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Error-Related Negativity and Feedback-Related Negativity on a Reinforcement Learning Task

Elizabeth Ridley
East Tennessee State University

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Elizabeth A. Ridley

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Eric W. Sellers, Ph.D., Chair

Alyson Chroust, Ph.D.

Gerald Deehan, Ph.D.

David Ryan, Ph.D.

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ABSTRACT

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Event-related potentials play a significant role in error processing and attentional processes. Specifically, event-related negativity (ERN), feedback-related negativity (FRN), and the P300 are related to performance monitoring. The current study examined these components in relation to subjective probability, or confidence, regarding response accuracy on a complicated learning task. Results indicated that confidence ratings were not associated with any changes in ERN, FRN, or P300 amplitude. P300 amplitude did not vary according to participants' subjective probabilities. ERN amplitude and FRN amplitude did not change throughout the task as participants learned. Future studies should consider the relationship between ERN and FRN using a learning task that is less difficult than the one employed in this study.

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Chapter 1. Introduction

Electroencephalograms (EEGs) record neural activity at the scalp and allow us to observe changes associated with cognitive processing. Event-related potentials (ERPs) are neural responses reflected in the EEG that are time-locked to specific external or internal events (Hugdahl, 1995). In order to observe an ERP component, the EEG signal is averaged across multiple trials, resulting in a waveform time-locked to an event. Specific ERP components can be influenced by stimulus characteristics (e.g., emotional content of the stimulus; Olofsson et al., 2008) or cognitive processes such as attention, memory, or error processing. ERPs have been used to gain a better understanding of the cognitive mechanisms related to performance monitoring, which allows people to modify behavior in favor of positive outcomes (e.g., adjusting behavior after error commission or negative feedback; Holroyd & Coles, 2002).

Two specific ERPs have been investigated in response to error commission and feedback presentation. First, error-related negativity (ERN) is an ERP component observed after error commission on reaction time tasks. Second, feedback-related negativity (FRN) is observed after feedback is presented regarding the accuracy of a response. ERN and FRN amplitudes are affected by the reinforcement learning process which will be discussed below. The P300 is an ERP related to attentional processes. Largely considered to reflect context or memory updating (Donchin, 1981), it is also affected by subjective probability, or a person's belief about the likelihood of an outcome (Horst et al., 1980). As new associations are formed throughout the learning process, people become more confident in their responses on cognitive decision-making tasks. The amplitudes of ERN and FRN are impacted as a result of learning and subjective probability (Heldmann et al., 2008; Krigolson et al., 2009). The current study examined the relationship between the above-mentioned ERP components and confidence levels throughout a complicated learning task.

The proposed study replicated the design used by Horst et al. (1980) while examining ERN, FRN, and the P300 in relation to subjective probability, or confidence. The original study examined how P300 amplitude varies according to participants' confidence levels. This study used a similar experimental design with an extension of the original hypotheses to analyze the relationship between ERN, FRN, and subjective probability.

Error-Related Negativity

Error-related negativity (ERN) is a negative deflection that occurs approximately 50-100ms after error commission with a frontocentral scalp distribution, meaning there is increased neural activity throughout the frontocentral region of the brain (Falkenstein et al., 1990; Gehring et al., 1993). Generated in the anterior cingulate cortex (ACC), the ERN is considered to be a reflection of a performance monitoring system, or a system that detects errors and adjusts behavior accordingly (Gehring et al., 1993; Scheffers & Coles, 2000). In the context of a performance monitoring system, error commission reflects the discrepancy between the response made and the known correct response. According to the two leading theories of ERN, the error detection theory and the conflict-monitoring theory, this negative deflection is thought to reflect either the detection of an error or the degree of conflict between multiple potential responses (Heldmann et al., 2008).

Reinforcement learning theory. In the reinforcement learning model, also referred to as the error detection theory, proposed by Holroyd and Coles (2002), the basal ganglia continuously monitors ongoing events. The basal ganglia sends a positive or negative temporal difference (TD) signal to the ACC to indicate whether the ongoing events are better or worse than predicted. For example, a positive TD signal indicates that ongoing events are better than expected or expected, whereas a negative TD signal indicates ongoing events are worse than expected. The reinforcement learning model hinges on the concept that ERN is an indicator of detection of an erroneous response. The dopamine signals sent to the ACC directly affect the amplitude of the ERN (Heldmann et al., 2008; Holroyd & Coles 2002). Specifically, decreases in dopamine after an incorrect response result in larger ERN amplitudes. This model suggests that the ACC plays a critical role in learning, as it is involved in adjusting behavior after erroneous responses.

Dasgupta et al. (2014) also suggest that the reinforcement learning model, based on operant conditioning, works in conjunction with the input correlation learning model, based on classical conditioning. They propose that the structures involved in each model, the basal ganglia and cerebellum, are linked by the thalamus in order to form a combined learning network. Other studies suggest that structures involved in the reinforcement learning theory, namely the ACC, are related to attentional processes. For example, fMRI studies involving the Cingulo-Opercular Network show that the dorsal ACC, medial superior frontal cortex, and bilateral anterior insula are activated when participants must sustain attention, specifically during speech recognition tasks (Dosenbach et al., 2006; Sadaghiani & D’Esposito, 2015; Vaden et al., 2013).

Further, Lak et al. (2017) extended the reinforcement learning model by examining the role of midbrain dopamine neurons in perceptual uncertainty. Their results are consistent with the traditional reinforcement learning model in that midbrain dopamine neurons reflect a reward prediction error (RPE), with the addition of incorporating predictions about belief-state, or confidence. Therefore, the model proposed by Holroyd and Coles (2002) can be modified to more accurately include the component of belief states in relation to error signals

Conflict monitoring theory. In contrast to the error detection theory, the conflict monitoring theory of ERN suggests that the ACC does not necessarily detect an error, but rather the conflict between correct and incorrect responses. According to this theory, the ACC's response to discrepancy between the actual and correct response results in behavioral adjustments (Botvinick et al., 2004). In other words, ERN amplitude depends on the degree of conflict between competing responses. The ACC serves as a "control" that monitors and adjusts performance when conflict arises, such as after an erroneous response. The conflict monitoring theory implies that in addition to ERN elicited from erroneous responses, there should also be an ERP for correct responses. Indeed, Carter et al. (1998) reported increased activity in the ACC during both incorrect and correct responses, suggesting that the ACC may be involved in a more general response-conflict mechanism, as opposed to solely error detection. Multiple studies have also demonstrated a response-conflict effect in a potential called the N2, an ERP with a scalp distribution similar to ERN that peaks approximately 250 milliseconds after response inhibition, although not specific to error commission (Nieuwenhuis et al., 2003; Van Veen & Carter, 2002; Yeung et al., 2004). In go/no-go tasks designed to study inhibitory control, the N2 was believed to be associated with response inhibition on no-go trials. However, Nieuwenhuis et al. (2003) suggest that the N2 is elicited when response conflict is high, rather than as part of an inhibitory process. Several studies have shown a correct-related negativity after correct responses (Allain et al., 2004; Vidal et al., 2009). In general, this theory suggests that ERN reflects the discrepancy, or conflict, between possible responses so the ACC can adjust behavior accordingly.

Other studies, such as Frank et al. (2008), support both the reinforcement learning theory and the conflict monitoring theory. This study examined the difference in ERN amplitude between positive (choosing a correct response) and negative (avoiding an incorrect response) learners. Results showed that negative learners had a larger ERN, which suggests that they learn more from their errors which supports the reinforcement learning theory. Although there was no difference between high conflict and low conflict errors, positive learners had larger ERNs for win/win decisions, while negative learners showed increased ERN for lose/lose decisions. This finding lends support to the conflict monitoring theory by showing that different types of decisions elicit different levels of conflict, depending on learner type. Potts et al. (2011) examined response ERN and feedback ERN amplitudes and discovered that both components involve the ACC and that the error detection system was activated even in the absence of a motor response. This suggests that the ACC may have a more general role in error processing as opposed to a more specific role in error detection. Given that there is data to support both theories, there is increasing support for a more integrative approach to error processing.

Additionally, ERN amplitudes are correlated with subjective judgments of response accuracy, as well as the subjective importance of accuracy to the participant (Gehring et al., 1993; Scheffers & Coles, 2000). In other words, the degree to which a person knows the response is correct or incorrect determines the amplitude of the ERN. Variations of ERN amplitude reflect the subjective view of the response, or the likelihood of error commission (Heldmann et al., 2008). If a person does not perceive a response as an error, ERN amplitude will be smaller compared to the amplitude when a person believes they committed an error. The amplitude of the ERN component can be interpreted as a reflection of the degree to which a person judges a response to be incorrect.

Typically, ERN is elicited under conditions in which accuracy is emphasized rather than speed (Gehring et al., 1993). As a result, the majority of studies involving ERN use a variation of the Flanker task (Pailing & Segalowitz, 2004; Van der Borght et al., 2016). A Flanker task requires a participant to respond to one stimulus that is flanked by either congruent or incongruent stimuli. ERN can also be examined within a learning context. For example, Frank et al. (2005) demonstrated that larger ERN amplitudes are associated with learning to avoid maladaptive responses on a decision-making task rather than learning from positive outcomes. Heldmann et al. (2008) concluded that increased ERN amplitudes are related to judgment about the accuracy of the response. Pailing and Segalowitz (2004) found that when there is a high degree of uncertainty, errors and correct responses are processed similarly. If a participant is unsure of the correct response, (e.g., at the beginning of a learning task before the correct response is known), the ERN amplitude will be much smaller, or not appear at all, compared to errors committed when the correct response is known (Scheffers & Coles, 2002). As people learn a task, the ERN amplitude should increase as they develop the associations required to recognize when they commit an error. Consequently, ERN should be smaller at the beginning of learning tasks, as there is a higher degree of uncertainty about the correct response.

Feedback-Related Negativity

Feedback-related negativity (FRN) is another ERP related to error processing that occurs between 200-350ms after feedback indicating an erroneous response (Miltner et al., 1997). Like the ERN, FRN originates in the ACC and has a frontocentral scalp distribution. This negativity is thought to reflect a reward prediction error (Holroyd & Coles, 2002). Reward prediction errors (RPEs) are violations of a prediction (e.g., outcome is better or worse than expected) that are coded in midbrain dopamine neurons (Schultz et al., 1997). The RPE that is sent from the basal ganglia to the ACC is considered to code the outcome evaluation (Philiastides et al., 2010). This signal is what tells the ACC whether the outcome was better or worse than expected. If the RPE is positive (i.e., outcome is better than expected), then FRN amplitude should decrease, because the positive feedback will trigger an increase in dopaminergic activity. On the other hand, if the RPE is negative (i.e., outcome is worse than expected), then FRN amplitude should be larger, as negative feedback produces inhibition of dopaminergic activity. Several studies have interpreted this increase in FRN amplitude in response to negative feedback as a reflection of a reward prediction error (Bismark et al., 2013; Hajcak et al., 2007; Pfabigan et al., 2010).

Generally, FRN amplitudes are larger for negative feedback than positive feedback suggesting FRN amplitude is sensitive to feedback valence (Bellebaum & Daum, 2008; Ichikawa et al. 2010; Martín, 2012; Potts et al., 2011). However, some studies report that FRN is not necessarily dependent on outcome valence but rather on the discrepancy between actual and expected feedback (Oliveira et al., 2007; Yu et al., 2011). Hajcak et al. (2007) also concluded that FRN amplitude is influenced by an interaction of feedback expectancy and valence. It is determined by the value of the outcome as compared to the other possible outcomes (Holroyd et al., 2004). In other words, it is context dependent and a positive outcome, such as a monetary reward, may still elicit an FRN if it were the worst possible outcome among a range of outcomes (e.g., lowest monetary reward available).

Furthermore, FRN will only be observed in instances where expectations are allowed to develop. Bismark et al. (2013) found that there was no FRN response for trials in which feedback and answer selection were presented simultaneously, but there was an FRN response when participants received feedback 750ms after response selection. They concluded that if feedback is presented at the time of response, there is no time for an outcome expectation to develop and an FRN response will not be generated. If FRN is a reflection of the reward prediction error, then there must be sufficient time for a prediction to develop in order for FRN to occur.

According to Potts et al. (2011), FRN is elicited when the correct response on a task is unknown. Most of the studies examining FRN amplitude use a probabilistic gambling paradigm in order to manipulate feedback expectancy (Foti et al., 2011; Hajcak et al., 2007; Pfabigan et al., 2010). However, several studies have considered FRN amplitude in the context of a reinforcement learning task, with results indicating that as participants learn response-outcome associations FRN amplitude decreases (Holroyd & Coles, 2002; Krigolson et al., 2009). As participants learn a task the amplitudes of FRN should decrease on trials where there is no outcome expectancy violation. FRN is elicited as a result of feedback that contains new information; as a task is learned, this feedback becomes less novel, causing amplitude to decrease (Gentsch et al., 2009; Heldmann et al., 2008). However, Bultena et al. (2017) reported that FRN was still elicited across trials, though amplitude was decreased, suggesting that feedback may still serve to update memory throughout learning. Although feedback becomes less surprising as learning occurs, it may still be useful to reinforce new associations.

Larger FRN amplitudes may result in faster learning (Schmid et al., 2017). This could be due in part to a more salient "surprise" effect from the negative feedback. A larger FRN amplitude would be indicative of a larger violation of expectation. This may in turn generate a more salient association, resulting in a greater likelihood of remembering the association. van der Helden et al. (2010) also showed that larger FRN amplitudes in response to negative feedback were predictive of future performance on a learning task.

P300

An additional ERP, the P300, is also related to learning and attention-based cognitive tasks. The P300 is a positive deflection that occurs approximately 300ms after stimulus presentation. The P300 is elicited when participants are asked to attend to a certain stimulus and ignore another, as in the oddball task. Yeung and Sanfey (2004) propose that in relation to errors and feedback, the P300 is sensitive to magnitude (large vs. small rewards or punishments), whereas FRN is sensitive to valence (positive or negative rewards or punishments). The amplitude of the P300 depends on the magnitude of the outcome, with large magnitude alternative outcomes reflecting increased amplitudes. Essentially, larger rewards or punishments elicit greater amplitudes compared to smaller rewards or punishments.

The P300 also has an inverse relationship with subjective probability. Outcomes that are highly expected by the participant elicit a small P300; events that occur less frequently, however, elicit a much larger P300 (Horst et al., 1980). In relation to learning, the P300 would have larger amplitudes when outcomes are unexpected and smaller amplitudes when the outcome matches the participant's subjective probability toward the outcome. If feedback aligns with participants' expectations of the outcome (e.g., correct or incorrect) then the amplitude of the P300 will decrease because the outcome will be highly expected. On the other hand, if the outcome is unknown or uncertain, the P300 amplitude will increase because the outcome was not expected. Unknown outcomes receive more attention and thus generate larger P300 amplitudes (Martín, 2012).

Subjective probability is a reflection of outcome expectation when making decisions. Before learning occurs, subjective probability is relatively low regarding the correct response. As new associations form, outcome expectations become more solidified. In terms of ERP components, subjective probability can be measured by assessing confidence levels after each trial throughout a task (Horst et al., 1980). Confidence levels represent the degree to which outcomes are expected. This is reflected by the shift from feedback-related negativity to error-related negativity across trials (Krigolson et al., 2009). As learning occurs, the feedback becomes less surprising and results in a decrease in FRN amplitude (Heldmann et al., 2008). Conversely, the ERN amplitude should increase as learning occurs because new associations result in the ability to discern whether an error was committed.

Current Study

Horst et al. (1980) examined the relationship between subjective probability and P300 amplitude. P300 amplitude varied as confidence changed throughout a complex learning task. As ERN was not discovered until the 1990s (Falkenstein et al., 1990; Gehring et al., 1993), the original study focused only on P300 amplitude. Since the discovery of the ERN, studies have concluded that errors committed due to uncertainty result in smaller amplitudes for ERN and larger amplitudes for FRN (Scheffers & Coles, 2000; Potts et al., 2011). Several studies analyzing both ERN and FRN report a "shift" from FRN to ERN as learning occurs (Holroyd & Coles, 2002; Krigolson et al., 2009; Nieuwenhuis et al., 2002). Studies that include both ERN and FRN typically either modify a Flanker task by incorporating feedback, or use a reinforcement learning task (Heldmann et al., 2008; Krigolson et al., 2009). A replication and extension of the Horst et al. (1980) study using a reinforcement learning task should reveal that in addition to the P300 component, both ERN and FRN should be elicited by error commission and feedback presentation, respectively, and the responses should be related to subjective probability.

Consistent with the reinforcement learning theory, the present study sought to replicate and extend the design used by Horst et al. (1980) in an attempt to elicit both ERN and FRN responses throughout a learning task. To date, no study has looked at both ERN and FRN in conjunction with subjective probability throughout a difficult reinforcement learning task. Participants were asked to report their confidence levels after each trial of a learning task. During the task participants learned five stimulus-response pairs of nonsense syllables, with each syllable consisting of a consonant, vowel, and consonant (CVC). The confidence ratings served as an indication of learning in that higher confidence ratings reflected that participants believed they had learned the task. We expected the confidence ratings to predict both ERN and FRN amplitude, with lower ratings predicting greater amplitudes for ERN on incorrect trials, and higher ratings predicting greater FRN amplitudes on incorrect trials.

Hypotheses

ERN. ERN amplitude will be higher when participants commit errors than when they are correct. In addition, ERN amplitude on incorrect trials will be higher when the participant's confidence ratings are low.

a. Overall ERN amplitude will be greater on incorrect trials at the end of the experiment than incorrect trials at the beginning of the experiment, as participants will be able to recognize that they have committed an error.

FRN. FRN amplitude will be greater after erroneous feedback when confidence ratings are high.

a. Overall FRN amplitude will be higher for incorrect trials at the beginning of the experiment than incorrect trials at the end of the experiment because feedback will become less salient.

P300. P300 amplitude will increase on trials in which the trial outcome violates the participant's subjective probability of the outcome.

Chapter 2. Methods

Participants

31 undergraduate students from East Tennessee State University participated in the study following approval from ETSU's Institutional Review Board. Students received three SONA credits for participation. All participants were recruited from undergraduate courses through the institution's SONA website and were over 18 years of age (mean age = 20.1 years, SD = 3.85). 63.3% of the participants identified as female and 36.67% identified as male. All participants were right-handed with normal or corrected to normal vision. Approximately 77.4% of the participants identified as white, 6.4% as Asian, 3.2% as American Indian/Alaska Native, 3.2% as African American, 3.2% Native Hawaiian/Pacific Island, and 3.2% as other; 10% of participants identified as Hispanic/Latino. Data was collected in the Spring 2019 and Fall 2019 semesters at East Tennessee State University.

Materials

Participants wore a 32-channel electrode cap (Electro-Cap International, Inc.) throughout the task to record brain activity. The stimuli were presented on the monitor using E-Prime 3.0 (Psychology Software Tools, USA). EEG signal was digitized at 256 Hz with bandpass-filter settings at [.5Hz, 30Hz]. Data was collected using two 16 channel g.tec g.USBamp amplifiers. Impedance for each channel was no greater than 20k. Data was analyzed using the EEGLAB plugin for Matlab and right-mastoid referenced (Matlab 2016b, The MathWorks, Inc., Natick, Massachusetts, USA).

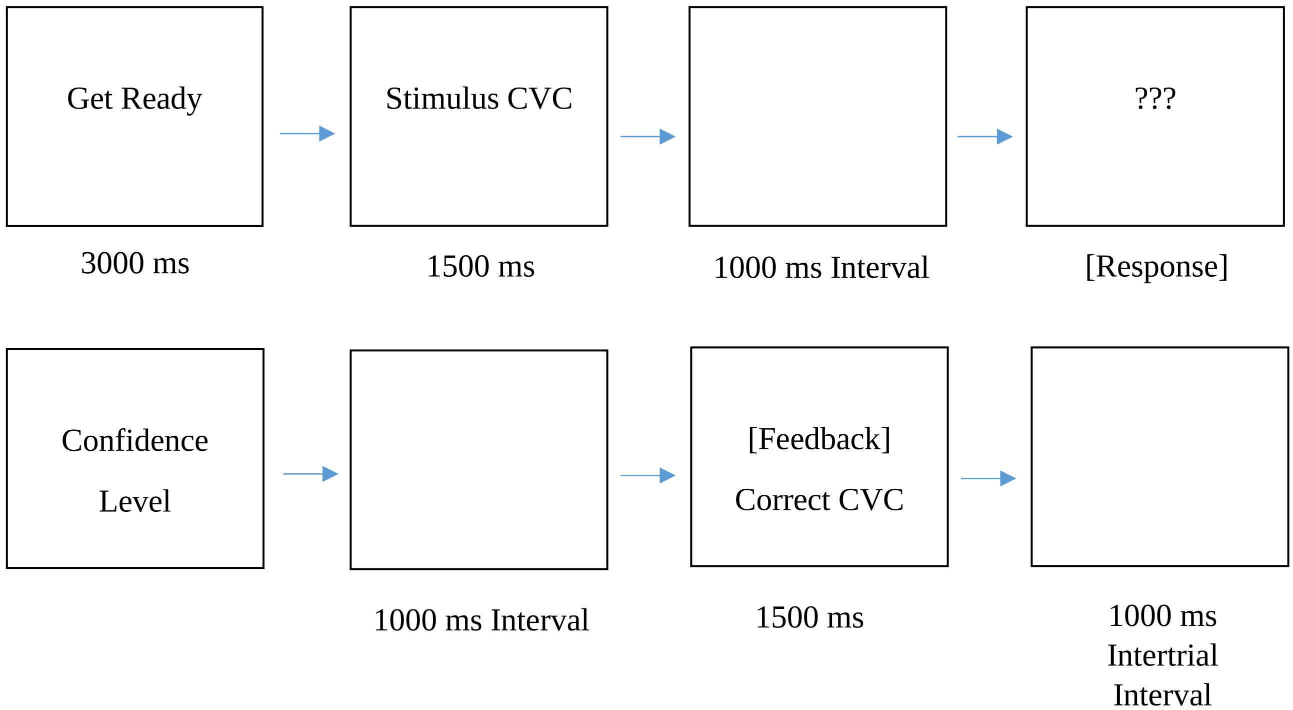
Procedure

All participants signed an informed consent document and completed a demographic questionnaire asking for age, gender, race, ethnicity, and handedness prior to the start of the task.

During the session, the participants completed a complex paired associate task in which they were required to learn three lists, each consisting of five pairs of nonsense syllables. Pairs were made up of two consonant-vowel-consonant (CVC) nonsense syllables. In order to terminate a block of trials participants were required to make eight correct CVC pairings in a row. As in the original paper, the CVC syllables had a meaningfulness scale rating no higher than 1.5 according to the Noble (1961) norms; thus, the syllables did not resemble words from the English language. The experimental task is shown in Figure 1. Each trial began with a ‘Ready’ slide that was shown for 1500ms. Following the ‘Ready’ slide, participants were shown a CVC stimulus and prompted to make their response of which CVC they believed to be correct. Then, participants typed their confidence ratings on a scale from 0-100. Following the response and confidence rating, the correct answer was presented on the screen along with feedback regarding the accuracy of the response. The stimulus CVC and the correct corresponding CVC were each presented for 1500ms. The block ended when the participant responded correctly on eight consecutive trials, indicating that learning has occurred. All participants completed a practice block that included three CVC pairs, which did not appear in the main experiment, to ensure understanding of the task. Next, all participants started the three experimental blocks, the order of which was counterbalanced across participants.

Figure 1.

Example of One Complete Trial



Following the design of Horst et al. (1980), participants were presented with a stimulus CVC, a 1000ms interval, then three question marks prompting participants to make a response. Then, participants entered their confidence levels. Following a 1000ms interval, the correct CVC was presented, along with whether the participant's response was correct. After the feedback, there was a 1000ms intertrial interval before the next trial began.

Chapter 3. Results

Determining Confidence Intervals

Participants rated their confidence for each trial on a scale of 0-100. Each participant's ratings were categorized into either high or low confidence. Ratings of 0-49 were considered low confidence and ratings of 50-100 were considered high confidence. In the Horst et al. (1980) study, confidence data were collapsed into four separate confidence ranges; however, in the current study, confidence ratings were mainly near the extremes (0 and 100) of the 101-point scale. Therefore, ratings were dichotomized into either high or low confidence. Consequently, there were four possible trial outcome categories: incorrect/low confidence, incorrect/high confidence, correct/low confidence, and correct/high confidence.

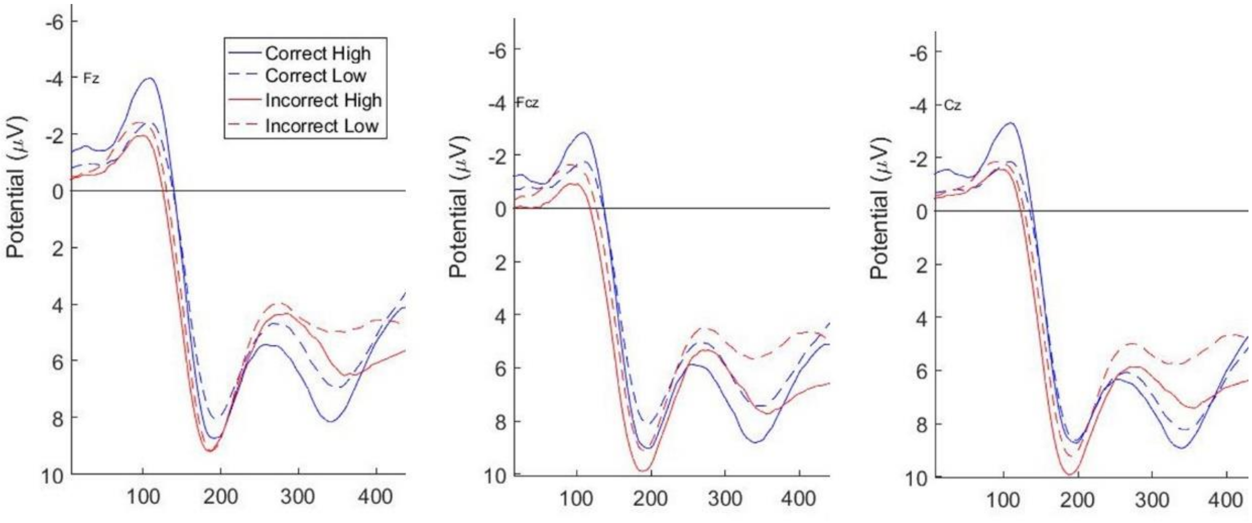
Analyses

We removed electrodes FP1 and FP2 from data analysis for seven participants due to excessive channel noise. Independent component analysis (EEGLab toolbox) was used to remove eyeblink components and, after the data were segmented, excessively noisy epochs were removed via visual inspection. Previous studies have used independent component analysis, principal component analysis, or frequency cut-off to remove artifacts (Di Gregorio et al., 2016; Philiastides et al., 2010). ERN amplitude was examined 0-150ms after error commission, measured from the time the participants entered their responses during the task; FRN amplitude was examined 200-350ms after feedback presentation; P300 amplitude was examined 250-400ms after feedback presentation. ERPs were examined at electrode sites Fz, FCz, Cz, Pz, and POz. Averages at each site were computed for each of the four conditions. The amplitudes of the P300, ERN, and FRN were analyzed in each category using analysis of variance.

FRN analysis. Feedback-related negativity was examined at electrode sites Fz, FCz, and Cz 200-350ms after feedback presentation. We hypothesized that amplitude would be greatest after erroneous feedback when confidence was high compared to low. Figure 2 shows the waveforms for electrodes Fz, FCz, and Cz. At Fz, results revealed no significant differences in amplitude between the incorrect low (M = 2.66 μV, SD = 5.73), incorrect high (M = 3.31 μV, SD = 6.42), correct low (M = 3.84 μV, SD = 6.59), and correct high (M = 4.24 μV, SD = 5.83) conditions, $F(3, 120) = 0.384$, $p = 0.765$. FRN amplitude at FCz also showed no significant differences between conditions: incorrect low (M = 3.34 μV, SD = 4.86), incorrect high (M = 4.30 μV, SD = 5.75), correct low (M = 4.38 μV, SD = 5.39), correct high (M = 4.86 μV, SD = 5.21), $F(3, 120) = 0.441$, $p = 0.724$. There was no significant difference in amplitude between conditions at electrode site Cz: incorrect low (M = 3.69 μV, SD = 5.39), incorrect high (M = 4.28 μV, SD = 6.13), correct low (M = 5.05 μV, SD = 5.16), correct high (M = 5.24 μV, SD = 5.79), $F(3, 120) = 0.494$, $p = 0.687$. Feedback-related negativity at electrode sites Fz, FCz, and Cz is greatest at approximately 280ms. Amplitude was greatest for the incorrect low condition, although there was no significant difference between conditions.

Figure 2.

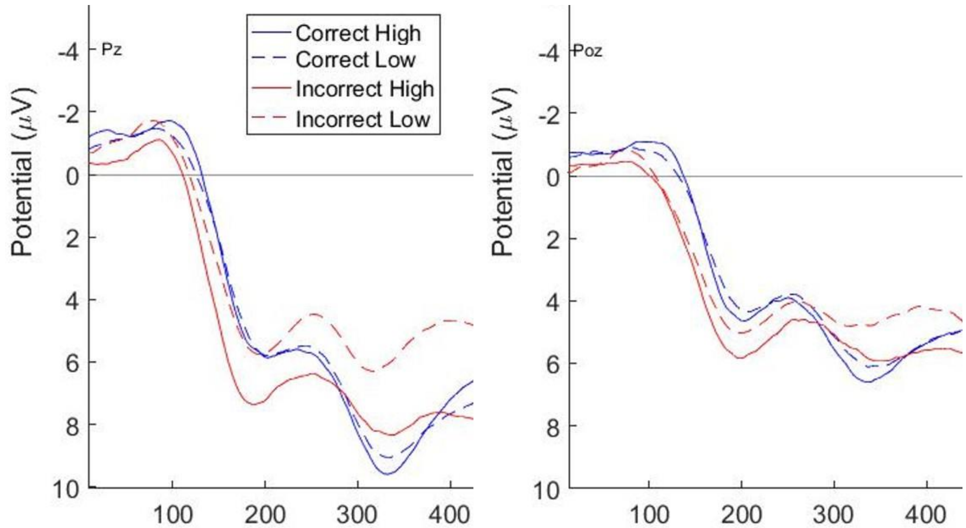
FRN Amplitude at Electrode Sites Fz, FCz, and Cz



P300 analysis. P300 amplitude was examined at electrode sites Pz and POz, 250-400ms after feedback presentation. We hypothesized that amplitude would be greatest for trials in which the outcome violated participants' expectation (e.g. incorrect response, high confidence). Figure 3 shows the waveforms for electrodes Pz and POz. At Pz there was not a significant difference in amplitude between conditions: incorrect low (M = 7.008 µV, SD = 5.09), incorrect high (M = 8.98 µV, SD = 5.96), correct low (M = 9.89 µV, SD = 6.31), correct high (M = 10.61 µV, SD = 7.27), $F(3, 120) = 1.96$, $p = 0.124$. At POz, there was no significant difference in amplitude between conditions: incorrect low (M = 6.14 µV, SD = 3.81), incorrect high (M = 7.27 µV, SD = 4.61), correct low (M = 7.76 µV, SD = 5.24), correct high (M = 8.24 µV, SD = 5.63) $F(3, 120) =$ 1.05, $p = 0.373$. P300 amplitude was greatest for the correct high condition and smallest for the incorrect low condition.

Figure 3.

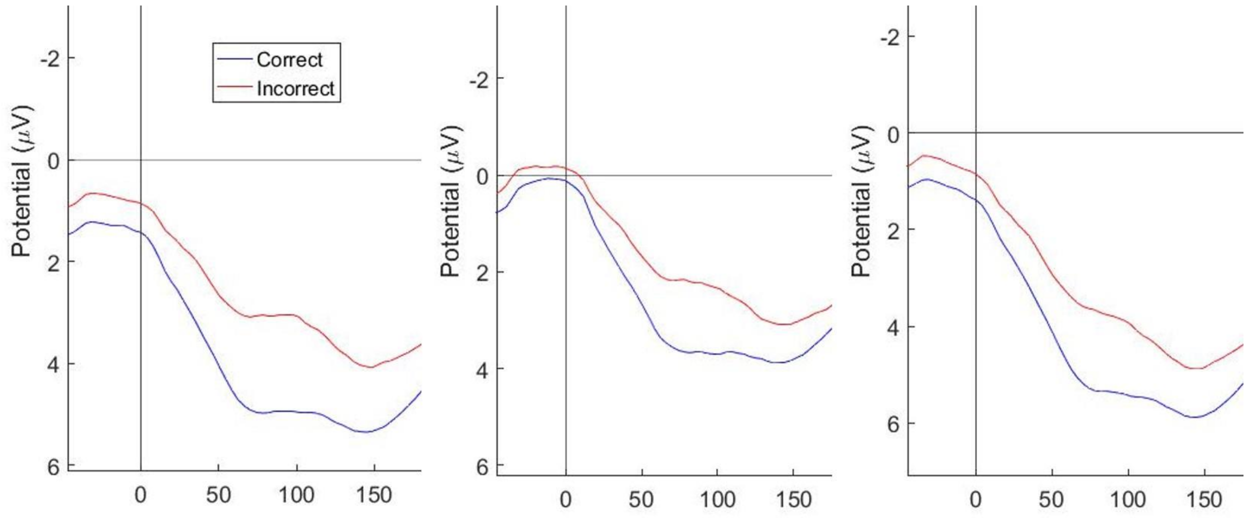
P300 Amplitude for Each Condition at Electrode Sites Pz and POz



ERN analyses. Error-related negativity was measured at electrode sites Fz, FCz, and Cz 0-150ms after a response was entered. We hypothesized that there would be greater negativity for incorrect trials than correct trials. Waveforms for electrodes Fz, FCz, and Cz are shown in Figure 4. A paired samples t-test revealed no significant difference between incorrect (*M* = .006 μV, *SD* = 3.24) and correct (*M* = .503 μV, *SD* = 4.052) trials at Fz, t(30) = -1.334, *p* = .192. At electrode FCz, there was no significant difference in amplitude between incorrect (*M* = .77 μV, *SD* = 2.31) and correct (*M* = .66 μV, *SD* = 2.83) trials, t(30) = -.379, *p* = .707. There was also no significant difference in amplitude at electrode site Cz between incorrect (*M* = .39 μV, *SD* = 2.96) and correct (*M* = .65 μV, *SD* = 3.62) trials, t(30) = -.771, *p* = .447. Amplitude was more negative for incorrect trials than correct trials at approximately 75ms although the difference was not significant.

Figure 4.

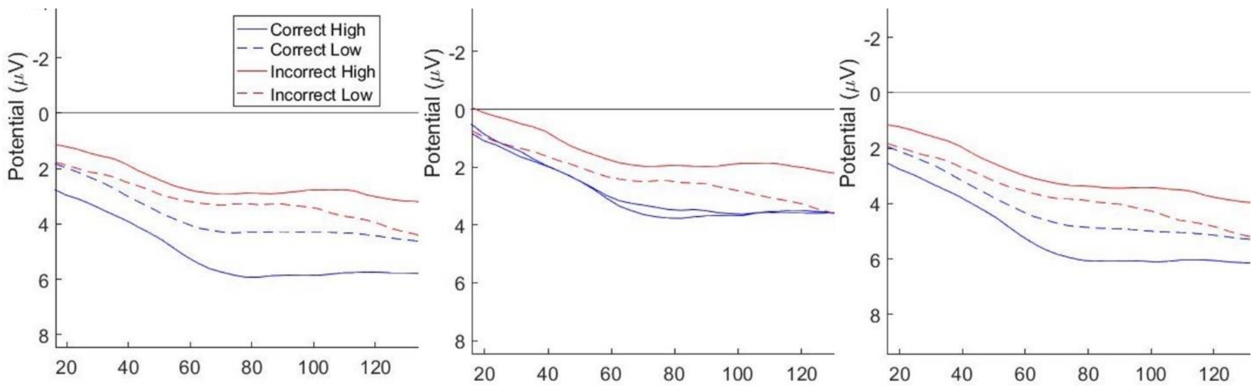
Average ERN at Electrode Sites Fz, FCz, and Cz for Correct and Incorrect trials.



We also examined ERN amplitude in each condition at electrode sites Fz, FCz, and Cz. We hypothesized that amplitude for incorrect trials would be greatest when confidence is low. Results suggested that there was no difference in amplitude between incorrect high (M = -.063 μV, SD = 3.466), incorrect low (M = -.66 μV, SD = 3.46), correct high (M = -.044 μV, SD = 3.98) and correct low (M = .71 μV, SD = 4.48) at Fz, $F(3, 120) = .656$, p = 0.581, as shown in Figure 5. At FCz, there was also no significant difference in amplitude between incorrect high (M = -.704 μV, SD = 2.46), incorrect low (M = -1.62 μV, SD = 2.82), correct high (M = -1.02 μV, SD = 2.85), and correct low (M = -.867 μV, SD = 3.51), $F(3, 120) = .568$, p = .637. At Cz, we did not observe any difference in amplitude between incorrect high (M = .313 μV, SD = 3.17), incorrect low (M = -.12 μV, SD = 3.25), correct high (M = .332 μV, SD = 3.54), and correct low (M = .76 μV, SD = 3.93), $F(3, 120) = .326$, p = .806. Amplitude was greatest for the incorrect high condition and lowest for the correct high condition.

Figure 5.

Average ERN Amplitude for Each Condition at Fz, FCz, and Cz



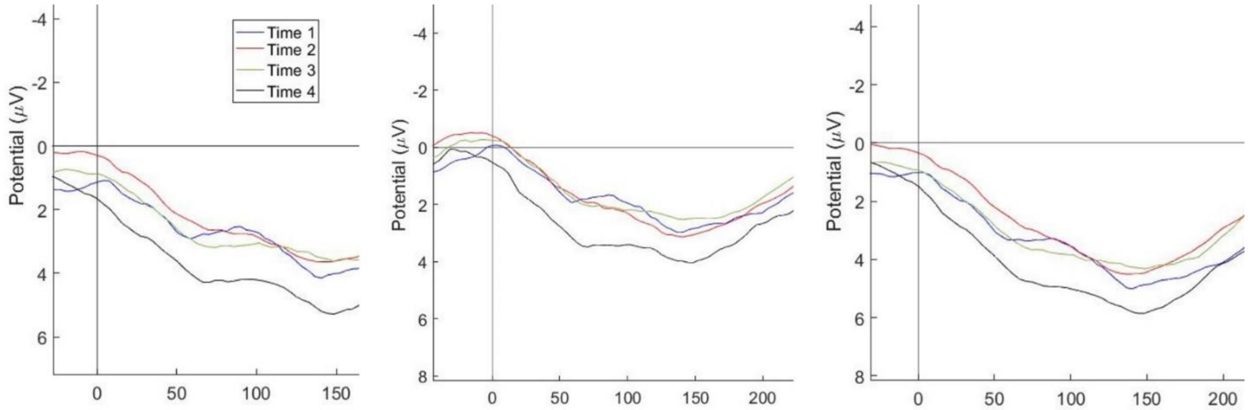
ERN and FRN across time. To determine how the amplitudes of ERN and FRN change throughout the learning process, we divided each list into quartiles based on the number of incorrect trials throughout that list, then averaged across each list. This created four "time bins" each containing an equal number of incorrect responses. We compared the amplitudes for ERN and FRN in each bin by using a one-way analysis of variance.

We hypothesized that ERN amplitude would be greatest for incorrect responses made during the last time bin and that amplitude would be smallest for incorrect responses made during the first time bin. Figure 6 shows waveforms at Fz, FCz, and Cz. The ERN analysis at Fz revealed no significant difference in amplitude between time 1 (M = .772 μV, SD = 3.34), time 2 (M = .80 μV, SD = 3.84), time 3 (M = .91 μV, SD = 4.74) and time 4 (M = .24 μV, SD = 4.57), $F(3,120) = 0.517$, $p = .672$. At FCz, there was no significant difference in amplitude between time 1 (M = 1.52 μV, SD = 2.58), time 2 (M = 1.24 μV, SD = 3.06), time 3 (M = 1.52 μV, SD = 3.35), and time 4 (M = 0.66 μV, SD = 3.37), $F(3, 120) = 0.528$, $p = 0.664$. At Cz there was not a significant difference in amplitude between time 1 (M = .12 μV, SD = 3.14), time 2 (M = .56 μV, SD = 3.56), time 3 (M = .28 μV, SD = 4.25), and time 4 (M = .59 μV, SD = 3.68), $F(3, 120)$ =

.551, p = .648. ERN amplitude was most negative during Time 2 and least negative during Time 4.

Figure 6.

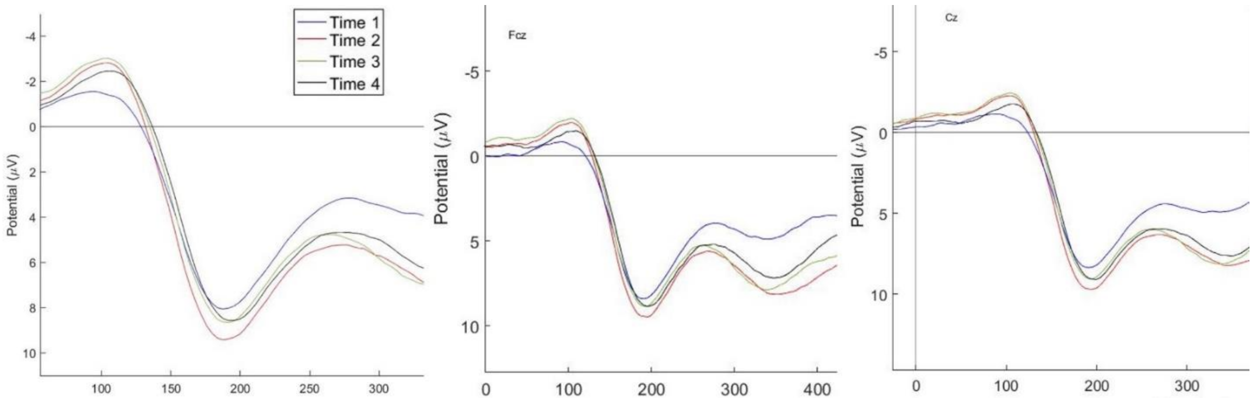
ERN Amplitude for Each Time Period at Electrode Sites Fz, FCz, and Cz



For FRN, we hypothesized that amplitude for incorrect trials would be greatest at the beginning of the blocks during time bin 1 and that amplitude would be smallest during time bin 4. As shown in Figure 7, the FRN analysis at Fz showed no significant difference in amplitude between time 1 (M = 2.25 μV, SD = 5.89), time 2 (M = 3.99 μV, SD = 5.92), time 3 (M = 3.72 μV, SD = 6.09), and time 4 (M = 3.61 μV, SD = 7.00), $F(3, 120)$ = .484, p = .694. At FCz there was no significant difference in amplitude between time 1 (M = 3.25 μV, SD = 5.05), time 2 (M = 4.48 μV, SD = 4.91), time 3 (M = 4.49 μV, SD = 5.22), and time 4 (M = 4.39 μV, SD = 6.15), $F(3, 120)$ = .395, p = .757. We also did not find a significant difference in amplitude at Cz between time 1 (M = 3.20 μV, SD = 5.04), time 2 (M = 4.79 μV, SD = 5.79), time 3 (M = 4.71 μV, SD = 5.14), and time 4 (M = 4.73 μV, SD = 6.55), $F(3, 120)$ = .579, p = .630. FRN amplitude was greatest for Time 1 and smallest for Time 2.

Figure 7.

FRN Amplitude for Each Time Period at Electrode Sites Fz, FCz, and Cz



Chapter 4. Discussion

Performance feedback, as well as internal error monitoring are essential to improve and adapt behavior. This study examined the relationship between multiple event-related potentials and subjective probability. Our goal was to replicate and extend the findings reported by Horst et al., (1980) that found a relationship between P300 amplitude and the subjective probability of participants. By extending the analyses to include ERN and FRN, we expected to find a relationship between the ERP components, as well as a relationship between the components and subjective probability. Specifically, we expected both ERN and FRN to vary with respect to confidence. ERN was expected to be smallest at the beginning of the blocks before learning occurred and greatest at the end of the blocks after learning occurred. FRN was expected to be greatest at the beginning of the blocks and smallest at the end, showing a tradeoff relationship with ERN. Additionally, we hypothesized that ERN amplitude would be smallest for incorrect trials when confidence was low and FRN would be greatest for incorrect trials when confidence was high.

The results showed no difference in P300, FRN or ERN across conditions based on confidence levels. In line with previous findings, we expected to observe an increase in P300 amplitude at parietal locations for trials on which the outcome violated participants' expectations (e.g. incorrect response, high confidence; correct response, low confidence). However, the current results revealed no differences of P300 amplitude between conditions, regardless of outcome expectations. We also expected a decrease in FRN and an increase in ERN amplitude across trials. The results showed no significant change across trials, suggesting that ERN and FRN may not be as sensitive to the learning process as hypothesized.

Limitations

There are several factors to consider as to why significant results were not obtained. First, ERN is typically elicited during timed reaction tasks that emphasize accuracy. The task in this study was not timed; therefore, participants did not experience any time pressure. Another possibility for why we did not observe any changes in ERN could be due to higher physical demands during the task. Studies examining ERN usually involve a Flanker task, which requires one button press as a response. The current task required four button presses, three for the response and one for submission. ERN was analyzed after the fourth button press, the participant's submission of the response. However, participants could commit an error at various stages of their response. For example, error commission could occur at button press one when participants type the first letter of the response, button press two for the second letter, or button press three for the third letter. Inconsistency of the timing of error commission could account for a less pronounced ERN in comparison with ERN elicited by the one-button response during a Flanker task. Future studies examining the relationship between ERN and FRN should consider a task that requires only one response from the participant to minimize motor movement. In fact, Liu and Huo (2020) used a probabilistic forced choice task that only required one button press as a response and observed a tradeoff effect between ERN and FRN amplitude throughout the task. Specifically, ERN amplitude increased and FRN amplitude decreased as learning occurred.

The original study used a 101-point confidence scale and collapsed the scale into four ranges for each participant. The ratings obtained in the current sample were only reflective of the extremes of the scale (e.g. 0, 100). We were not able to divide the ratings into the appropriate ranges and instead dichotomized the ratings into low and high. Ideally, we would have been able to use the entire 101-point scale, as dichotomizing the confidence variable may not accurately reflect the participants' subjective probability. Due to the nature of the task, each participant completed a different number of trials throughout the task. Future studies should consider using a task for which each participant completes the same number of trials. For example, an experimental design that uses a probabilistic forced choice task would allow for all of the participants to complete the same number of trials. For instance, a study published by Liu and Huo (2020) utilized a forced choice paradigm that required participants to learn which symbol provided correct feedback the majority of the time for a set number of trials. Their results showed the tradeoff relationship between ERN and FRN that we expected to observe in the current study, perhaps due to the more appropriate nature of the forced choice paradigm.

Another possible reason we did not obtain significant results could be due to the age/educational level of the participants in this sample. The original study had only six participants, but each participant was a graduate student. Conversely, although the current study included 31 participants, the majority of participants were college freshmen. As P300 amplitude is modulated by the amount of attentional resources available for the task (Polich, 2007), the significant difference in educational level could also be accompanied by a difference in attentional abilities, with graduate students able to devote more attention to the task at hand. Velanova et al. (2008) also observed that adolescents and young adults showed differences in ACC activity, suggesting that as the ACC develops, error processing and inhibitory control improve. This development may account for the more pronounced P300 response reported in the original study with older participants.

Conclusion

Overall, the current study did not replicate the results obtained by Horst et al. (1980). We hypothesized that in addition to the P300, ERN and FRN would also be influenced by participants' subjective probability. We also expected to observe a tradeoff relationship between

ERN and FRN, with ERN amplitude increasing across time and FRN decreasing across time, consistent with the reinforcement learning theory. Our results showed no significant P300 response for trials that violated participants' subjective probability. We did not observe a change in ERN and FRN throughout the blocks, nor did we observe any changes in amplitude across conditions relating to subjective probability. Although our hypotheses were not supported, other studies have reported a relationship between ERN and FRN (Krigolson et al., 2009; Liu & Huo, 2020), suggesting that task difficulty may play a significant role in error monitoring (Pailing & Segalowitz, 2004). Overall, results indicated that there is not a significant relationship between ERN, FRN, and subjective probability. However, future studies should use a more appropriate experimental task in order to more accurately examine the relationship between ERN and FRN.

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VITA

ELIZABETH A. RIDLEY

Education: M.A. Psychology, East Tennessee State University, Johnson City, Tennessee, 2020

B.A. Psychology, Grove City College, Grove City, Pennsylvania, 2017

Public Schools, Bradford, Pennsylvania

Professional Experience: Instructor, East Tennessee State University; Johnson City, Tennessee, 2019-2020

Supplemental Instructor, East Tennessee State University; Johnson City, Tennessee, 2019-2020

Graduate Assistant, East Tennessee State University, College of Arts and Sciences, 2018-2020

Panel Member, Psi Chi, East Tennessee State University, March 2019

Academic Resources Tutor, Grove City College, Grove City, Pennsylvania, 2016-2017

Poster Presentations: **Society for Psychophysiological Research**

Ridley, E., Jones, M., Ashworth, E., & Sellers, E.W. (2019) "Error-related negativity and feedback-related negativity on a reinforcement learning task." Poster presented at the Society for Psychophysiological

Research annual meeting in Washington, D.C.

Conference Presentations of Supervised Student Research

Stahl, C., Donnellon, E., Ridley, E., Hafner, A., Newton, A., & Horton, J. (2017). "Effects of moral and religious primes on dishonesty." Poster presented at Grove City College Family Weekend.