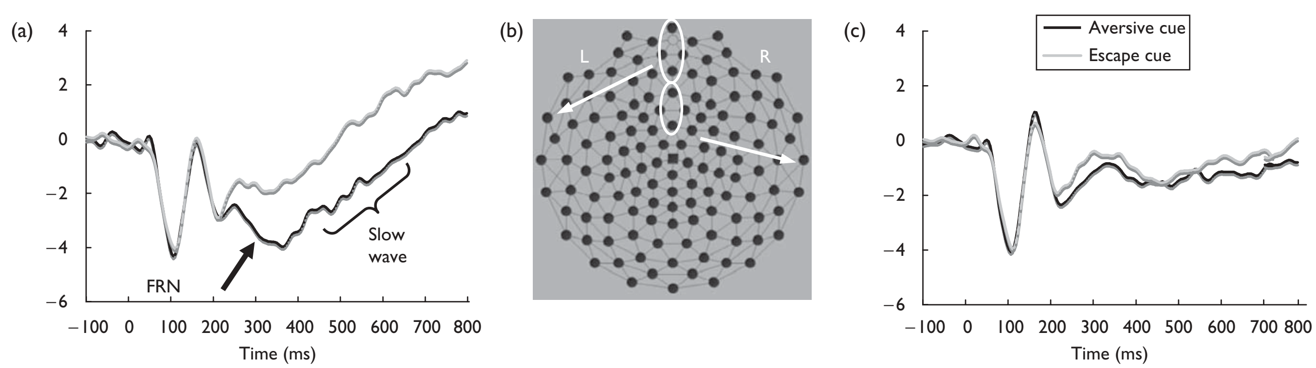
In line with earlier research with positive reinforcement and the FRN, we examined anterior midline electrodes (Fig. 2b). For reference, we use GSN electrode numbers and 10–20 system nomenclature here (e.g. the 10–20 system electrode Fz is listed as #11).

The average ERPs from two medial frontal electrodes corresponding to fCz (#6) and Fz (#11) (Fig. 2b, bottom oval) and two midline electrodes anterior to these, AFz (#16) plus GSN electrode #17, (Fig. 2b, broken oval) were compared for successful and unsuccessful escape from an aversive sound. Figure 2a displays the average ERPs for these two anterior frontal pairs of electrodes. A clear frontal negativity is visible at the more anterior site at approximately 350 ms for the aversive cue, with a slow wave following. The ERP for less anterior site (Fig. 2c, Fz/fCz) did not reflect a negativity or slow wave. ERP data were submitted to a two-step analysis procedure that applied a temporal principal components analysis (PCA) to window the ERP data in time, following Dien *et al.* [13]. Next, mean voltage values resulting from the PCA-derived windows for the average ERPs (#6, #11 and #16, #17) were examined with a repeated-measures analysis of variance (ANOVA), followed by a set of univariate ANOVAs. All analyses were performed using the SPSS v.16 software package (SPSS Inc., Chicago, Illinois, USA).

Temporal PCA with varimax rotation yielded three components. Factor 1 accounted for of the 52.62% variance and consisted of a negative slow wave, time interval 404–800 ms (peak time: 780 ms) persisting after the negativity. Factor 2 accounted for 15.25% of the variance and consisted of a negativity (200–568 ms peak time: 364 ms). Factor 3 accounted for: 10.25% and appeared as an N1–P1 complex within a 108–176 ms time interval (peak time: 148 ms). Mean voltage data were analyzed with repeated measures ANOVAs and all F-tests reported with Greenhouse–Geisser correction [14]. Repeated-measures ANOVAs consisted of an ANOVA, condition $(2) \times$ frontal site (2) for the ERP voltage from each component window (separately for Factor 1, Factor 2, and Factor 3).

The slow wave (factor 1) yielded a main effect of condition, $F(1,19) = 16.87$, $P < 0.005$, partial $\eta^2 = 0.47$, a main effect of anteriority, $F(1,19) = 8.06$, $P < 0.05$, partial $\eta^2 = 0.30$, and a condition $\times$ anteriority interaction, $F(1,19) = 10.21$, $P < 0.01$, partial $\eta^2 = 0.35$. Post-hoc comparisons indicated an effect at the anterior midline channels (#16 and #17), with the aversive cue producing a significantly more negative amplitude slow wave than the escape cue, $t(21) = -4.07$, $P < 0.005$, (mean $= -1.03$ vs. $1.15\,\mu V$). The posterior frontal channels at Fz/fCz channels (#11 and #6) produced no significant difference between aversive cue and the escape cue, $t(21) = -1.59$, NS (mean $= -1.22$ vs. $-0.811\,\mu V$).

Fig. 2



Event-related potentials (ERPs) and electrode layout for frontal midline sites. Electrodes are referenced with Geodesic Sensor Net (GSN) and 10–20 system nomenclature. (a) Displays ERPs for the aversive cue (black) and escape cue (gray) at the anterior frontal region [the average of channel AFz (#16) and (#17)]. The feedback-related negativity can be seen for the aversive cue in (a), but is absent in (c). Similarly, a slow wave is apparent for the aversive cue in (a), but is absent in (c). (b) Displays the layout for a 128-electrode net (EGI GSN 128 2.1), frontal midline regions marked with white ovals. The top oval corresponds to AFz (#16) and the midline electrode anterior to that (#17). The bottom oval corresponds to site Fz (#11) and fCz (#6). (c) Displays ERPs for the aversive cue (black) and escape cue (gray) at the less anterior frontal region [the average of channel Fz (#11) and channel fCz (#6)].

Copyright © Lippincott Williams & Wilkins. Unauthorized reproduction of this article is prohibited.

The frontal negativity (factor 2) yielded a main effect of condition, $F(1,19) = 13.017$, $P < 0.005$, partial $\eta^2 = 0.41$, a main effect of anteriority, $F(1,19) = 4.99$, $P < 0.05$, partial $\eta^2 = 0.208$, and a condition $\times$ anteriority interaction, $F(1,19) = 9.86$, $P < 0.01$, partial $\eta^2 = 0.34$. Post-hoc comparisons indicated an effect at the anterior channels (#16, #17), with the aversive cue producing a significantly more negative mean amplitude than the escape condition, $t(21) = -3.76$, $P < 0.005$ (mean $= -2.82$ vs. $-1.082\,\mu V$) at the more anterior midline channels (#16 and #17). The posterior frontal channels at Fz/fCz channels (#11 and #6) produced no significant difference between the aversive and the escape condition, $t(21) = -1.627$, NS (mean $= -1.44$ vs. $-1.07\,\mu V$).

Factor 3 showed no effect of condition, $F(1,19) = 0.002$, NS, $\eta^2 < 0.001$, a main effect of anteriority $F(1,19) = 5.73$, $P < 0.005$, partial $\eta^2 = 0.23$, with anterior channels producing a greater negative amplitude than posterior channels (mean $= -1.81$ vs. $-1.36\,\mu V$). The condition $\times$ anteriority interaction was not significant, $F(1,19) = 0.93$, NS, partial $\eta^2 = 0.05$.

Discussion

In this study, participants received feedback about successful and unsuccessful avoidance of an aversive noise. We conducted an analysis of frontal midline sites leading to two main findings. First, a negative deflection in the ERP in response to a cue reflecting an unsuccessful escape (aversive cue), emerged at approximately 350 ms. Analyses of the frontal midline region indicated that the FRN for aversive feedback was more anterior than that typically observed in nonreward or loss with positive reinforcement studies – the effect was nonsignificant for the average of the cites Fz and fCz. Second, we observed a positive going slow wave difference for the escape cue vs. the aversive cue, which was more negative for the aversive cue. This slow wave effect has not been reported to follow the FRN in positive reinforcement work and seems to be specific to the FRN for an aversive outcome.

Overall, our results are in agreement with our proposal that unsuccessful avoidance of an aversive outcome produces a frontal negativity similar to the FRN for an expected reward. In turn, our data suggest that much like positive reinforcement, a similar process may be indexed for negative reinforcement at the level of the ERP. By extension, the RLT of Holroyd and Coles [9] might also be broadened to include negative reinforcement and prediction errors involving escape and avoidance. Neuroimaging work has already linked prediction errors for rewards to the striatum (e.g. Refs [15,16]), and recent studies have now linked the striatum to prediction errors for aversive outcomes with primary negative reinforcers (shocks) [11] and secondary negative reinforcers (monetary loss) [10]. However, the more anterior effect we observed for aversive feedback suggests that possibly a more anterior portion of the ACC or other frontal region could involved in prediction errors for aversive outcomes. Findings by Kim and colleagues [17] are consistent with this possibility. In a neuroimaging study of reward and avoidance of loss they asked 'Is avoiding an aversive outcome rewarding?' They observed that activity in the medial orbitofrontal cortex increased for both avoiding an aversive outcome and receiving a reward, but decreased during receipt of an aversive outcome and failure to obtain a reward. Future work with ERP source modeling and other imaging techniques will be needed to resolve the cortical neural generator(s) of the FRN for aversive outcomes.

Finally, emotional stimuli are known to elicit a sustained positive deflection in the ERP referred to as the late positive potential (LPP). The LPP is a positive wave occurring roughly 250 ms following stimulus onset. The LPP responds to the intensity of emotional stimuli, increasing for positive and negative compared with neutral stimuli [18] suggesting that it reflects perceptual and/or attentional processing of emotional content [19]. Although we did not predict an LPP effect in this study, based on the extant literature, this effect could have been expected for the aversive cue. Feedback monitoring studies with rewards typically do not show an LPP effect, but the reward symbol or nonreward symbol in these studies does not communicate any information about a future event. In contrast, our study used a cue, which predicted the occurrence of an impending aversive, and probably encouraged sustained attention for a future outcome.

Conclusion

In this study, we found that when participants sought to avoid an aversive sound, feedback indicating their attempt was unsuccessful led to a frontal negativity with a similar onset to the FRN for nonreward, though slightly later (approximately 250 vs. 350 ms), possibly more anterior cortically, and with a late positive slow wave following.

Acknowledgements

This research was supported by the NARSAD Young Investigator Award (M.J.C.); NIDA grants RO1-DA-06025 (L.C.M.), DA-017863 (L.C.M.) and KO5 (L.C.M.), and a grant from the Gustavus and Louise Pfeiffer Research Foundation (L.C.M.). The authors are thankful to David Reiss, MD for his comments on an earlier version of this manuscript and to Carl W. Lejuez, PhD, for discussions about negative reinforcement.

References

1 Gehring WJ, Fencsik DE. Functions of the medial frontal cortex in the processing of conflict and errors. *J Neurosci* 2001; **21**:9430–9437.
2 Falkenstein M, Hielscher H, Dziobek I, Schwarzenau P, Hoormann J, Sundermann B, *et al.* Action monitoring, error detection, and the basal ganglia: An ERP study. *Neuroreport: Rapid Commun Neurosci Res* 2001; **12**:157–161.

Copyright © Lippincott Williams & Wilkins. Unauthorized reproduction of this article is prohibited.

3 Gehring WJ, Goss B, Coles MG, Meyer DE, Donchin E. A neural system for error detection and compensation. *Psychol Sci* 1993; **4**:385–390.
4 Holroyd CB, Nieuwenhuis S, Yeung N, Cohen JD. Errors in reward prediction are reflected in the event-related brain potential. *Neuroreport: Rapid Commun Neurosci Res* 2003; **14**:2481–2484.
5 Gehring WJ, Willoughby AR. Medial prefrontal cortex and rapid processing of monetary gains and losses. *Science* 2002; **295**:2279–2282.
6 Dehaene S, Posner MI, Tucker DM. Localization of a neural system for error detection and compensation. *Psychol Sci* 1994; **5**:303–305.
7 Kiehl KA, Liddle PF, Hopfinger JB. Error processing and the rostral anterior cingulate: an event-related fMRI study. *Psychophysiol* 2000; **37**:216–223.
8 Schultz W, Tremblay L, Hollerman JR. Reward processing in primate orbitofrontal cortex and basal ganglia. *Cereb Cortex* 2000; **10**:272–283.
9 Holroyd CB, Coles MGH. The neural basis of human error processing: reinforcement learning, dopamine, and the error-related negativity. *Psychol Rev* 2002; **109**:679–709.
10 Delgado MR, Li J, Schiller D, Phelps EA. The role of the striatum in aversive learning and aversive prediction errors. *Philoso Trans Royal Soc London* 2008; **363**:3787–3800.
11 Schiller D, Levy I, Niv Y, LeDoux JE, Phelps EA. From fear to safety and back: reversal of fear in the human brain. *J Neurosci* 2008; **28**:11517–11525.
12 Oldfield RC. The assessment and analysis of handedness: the Edinburgh inventory. *Neuropsychologia* 1971; **9**:97–113.
13 Dien J, Tucker DM, Potts G, Hartry-Speiser A. Localization of auditory evoked potentials related to selective intermodal attention. *J Cogn Neurosci* 1997; **9**:799–823.
14 Greenhouse SW, Geisser S. On methods in the analysis of profile data. *Psychometrika* 1959; **24**:95–112.
15 O'Doherty JP, Dayan P, Friston K, Critchley H, Dolan RJ. Temporal difference models and reward-related learning in the human brain. *Neuron* 2003; **38**:329–337.
16 McClure SM, Berns GS, Montague PR. Temporal prediction errors in a passive learning task activate human striatum. *Neuron* 2003; **38**:339–346.
17 Kim H, Shimojo S, O'Doherty JP. Is avoiding an aversive outcome rewarding? Neural substrates of avoidance learning in the human brain. *PLoS Biology* 2006; **4**:e233.
18 Schupp HT, Cuthbert BN, Bradley MM, Cacioppo JT, Ito T, Lang PJ. Affective picture processing: The late positive potential is modulated by motivational relevance. *Psychophysiology* 2000; **37**:257–261.
19 Sabatinelli D, Lang PJ, Keil A, Bradley MM. Emotional perception: correlation of functional MRI and event-related potentials. *Cereb Cortex* 2007; **17**:1085–1091.

Copyright © Lippincott Williams & Wilkins. Unauthorized reproduction of this article is prohibited.