UNIVERSITY OF CALIFORNIA, MERCED

Violation of cognitive expectancy: An EEG account

A Thesis submitted in partial satisfaction of the requirements for the degree of Master of Science

In

Cognitive and Information Sciences

by

Adam John Holm

Committee in charge:

Professor Antoine Shahin, Chair
Professor Kristina Backer
Professor Carolyn Jennings

2022

The Thesis of Adam John Holm is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Kristina Backer

Digitally signed by Kristina Backer
Date: 2022.12.09 18:11:45 -08'00'

Kristina Backer

Carolyn Jennings

Antoine Shahin, Chair

University of California, Merced

2022

Table of Contents

List of Figures

Acknowledgements

I dedicate this thesis to my family, friends, and of course my fellow Lacanians Stephanie Gamino, Cody Moser, and New Aswamenakul. You were each crucial for my academic survival. To the other MS students, I salute you for facing and overcoming the additional challenges that come with being a program's first students. Special mention also goes to my advisory committee, I am grateful for the guidance and encouragement each one of you provided all along the way. This work was supported by National Institute of Deafness and Other Communications Disorders Grant R01 DC-013543 (A. J. Shahin).

Abstract

Violation of cognitive expectancy: An EEG account

by Adam John Holm for the partial satisfaction of the requirements for the degree of Master of Science in Cognitive and Information Sciences, University of California, Merced, 2022
Dr. Antoine Shahin, Chair

How do people process feedback that violates their expectations? To address this question, our study uses an auditory delayed match-to-sample task with a novel half-congruent, half-incongruent presentation of response feedback. We hypothesized that feedback-related surprise would have effects on event-related potential (ERP) amplitude and latency in a “dose-dependent” manner (largest effect on the easiest trials, smallest effect on the hardest). The resulting waveform was identified as the feedback-related negativity (FRN). While our hypothesis was not confirmed, the results were noteworthy. Despite the feedback’s visual nature, the scalp tomography was highly auditory. This suggests that the FRN may be partially generated in the auditory cortex. To the best of our knowledge, this is a new finding within the FRN literature.

Introduction

The study of error processing has revealed important insights into how cognition functions. While exploratory in nature, the current study is built upon the existing error procession literature. One important phenomenon is an event-related potential (ERP) known as the error-related negativity (ERN), a negative-amplitude waveform that peaks 50-150 ms after a participant makes an incorrect response on a reaction-time task (Falkenstein, Hohnsbein, Hoormann, & Blanke, 1991; Gehring, Goss, Coles, Meyer, & Donchin, 1993). The ERN is strongest in fronto-central channels, particularly FCz (for review, see Gehring, Liu, Orr, & Carp, 2012). Administering caffeine, offering performance-based rewards, or emphasizing the importance of accuracy are experimental factors known to elicit stronger ERN activity. ERN amplitude is insensitive to the sensory modality of trial stimuli (Holroyd & Coles, 2002).

The feedback-related negativity (FRN) is another ERP associated with error procession. While the ERN is elicited by making an incorrect response, the FRN is elicited by comprehension of feedback. It typically peaks around 200-300 ms after a participant receives negative feedback in a reaction-time task (Miltner, Braun, & Coles, 1997). In summary, the ERN and FRN represent different aspects of how the mind processes errors. The FRN also exhibits the same fronto-central focus as the ERN, though Miltner and colleagues showed that it has its own distinct scalp distribution. FRN amplitude is insensitive to the sensory modality of feedback stimuli (Miltner et al., 1997).

The FRN's cognitive role is a subject of ongoing debate. Botvinick, Cohen, & Carter (2004) claim that one function of the dorsal anterior cingulate cortex (dACC) is monitoring for conflicts in information processing (i.e., unexpected behavioral outcomes). This account of FRN function is known as conflict management. By this account, the dACC signals top-down cognitive processes to intervene via overriding the response, resolving the conflict. Other work (Holroyd & Coles, 2002) claims that the FRN is elicited by a dopaminergic system to encode reward prediction error in the brain. This account is known as reinforcement learning. At least one recent review (Sambrook & Goslin, 2015) supports this account of FRN function. However, the FRN is often measured inconsistently across studies (for a sampling of this diversity, see Bellebaum & Daum, 2008; Hajcak, Holroyd, Moser, & Simons, 2005; San Martin, Manes, Hurtado, Isla, & Ibañez, 2010; Walsh & Anderson, 2013; Yeung & Sanfey, 2004). Sambrook & Goslin argue that this is a serious difficulty for systematic review. Some work (Holroyd, Pakzad-Vaezi, & Krigolson 2008; Proudfit, 2014) argues that the FRN should instead be referred to as the reward positivity (RewP, or Pe). The rationale for this shift is succinctly summarized by Williams, Ferguson, Hassall, Abimbola, & Krigolson (2020). Originally, Miltner and colleagues (1997) showed that variance in FRN amplitude was driven by neural activity on incorrect trials. However, later work (Holroyd et al., 2008; Proudfit, 2014) indicated that the component's amplitude variance was actually driven by neural activity on correct trials. In other words, the FRN elicited by erroneous trials is essentially a diminished version of a phenomenon primarily occurring on correct trials. For simplicity's sake, all further mention will refer to this debated component as the FRN.

Our study uses these established ERP components as a springboard for a novel experimental paradigm. Until now, error studies have mostly employed congruent feedback measures, where correct responses receive "correct" feedback and vice versa.

Our study employs a novel split of congruent and incongruent feedback (for details, see the Procedure section of Methods). While our task emphasizes feedback recognition like many FRN studies, it differs from them by not implementing performance-driven gain/loss mechanics, such as a point counter for tallying correct responses. The presence of such mechanics is common in FRN studies (for review, see Sambrook & Goslin, 2015). Thus, instead of situating trial feedback within a broader goal-driven context, our study focuses simply on the participant's trial-to-trial recognition of feedback.

There are multiple possible hypotheses for this experiment. Given that the participant's expectations are being violated, we expect to find a neural correlate of that violation. Given this feedback-driven design, one possible correlate is the FRN. Another possible hypothesis is based on the three trial difficulty conditions. If neural activity (ERP/oscillatory activity) reflects feedback-related surprisal (i.e., being told that you were wrong when you were correct and knew you were correct, or vice versa), then the ERP amplitude/latency (and oscillatory power) should be observed in a "dose-dependent" manner – the effect being largest for the Easy condition, smallest for the Hard condition, and in between for the Intermediate condition.

Methods

Participants consisted of 15 neurotypical healthy individuals from the UC Merced student body (12 women, ages 18-30, right-handed with one ambidextrous exception). For each session, participants arrived individually at the laboratory and signed informed consent, approved by the research ethics Institutional Review Board (IRB) of the University of California, Merced. They then filled out forms screening for neurological disorders and hearing issues. Following informed consent, participants then underwent EEG testing using a 64-channel Biosemi system. Upon the experiment's conclusion, each participant was debriefed and informed of the experiment's previously undisclosed aspect, the trial feedback design. Participants were monetarily compensated.

The task was a delayed match-to-sample task utilizing pitch comparison. Participants were seated 42" away from a 26" Dell monitor in a sound-attenuated booth and given verbal instructions on the task. In addition, the same instructions were presented as onscreen text at the beginning of each block (see Appendix for full transcription). In each trial, participants heard two successive pure tones, responsive to tonal pitch via keyboard input following the second tone's presentation. Using their right hand, they pressed the up arrow if they believed the second tone was higher-pitched than the first, or the down arrow if they believed it was lower-pitched than the first. Catch trials consisting of animal pictures were included to ensure that participants were attentively watching the screen. If participants saw an animal picture, they pressed the space bar with their left hand. The keyboard remained in the participant's lap for the duration of each block. The researcher routinely checked in with participants between blocks to encourage them and re-gel channels if needed (ensuring maintenance of laboratory-standard impedance values, between -20 and 20 μV).

Auditory stimuli consisted of three 300 ms pure tones at the frequencies 400 Hz (medium-low pitched), 450 Hz (medium pitched), and 570 Hz (medium-high pitched). All were sampled at a rate of 48 kHz to match laboratory specifications. Audio was sent from the presentation PC to Yamaha HS8 speakers via an AME Fireface UFX II audio interface. Auditory stimuli was presented at 22 dB. All stimuli were delivered via Neurobehavioral Systems's Presentation software (version 22.1). A Biosemi ActiveTwo amplifier and software (Biosemi ActiView, version 7.07) were used to acquire EEG data.

Trials consisted of the six possible conditional pairings for these tones. Condition 1 was 400 Hz followed by 570 Hz and condition 2 was 570 Hz followed by 400 Hz (Easy conditions). Condition 3 was 450 Hz followed by 570 Hz and condition 4 was 570 Hz followed by 450 Hz (Intermediate conditions). Condition 5 was 400 Hz followed by 450 Hz and condition 6 was 450 Hz followed by 400 Hz (Hard conditions). Each block's introductory text instructed participants to watch the feedback and respond as quickly and accurately as possible. For the catch trials, 32 pictures of animals were exported from Hemera PhotoObjects software (company now defunct) for this purpose. Catch trials were presented for 200 ms in between auditory trials; each picture was presented once per session, for a total of 32 catch trials (2 in practice block, 30 in test blocks).

Each auditory trial consisted of two auditory stimuli, presented separately (see Figure 1). The first stimulus was presented for 300 ms, a 500 ms delay ensued, then the second stimulus was presented for 300 ms. The inter-trial interval (ITI) was jittered from 1500 to 2517 ms. Feedback was presented following participant response, response only being possible after the second stimulus's onset. The delay between response and feedback was jittered from 1000 to 1500 ms. Feedback ("Correct" or "Incorrect") was displayed for 1000 ms. Following that, the next trial would begin, in most cases. Otherwise, a catch trial was presented. Catch trials consisted of a 500 ms fixation cross following the previous trial's feedback, an animal picture being shown for 200 ms, then another 500 ms fixation cross before the ITI began.

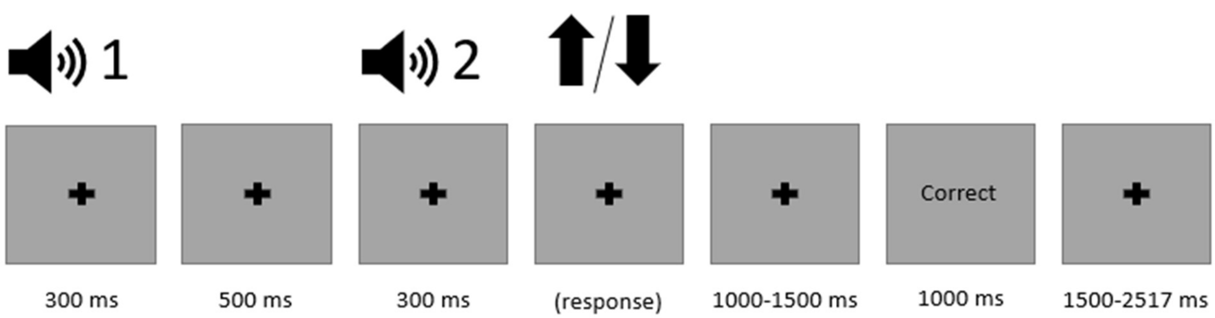

Fig. 1 A typical trial (presented with correct feedback, reflecting congruent-correct and incongruent-correct feedback conditions)

The practice block contained 26 trials, four of each stimulus condition and two catch trials. For this block only, all feedback was congruent. Upon completion, the researcher checked in to verify participant comfort and answer any questions. No practice data was incorporated into experimental analyses. Following the practice block, there were ten blocks with 60 trials each, a total of 600 trials. The order of task trials and feedback conditions were randomized for each participant. 50% of trials had congruent feedback (told "Correct" when response was correct, told "Incorrect" when response was incorrect) and 50% of trials had incongruent feedback (told “Incorrect” when response was correct, told “Correct” when response was incorrect). This 50-50 ratio was chosen to avoid eliciting a P300 oddball effect, which is known to be elicited by the minority trials of an 80-20 stimulus ratio. All four possible feedback conditions (congruent-correct, congruent-incorrect, incongruent-correct, incongruent-incorrect) were unaffected by the individual trial number or the participant’s behavioral response.

Each block contained ten trials per stimulus pairing. 30 catch trials appeared across all ten blocks. Three blocks had two catch trials, four blocks had three catch trials, and three blocks had four catch trials. Catch trials were constrained to prevent two occurrences within four consecutive trials, any occurrences within the first five trials of a block, and an occurrence after a block’s final trial. The number of catch trials per block, which trial numbers were designated as catch trials, and the order of animal images were all counterbalanced for each participant. Participants must have responded to at least 24 of the 30 catch trials for their data to be included (80% hit rate), a criterion fulfilled by all.

Analysis

All data were analyzed in MATLAB using EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) toolboxes. The following steps were taken for pre-processing the data. First, individual continuous BioSemi bdf files were loaded and epoched around trial feedback triggers from -2000 to 2000 ms. Second, each epoch was baselined to the mean of the entire epoch (subtracting the epoch’s mean from each data point). Third, the remaining files were subjected to independent components analysis (ICA) to identify ocular artifacts and bad channels. Fourth, ocular artifacts were removed and bad channels were interpolated for each individual file. Following pre-processing, individual files were firstly average referenced (subtracting the global signal average from each electrode). Second, they were bandpass filtered between .1 and 30 Hz (Butterworth filter of order of 4) to account for EEG’s frequency range. Third, they were re-epoched between -200 to 1000 ms. Fourth, epochs with an amplitude exceeding ±200 µV were rejected and re-baselined to the 200 ms pre-stimulus period. Fifth, congruent and incongruent trials were separated into different condition files for subsequent statistical analysis.

Individuals’ data for each condition were loaded into MATLAB and averaged across all epochs within each condition. Averaged files were then subjected to cluster-based permutation testing using the FieldTrip toolbox (Maris & Oostenveld, 2007; Oostenveld, Fries, Maris, & Schoffelen, 2011). This statistical method was chosen to address the problem of multiple comparisons (MCP), a leitmotif of EEG research. EEG signal is sampled at many locations and time points. Due to this high spatio-temporal correlation of the data, there is a high likelihood of obtaining false positive results if the MCP is not controlled for (Miljevic, Bailey, Vila-Rodriguez, Herring, & Fitzgerald, 2021). This is because the family-wise error rate (i.e., the false alarm rate) for such a dataset cannot be controlled with statistical methods designed for assessing individual channel-time pairs (i.e., the t-test). Cluster-based testing rests on the assumption that strong effects are prone to appear in continuous clusters. These clusters are based on univariate t-tests performed on each time-point within each electrode, comparing amplitudes between conditions. Time-points with a significant univariate p-value (< 0.05)

are grouped together if they occur at neighboring time-points and within neighboring channels. Neighboring channels were defined by FieldTrip's triangulation method. These were used to generate clusters, where univariate condition-based t-tests were performed (i.e., t-test at congruent-correct vs. incongruent-correct). Final cluster statistics were calculated as the sum of all t values for each cluster. To assess cluster-level significance, a nonparametric null distribution was made with a Monte Carlo approximation by repeating the above steps for 5000 random partitions (permutations) of the data, randomly shuffling labels for the four conditions (congruent-correct, congruent-incorrect, incongruent-correct, incongruent-incorrect). After each permutation, the null distribution was made with the maximum of the cluster-level test statistics. Conditional differences were considered significant if a cluster's Monte Carlo p-value was 0.05.

Results

We hypothesized that the experience of feedback-related surprise would lead to differences in effect size across trial difficulty conditions, largest for the Easy condition and smallest for the Hard condition. To the contrary, difficulty had no significant effect on the ERP results.

Figure 2 shows the grand-averaged ERP waveforms of the congruent (red) and incongruent (blue) feedback conditions. The waveforms represent the average across the fronto-central channels. The ERP shows a significant incorrectness-negativity effect between 300-400 ms, the FRN. Figure 3 shows the difference t-value topography. The stars represent individual channels, with greater thickness representing greater effect. A fronto-central focus is clear. Interestingly, the lateralized nature of this topography strongly suggests that even though the feedback was visual, the corollary brain activity is auditory in nature. This suggests that the current FRN is at least partly generated in the auditory cortex.

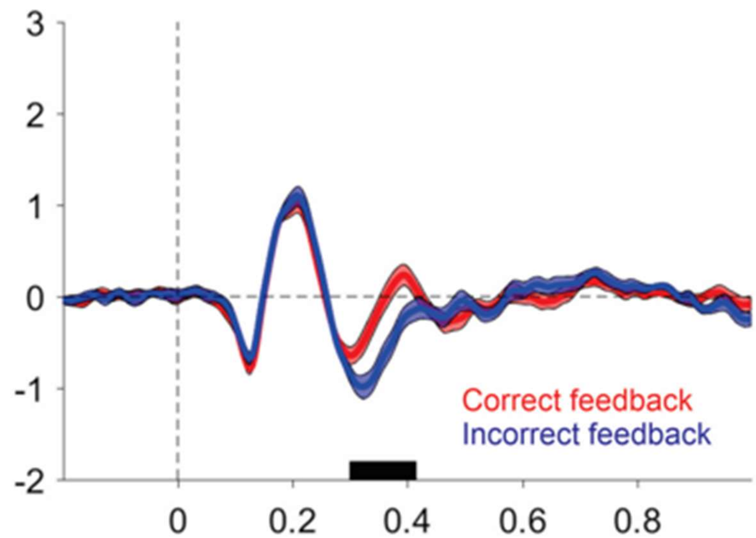

Fig. 2 Grand-averaged ERP (positive-up, temporal window of interest highlighted in black)

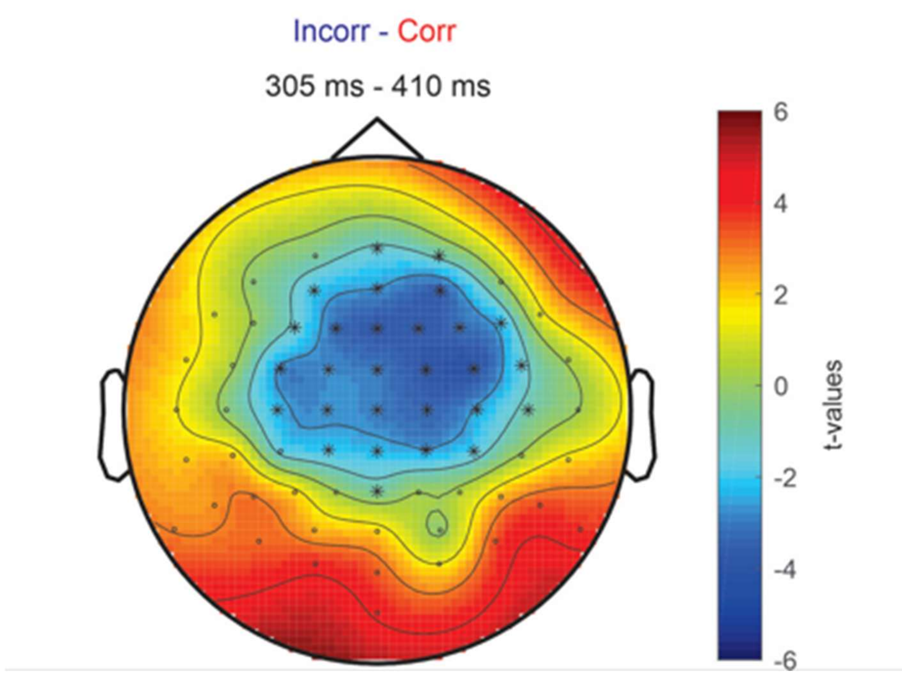

Fig. 3 Scalp topography of the t-value difference between the two conditions

Discussion

Our results seem to indicate that the FRN is at least partially generated in the auditory cortex. While FRN amplitude is insensitive to the sensory modality of feedback stimuli (Miltner et al., 1997), this does not necessarily imply that there are no modality-specific interactions between feedback delivery and the FRN. The auditory nature of both our main task (pitch discrimination) and the resulting scalp topography suggests that the visually elicited FRN relates back to auditory processing. Our interpretation is that incongruent feedback violates cognitive expectations, which instigates a “repair” mechanism due to a top-down modulation of the stimulus’s sensory modality. Alternatively, the auditory topography could be the result of participants mentally recalling trial stimuli after receiving feedback. Some fMRI work on perceptual memory (Backer, Buchsbaum, & Alain, 2020; Linke & Cusack, 2015) shows that later retrieval of cue stimuli produces activity that varies across feedback modalities.

There are a few possible reasons why our dose-dependent hypothesis was not proven. Firstly, while the three trial difficulty conditions are demarcated as Easy, Intermediate, and Hard for taxonomic purposes, the perceived difficulty is fairly similar across conditions. Tones in harder conditions are more similar to each other than in easier conditions, but the frequency range of all stimuli was fairly narrow. Perhaps this clustering of perceived difficulty mitigated potential difficulty-related effects. However, we believe that keeping task difficulty on the easy side was important for maintaining experimental integrity. A difficult task would be less suitable for studying incongruent feedback because participants would be less surprised by (i.e., less likely to question) incongruent-incorrect feedback if they generally struggle to respond correctly. The experience of this half-congruent, half-incongruent feedback design might have felt chaotic for participants. While debriefing notes indicate that many of them developed a piecemeal understanding of the feedback’s design, it is possible that the constant violation of expectations might have overshadowed any difficulty-related conditional effects. The potential effects of inattention were mitigated by catch trials, frequent check-ins between blocks, and close monitoring of the live data for inattention-related artifacts (such as frequent saccades or a pronounced presence of alpha-band activity).

While our experiment does not aim to localize the FRN component, there has already been much written on the subject. Various studies point to the anterior cingulate cortex, posterior cingulate cortex, and the basal ganglia as prime candidates for FRN generation (for review, see Walsh & Anderson 2012). More recently, Hauser, Iannaccone, Stämpfli, Drechsler, Brandeis, Walitza, & Brem (2014) localized the FRN to the dorsal anterior cingulate cortex, utilizing simultaneous EEG-fMRI with effective connectivity measures. To the best of our knowledge, the auditory cortex has not yet been implicated in the FRN literature. The current FRN topography, while resembling a typical topography for an auditory neural source, does not rule out an overlapping cingulate source.

We believe this auditory delayed match-to-sample task with manipulated feedback is novel. The closest known comparison comes from a P300 study by Zheng, Wang, Zhou, & Xu (2020) (modified from Proudfit, 2014). In this study, participants chose between two doors on each trial, with the goal of collecting as many points as possible (supposedly exchanged for a monetary bonus when the experiment was concluded). There were two conditions, free choice at the participant's inclination and forced computer choice (condition was indicated by a symbolic cue at each trial's beginning). Importantly, the promise of bonus compensation was deceptive and all feedback was of a pseudorandom half-correct/half-incorrect design similar to our own. Despite that similarity, this task differs from our own for its visual trial stimuli, computer-choice condition, and being a P300 study (though both the FRN and P300 are influenced by a common process of goal relevance, see Severo, Paul, Walentowska, Moors, & Pourtois, 2020). At least one FRN study (de Bruijn, Mars, & Hulstijn, 2004) has employed deceptive feedback. In this study, a flanker task (Eriksen & Eriksen, 1974) was modified to deliver fake negative feedback for 4% of trials. This flanker variation was used to assess whether reinforcement learning processes were activated by unexpected feedback (this feedback was contextually irrelevant to refinement of task performance). Our study's aims of examining 4 feedback conditions necessitate more trials than this approach. In summary, we believe our paradigm makes a unique contribution to the FRN literature.

Another notable aspect of the present work is the observed temporal window. Our ERP waveform peaked 300-400 ms following feedback delivery. As review of the FRN literature shows (Sambrook & Goslin, 2015), this is a late window for the component, but is not without precedent. Walsh & Anderson (2013) measure the FRN as the mean amplitude of the difference wave at 240-400 ms. Hajcak et al. (2005) used the peak of the difference wave from 200-500 ms at Fz. Holroyd, Krigolson, Baker, Lee, & Gibson (2009) used the peak of the difference wave from 0-600 ms at FCz. Onoda, Abe, & Yamaguchi (2010) used the peak of the difference wave from 250-400 ms at FCz. In addition, Williams and colleagues (2020) point out that even Sambrook & Goslin's systematic review only cautiously suggests a specific time window for FRN research (270-300 ms, also recommending 240-340 ms to account for interstudy variability).

Conclusion

Utilizing a novel auditory delayed match-to-sample task with manipulated feedback, we hypothesized that feedback-related surprise would have effects on ERP amplitude and latency across trial difficulty conditions, largest for Easy trials and smallest for Hard trials. Contrary to this hypothesis, trial difficulty had no influence on the grand averaged waveform, which did exhibit a late incorrectness-negativity effect corresponding to the FRN. While the effect occurs at a later temporal window than with a typical FRN, previous work has already measured the FRN with even later temporal windows. Despite the visual presentation of feedback, our scalp topography is auditory, suggesting that the FRN may be generated in the auditory cortex, a claim that, to the best of our knowledge, is not found in the existing literature on FRN localization. Future work could incorporate time-frequency analyses, which are not used here due to the experiment's limited time window. Behavioral analyses and personality metrics are worthy analyses that were excluded for the same reason. Overall, this exploratory study presents noteworthy findings that necessitate elucidatory follow-up work.

Appendix

Onscreen text instructions (repeated at each block's beginning):

Instructions:

The purpose of this task is to compare the presented sounds, based on their pitch.

On each trial, you will hear a pair of two sounds.

Press the UP arrow if the second sound has a HIGHER pitch than the first

Press the DOWN arrow if the second sound has a LOWER pitch than the first

Once you've made your response, the screen will say

whether or not you were correct

Respond as quickly and accurately as possible.

Respond with whichever answer you think is correct -- even if you disagree

with the feedback.

Press either up or down to continue.

Bibliography

Backer, K. C., Buchsbaum, B. R., & Alain, C. (2020). Orienting Attention to Short-Term Memory Representations via Sensory Modality and Semantic Category Retro-Cues. *eNeuro*, *7*(6). https://doi.org/10.1523/ENEURO.0018-20.2020

Baker, T. E., & Holroyd, C. B. (2011). Dissociated roles of the anterior cingulate cortex in reward and conflict processing as revealed by the feedback error-related negativity and N200. *Biological Psychology*, *87*(1), 25-34. https://doi.org/10.1016/j.biopsycho.2011.01.010.

Bellebaum, C., & Daum, I. (2008). Learning-related changes in reward expectancy are reflected in the feedback-related negativity. *European Journal of Neuroscience*, *27*(7), 1823-1835. https://doi.org/10.1111/j.1460-9568.2008.06138.x

Botvinick, M. M., Cohen, J. D., & Carter, C. S. (2004). Conflict monitoring and anterior cingulate cortex: an update. *Trends in Cognitive Sciences*, *8*(12), 539-546. https://doi.org/10.1016/j.tics.2004.10.003

de Bruijn, E. R., Mars, R. B., & Hulstijn, W. (2004). 'It wasn't me... or was it? How false feedback affects performance. In M. Ullsperger & M. Falkenstein (Eds.), *Errors, Conflicts, and the Brain: Current Opinions on Performance Monitoring* (pp. 118-124). Max Planck Institute for Human Cognitive and Brain Sciences. https://hdl.handle.net/2066/64750

Delorme, A., & Makeig, S. (2004). EEGLAB: an open source toolbox for analysis of single-trial EEG dynamics including independent component analysis. *Journal of Neuroscience Methods*, *134*(1), 9-21. https://doi.org/10.1016/j.jneumeth.2003.10.009.

Donchin, E., & Coles, M. G. (1988). Is the P300 component a manifestation of context updating?. *Behavioral and Brain Sciences*, *11*(3), 357-374. https://doi.org/10.1017/S0140525X00058027

Eriksen, B. A., & Eriksen, C. W. (1974). Effects of noise letters upon the identification of a target letter in a nonsearch task. *Perception & Psychophysics*, *16*(1), 143-149. https://doi.org/10.3758/BF03203267

Falkenstein, M., Hohnsbein, J., Hoormann, J., & Blanke, L. (1991). Effects of crossmodal divided attention on late ERP components. II. Error processing in choice reaction tasks. *Electroencephalography and Clinical Neurophysiology*, *78*(6), 447-455. https://doi.org/10.1016/0013-4694(91)90062-9

Gehring, W. J., Goss, B., Coles, M. G., Meyer, D. E., & Donchin, E. (1993). A neural system for error detection and compensation. *Psychological Science*, *4*(6), 385-390. https://doi.org/10.1111/j.1467-9280.1993.tb00586.x

Gehring, W. J., Liu, Y., Orr, J. M., & Carp, J. (2012). The error-related negativity (ERN/Ne). In S. J. Luck & E. S. Kappenman (Eds.), *The Oxford Handbook of Event-Related Potential Components* (pp. 231–291). Oxford University Press.

Hajcak, G., Holroyd, C. B., Moser, J. S., & Simons, R. F. (2005). Brain potentials associated with expected and unexpected good and bad outcomes. *Psychophysiology*, *42*(2), 161-170. https://doi.org/10.1111/j.1469-8986.2005.00278.x

Hauser, T. U., Iannaccone, R., Stämpfli, P., Drechsler, R., Brandeis, D., Walitza, S., & Brem, S. (2014). The feedback-related negativity (FRN) revisited: new insights into the localization, meaning and network organization. *NeuroImage*, *84*, 159-168. https://doi.org/10.1016/j.neuroimage.2013.08.028

Holroyd, C. B., & Coles, M. G. (2002). The neural basis of human error processing: reinforcement learning, dopamine, and the error-related negativity. *Psychological Review*, *109*(4), 679. https://doi.org/10.1037/0033-295X.109.4.679

Holroyd, C. B., & Krigolson, O. E. (2007). Reward prediction error signals associated with a modified time estimation task. *Psychophysiology*, *44*(6), 913-917. https://doi.org/10.1111/j.1469-8986.2007.00561.x

Holroyd, C. B., Krigolson, O. E., Baker, R., Lee, S., & Gibson, J. (2009). When is an error not a prediction error? An electrophysiological investigation. *Cognitive, Affective, & Behavioral Neuroscience*, *9*(1), 59-70. https://doi.org/10.3758/CABN.9.1.59

Holroyd, C. B., Pakzad-Vaezi, K. L., & Krigolson, O. E. (2008). The feedback correct-related positivity: Sensitivity of the event-related brain potential to unexpected positive feedback. *Psychophysiology*, *45*(5), 688-697. https://doi.org/10.1111/j.1469-8986.2008.00668.x

Linke, A. C., & Cusack, R. (2015). Flexible information coding in human auditory cortex during perception, imagery, and STM of complex sounds. *Journal of Cognitive Neuroscience*, *27*(7), 1322-1333. https://doi.org/10.1162/jocn_a_00780

Lopez-Calderon, J., & Luck, S. J. (2014). ERPLAB: an open-source toolbox for the analysis of event-related potentials. *Frontiers in Human Neuroscience*, *8*, 213. https://doi.org/10.3389/fnhum.2014.00213

Maris, E., & Oostenveld, R. (2007). Nonparametric statistical testing of EEG-and MEG-data. *Journal of Neuroscience Methods*, *164*(1), 177-190. https://doi.org/10.1016/j.jneumeth.2007.03.024

Miljevic, A., Bailey, N. W., Vila-Rodriguez, F., Herring, S. E., & Fitzgerald, P. B. (2021). EEG-connectivity: A fundamental guide and checklist for optimal study design and evaluation. *Biological Psychiatry: Cognitive Neuroscience and Neuroimaging*, *7*(6), 546-554. https://doi.org/10.1016/j.bpsc.2021.10.017

Miltner, W. H., Braun, C. H., & Coles, M. G. (1997). Event-related brain potentials following incorrect feedback in a time-estimation task: evidence for a “generic” neural system for error detection. *Journal of Cognitive Neuroscience*, *9*(6), 788-798. https://doi.org/10.1162/jocn.1997.9.6.788

Onoda, K., Abe, S., & Yamaguchi, S. (2010). Feedback-related negativity is correlated with unplanned impulsivity. *NeuroReport*, *21*(10), 736-739. https://doi.org/10.1097/WNR.0b013e32833bfd36

Oostenveld, R., Fries, P., Maris, E., & Schoffelen, J. M. (2011). FieldTrip: open source software for advanced analysis of MEG, EEG, and invasive electrophysiological data. *Computational Intelligence and Neuroscience*, 2011. https://doi.org/10.1155/2011/156869

Proudfit, G. H. (2014). The reward positivity: From basic research on reward to a biomarker for depression. *Psychophysiology*, *52*(4), 449-459. https://doi.org/10.1111/psyp.12370

Sambrook, T. D., & Goslin, J. (2015). A neural reward prediction error revealed by a meta-analysis of ERPs using great grand averages. *Psychological Bulletin*, *141*(1), 213-235. https://doi.org/10.1037/bul0000006

San Martín, R., Manes, F., Hurtado, E., Isla, P., & Ibañez, A. (2010). Size and probability of rewards modulate the feedback error-related negativity associated with wins but not losses in a monetarily rewarded gambling task. *NeuroImage*, *51*(3), 1194-1204. https://doi.org/10.1016/j.neuroimage.2010.03.031.

Severo, M. C., Paul, K., Walentowska, W., Moors, A., & Pourtois, G. (2020). Neurophysiological evidence for evaluative feedback processing depending on goal relevance. *NeuroImage*, *215*. https://doi.org/10.1016/j.neuroimage.2020.116857.

Walsh, M. M., & Anderson, J. R. (2012). Learning from experience: event-related potential correlates of reward processing, neural adaptation, and behavioral choice. *Neuroscience & Biobehavioral Reviews*, *36*(8), 1870-1884. https://doi.org/10.1016/j.neubiorev.2012.05.008

Walsh, M. M., & Anderson, J. R. (2013). Electrophysiological responses to feedback during the application of abstract rules. *Journal of Cognitive Neuroscience*, *25*(11), 1986-2002. https://doi.org/10.1162/jocn_a_00454

Williams, C. C., Ferguson, T. D., Hassall, C. D., Abimbola, W., & Krigolson, O. E. (2020). The ERP, frequency, and time–frequency correlates of feedback processing: Insights from a large sample study. *Psychophysiology*, *58*(2). https://doi.org/10.1111/psyp.13722

Yeung, N., & Sanfey, A. G. (2004). Independent coding of reward magnitude and valence in the human brain. *Journal of Neuroscience*, *24*(28), 6258-6264. https://doi.org/10.1523/JNEUROSCI.4537-03.2004

Zheng, Y., Wang, M., Zhou, S., & Xu, J. (2020). Functional heterogeneity of perceived control in feedback processing. *Social Cognitive and Affective Neuroscience*, *15*(3), 329-336. https://doi.org/10.1093/scan/nsaa028