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Outcome valence and stimulus frequency affect neural responses to rewards and punishments

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Abstract

The Reward-Positivity (RewP) is a frontocentral event-related potential elicited following reward and punishment feedback. Reinforcement learning theories propose the RewP reflects a reward prediction error that increases following more favorable (vs. unfavorable) outcomes. An alternative perspective, however, proposes this component indexes a salience-prediction error that increases following more salient outcomes. Evidence from prior studies that included both reward and punishment conditions is mixed, supporting both accounts. However, these studies often varied how feedback stimuli were repeated across reward and punishment conditions. Differences in the frequency of feedback stimuli may drive inconsistencies by introducing salience effects for infrequent stimuli regardless of whether they are associated with rewards or punishments. To test this hypothesis, the current study examined the effect of outcome valence and stimulus frequency on the RewP and neighboring P2 and P3 components in reward, punishment, and neutral contexts across two separate experiments that varied how often feedback stimuli were repeated between conditions. Experiment 1 revealed infrequent feedback stimuli generated overlapping positivity across all three components. However, controlling for stimulus frequency, experiment 2 revealed favorable outcomes that increased RewP and P3 positivity. Together, these results suggest the RewP reflects some combination of reward- and salience-prediction error encoding. Results also indicate infrequent feedback stimuli elicited strong salience effects across all three components that may inflate, eliminate, or reverse outcome valence effects for the RewP and P3. These results resolve several inconsistencies in the literature and have important implications for electrocortical investigations of reward and punishment feedback processing.

KEYWORDS

ERP, feedback, frequency, punishment, reward, valence

1 | INTRODUCTION

Reward and punishment are two central features of learning. Electrophysiological research has identified several event-related potentials (ERPs) elicited following rewarding and punishing feedback. Most studies focus on the Feedback-Related Negativity (FRN), a relative frontocentral negativity elicited 250–350 ms elicited following worse (vs. better) than expected outcomes (Miltner et al., 1997). Variation in FRN amplitude has been linked to a wide range of psychopathology, especially depressive disorders (see Proudfit, 2015 for review), encouraging a growing interest in the FRN across the field of clinical psychophysiology. Understanding the functional significance of the FRN is essential to understand its growing associations with psychopathology and realize its promising clinical utility.

1.1 | Reward prediction errors

Despite decades of research, there remains debate surrounding the functional significance of the FRN. Reinforcement learning theories propose the FRN reflects a reward prediction error (RPE) generated by phasic differences in dopamine neuron signaling (Holroyd & Coles, 2002; Schultz et al., 1997). RPEs are neural representations of value generated by phasic increases or decreases in mesencephalic dopamine signaling directly following outcomes that are better or worse than expected, such as unexpected reward deliveries or electric shocks (Fiorillo et al., 2003). A central feature of RPEs is that they encode not only the size of a violated expectation (i.e., outcome salience) but also the positive or negative direction (i.e., outcome valence), allowing for a common neural currency of learning from rewards and punishments (Caplin & Dean, 2008). For example, positive RPEs also follow unexpectedly absent punishments while negative RPEs follow unexpectedly absent rewards, such as receiving no electric shock or reward delivery when one was expected (Kim et al., 2006; Schultz & Dickinson, 2000).

Most prior FRN studies examined the difference between monetary gains and omissions in reward contexts (see Glazer et al., 2018 for review). Early studies observed greater relative negativity after unexpectedly omitted rewards, leading to accounts that the FRN reflects a negative RPE specific to error-related processing in the anterior-cingulate cortex (ACC; Holroyd & Coles, 2002; Ruchsow et al., 2002). More recent studies suggest this component is rather a superimposed positivity following better (vs. worse) than expected outcomes and reflects reward-specific processing in the basal ganglia, which has been accordingly retitled the Reward-Positivity (RewP; Foti et al., 2011; Holroyd et al., 2008). These studies observed increased relative positivity after unexpected rewards, suggesting the RewP may rather reflect a positive RPE (see Walsh & Anderson, 2012, Sambrook & Goslin, 2015, and San Martín, 2012 for reviews). However, both FRN and RewP amplitude are typically quantified as the difference between favorable and unfavorable feedbacks, making it difficult to determine whether larger amplitude differences are due to increased positivity after rewards (positive RPE), increased negativity after reward omissions (negative RPE), or both. For consistency, we refer to this component as the RewP.

1.2 | Salience-prediction errors

Recent studies have challenged the RPE account proposing the RewP reflects a second kind of prediction error (Oliveira et al., 2007) called a salience-prediction error (SPE; see Bromberg-Martin et al., 2010 for review). Unlike RPEs, SPEs signal the size of unexpected outcomes independent of outcome valence and may display sensitivity for favorable or unfavorable feedback depending on which is more salient in the experimental context (Den Ouden et al., 2009; Lammel et al., 2011; Matsumoto & Hikosaka, 2009). While most prior RewP studies only contrasted rewards and their omissions (hereafter referred to as gains and no-gains for consistency), these studies observed an opposite pattern of activity in punishment conditions where unexpected losses elicited increased positivity compared to unexpected avoided-losses (Hird et al., 2018; Talmi et al., 2013). Under this account, gains and losses are more salient than their zero-value alternatives (i.e., no-gains and avoided-losses), leading to increased positivity consistent with an SPE. This polarity reversal in punishment contexts suggests the RewP reflects a more general neural mechanism sensitive to outcome salience rather than outcome valence.

However, evidence from RewP studies that included both reward and punishment conditions is mixed. In punishment conditions, prior studies have observed increased RewP positivity after losses (Clayson et al., 2019; Hird et al., 2018; Novak & Foti, 2015; Pfabigan et al., 2015; Rawls et al., 2020; Soder & Potts, 2018; Talmi et al., 2013), avoided-losses (Holroyd et al., 2004; Kreussel et al., 2012; Mulligan & Hajcak, 2018; Sambrook et al., 2012), or found no difference between them (Chen et al., 2018; Kujawa et al., 2013; Mei et al., 2018; Zheng et al., 2017). Therefore, it remains unknown whether the RewP is sensitive to more favorable outcomes, more salient outcomes, or both. Resolving this debate is not only essential to establish the construct validity of the RewP across reward and punishment contexts but also vital to understand growing associations with psychopathology. For example, substantial prior work has linked attenuated RewP amplitudes to depressive disorders, putatively reflecting reward-specific neural deficits characteristic of abnormal dopaminergic RPE signaling (see Proudfit, 2015 for review). Drawing from this work, emerging clinical research has begun to target these reward-specific processing pathways underlying dopaminergic RPE signaling as promising treatment approaches for depressive disorders (Burkhouse et al., 2016, 2018; Kujawa et al., 2019). However, if the RewP rather reflects an SPE, associations with depression may instead result from more general deficits in salience-related processing and require accordingly different treatment approaches.

1.3 | Stimulus frequency

One overlooked methodological difference between these prior studies is the nature of feedback stimuli between conditions. Studies that repeat feedback stimuli to denote both no-gains and avoided-losses tend to observe either no effect of outcome valence or a RewP polarity reversal in punishment conditions. Repeating the same stimulus to represent zero-value feedback across reward and punishment conditions (e.g., commonly represented by “0”) decreases the frequency of feedback stimuli representing gains in reward contexts and losses in punishment contexts (e.g., commonly represented by “+” or “−”). This experimental manipulation may introduce a more general feature of neural processing associated with stimulus frequency regardless of whether that stimulus represents rewarding or punishing information (see Barto et al., 2013 for review). As a task progresses, frequent stimuli become more expected while infrequent stimuli become less expected. When an infrequent stimulus is presented, this prior expectation is violated and therefore may generate an SPE. Under this account, infrequent feedback stimuli may generate an overlapping positivity that is superimposed onto the typical post-feedback RewP waveform. This superimposed positivity may artificially eliminate or reverse RewP polarity in punishment contexts when monetary losses (compared to avoided-losses) are delivered using more infrequent feedback stimuli.

Therefore, prior studies may have conflated two distinct types of “outcome”: a given feedback stimulus (i.e., “+” or “−”) and what that stimulus abstractly represents (i.e., monetary gain or loss). It remains unknown whether the RewP polarity reversal in punishment conditions is driven by valence-related processing specific to rewards and punishments, a more general salience-related processing sensitive to the frequency of feedback stimuli, or some combination of both. The current study aims to disentangle the influence of stimulus frequency and outcome valence on the RewP across reward and punishment contexts.

1.4 | Feedback-related P2 and P3

Decades of electrophysiological research have identified two additional ERP components elicited during reward and punishment processing that surround the RewP called the P2 and P3 (Polich, 2007; Potts et al., 2006). While both components are inconsistently associated with outcome valence (San Martín, 2012; San Martín et al., 2010), far less work has investigated the effect of stimulus frequency on either component during reward and punishment processing. In line with recent recommendations to broaden the time course of ERP analysis during feedback processing (Glazer et al., 2018), we also examined the effects of outcome valence and stimulus frequency on the post-feedback P2 and P3 across reward and punishment contexts.

First, the P3 is a positive centroparietal deflection associated with stimulus categorization and context updating elicited from 350 to 500 ms following salient stimuli (Donchin & Coles, 1988). Numerous studies confirm infrequent stimuli increase P3 positivity across various experimental contexts and neural generators (see Polich, 2007 for review). While this general sensitivity to stimulus frequency is found across several different kinds of task contexts, previous evidence also supports a more specific role for the P3 during reward and punishment feedback processing. During feedback processing, the P3 is sensitive to the motivational significance of feedback and updates predictive models of the environment to optimize future action selection (see Nieuwenhuis, 2011 for review). Under these accounts, the P3 may increase following either favorable or unfavorable feedback depending on which outcome is more motivationally salient in the experimental context.

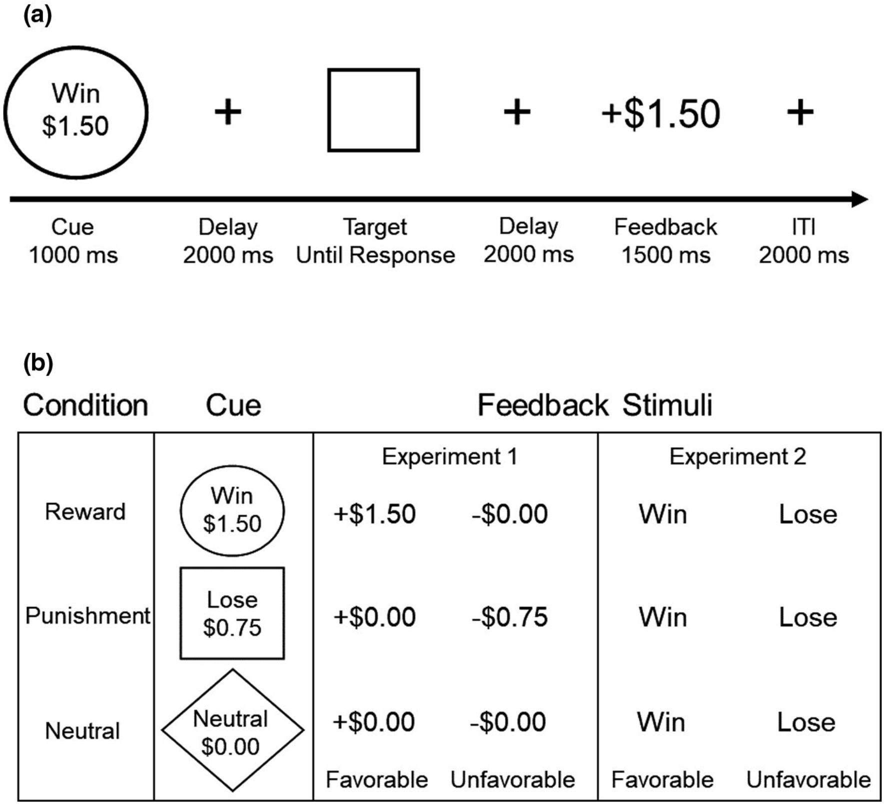
However, evidence supporting consistent P3 sensitivity to outcome valence across reward and punishment contexts is mixed (see San Martín, 2012 for review). Interestingly, many of the same studies that repeated feedback stimuli to examine the RewP observed a similar pattern of P3 activity where favorable outcomes increased positivity in reward conditions while this effect was absent or reversed in punishment conditions (Chen et al., 2018; Clayson et al., 2019; Kujawa et al., 2013; Mei et al., 2018; Pfabigan et al., 2015; Zheng et al., 2017). These results suggest an overlapping positivity associated with differences in stimulus frequency may similarly lead to inconsistent P3 sensitivity to outcome valence across reward and punishment contexts. Therefore, favorable outcomes may increase P3 positivity across reward and punishment contexts, but only when all feedback stimuli are equally frequent.

Second, the P2 is a positive frontocentral deflection from 150 to 250 ms associated with early selective attention toward task-relevant stimuli (Potts et al., 2006). Although less work has examined the P2 in reward and punishment feedback contexts, prior studies indicate the P2 is also sensitive to outcome salience and stimulus frequency, increasing selective attention following more task-relevant and less frequent stimuli (Luck & Hillyard, 1994). While some studies indicate the P2 is involved in goal-directed attention (Potts & Tucker, 2001), suggesting a shared role in reward and punishment processing, sensitivity to outcome valence is less consistent (Groen et al., 2008; Nadig et al., 2019; San Martín et al., 2010). Therefore, while the P2 may be insensitive to outcome valence following feedback, infrequent feedback stimuli may require greater early attention and increased P2 amplitude, leading to inconsistent results in prior studies.

1.5 | Modified monetary incentive delay task

The current study examined outcome valence and stimulus frequency effects on the feedback-related P2, RewP, and P3 in reward, punishment, and neutral contexts across two identical experiments that only varied how often feedback stimuli were repeated between conditions (see Figure 1). Both experiments utilized identical versions of a modified electrophysiological monetary incentive delay task (eMID; Broyd et al., 2012; Novak & Foti, 2015). Cues before each trial indicated reward (monetary gains vs. no-gains), punishment (monetary losses vs. avoided-losses), or neutral (favorable vs. unfavorable feedback with no monetary consequences, hereafter referred to as neutral-gain and neutral-loss for consistency) conditions. Participants then responded as quickly as possible to a target stimulus (white square) and received feedback indicating good (i.e., quick enough) or bad (i.e., too slow) performance. However, several studies indicate that performative tasks influence feedback-related ERPs when outcomes are dependent on participant performance (see Walsh & Anderson, 2012 and Sambrook & Goslin, 2015 for reviews). For example, when outcomes are contingent on reaction time, participants may alter their trial-by-trial outcome predictions for upcoming feedback based on subjectively quicker or slower responses (Balleine et al., 2009), leading to expectation violations that may modulate both RewP and P3 amplitudes (see San Martín, 2012 for review). To control for performative effects, we modified the eMID so participants simply completed a two-choice gamble by guessing left or right direction following the presentation of the target stimulus.

Critically, each experiment varied how often feedback stimuli were repeated between conditions. In experiment 1, while monetary gains and losses were represented by unique feedback stimuli (i.e., +$1.50 vs. −$0.75), feedback stimuli that delivered no-gains and avoided-losses were repeated to represent neutral-gains and neutral-losses (i.e., +$0.00 and −$0.00) and were therefore presented twice as often throughout the experiment. Repeating feedback stimuli for zero-value outcomes may increase positivity across all three ERP components for less frequently



Condition	Cue	Experiment 1		Experiment 2	
Reward	Win $1.50	+$1.50	-$0.00	Win	Lose
Punishment	Lose $0.75	+$0.00	-$0.75	Win	Lose
Neutral	Neutral $0.00	+$0.00	-$0.00	Win	Lose
		Favorable	Unfavorable	Favorable	Unfavorable

FIGURE 1 Task structure and stimuli for the modified eMID. (a) (top) Trial structure displaying an example Reward trial with favorable feedback. (b) (bottom) Cue stimuli for both experiments in each condition (left) and feedback stimuli for each condition separated by experiment (right)

presented stimuli (i.e., monetary gains and losses) even when favorable and unfavorable feedback are equiprobable within each condition. To test this hypothesis, we conducted a second experiment that presented all feedback stimuli equally often. Experiment 2 was identical to the first experiment except all favorable and unfavorable feedback stimuli were indicated by the words Win and Lose in each condition. To separate independent effects of stimulus frequency from outcome expectancy, both experiments kept the ratio of favorable to unfavorable feedback at 50% within each condition. Therefore, all outcomes were equally unexpected.

This methodological approach has two important advantages. First, this two-experiment design isolates valence-related processing specific to reward and punishments from more general salience-related processing associated with stimulus frequency. We predicted that infrequent feedback stimuli would increase both the P2 and P3 components in experiment 1, consistent with related research (see Polich, 2007 for review; Luck & Hillyard, 1994). We further predicted that only the P3 would display an additional sensitivity for favorable outcomes when feedback stimulus frequency is kept constant in experiment 2, consistent with a specific role for the P3 during reward and punishment feedback processing (Nieuwenhuis, 2011). Secondly, although this design cannot directly examine whether the RewP reflects a reward- or salience-prediction error because these experiments did not manipulate outcome expectancy, it allows for a direct test of competing hypotheses. When favorable and unfavorable feedbacks are equiprobable in punishment conditions, RPE theories predict increased RewP positivity following more favorable outcomes (i.e., avoided-losses) while SPE theories predict increased positivity following more salient outcomes (i.e., monetary losses). Collectively, results will have important implications for the construct validity of the RewP, interpreting associations with psychopathology, and for the use of ERP methodologies to examine reward and punishment feedback processing.

2 | METHOD

2.1 | Experiment 1 participants

50 healthy and unmedicated Northwestern undergraduates were recruited. Participants were first consented and completed a variety of questionnaires as part of a larger study not presented here. Participants then completed the modified two-choice eMID task while EEG was recorded. Participants were then paid and thoroughly debriefed. Although participants were told the sum of their monetary gains and losses at the end of the task would determine their final earnings, all participants received $10 following the experiment to ensure fairness in addition to receiving course credit. Two participants were excluded, one due to a computer error and excessive artifact rejection for the other, resulting in a total of 48 participants retained for analysis (25 females, mean age = 18.65, age SD = 0.85, 68% Caucasian, 13% Multiracial, 9% Asian, 6% Latino, and 4% African American).

This sample size was chosen to ensure sufficient power to detect outcome valence effects on the RewP in both reward and punishment conditions, which is hypothesized to be large in size. Specifically, an a priori power analysis was conducted using data from a prior EMID study that reported gains were more positive than no-gains in the reward condition while losses were more positive than avoided-losses in the punishment condition (Novak & Foti, 2015, experiment 1). The power analysis was conducted using the G*Power software using an a priori power analysis from the *t*-test family using a two-tailed statistical test of the difference between dependent means. Error probability was set to 0.05, power was set to 0.80, and the effect size was set to 0.575 as the average effect size of outcome valence on the RewP across reward and punishment conditions reported by Novak and Foti (2015) (experiment 1). Results revealed that a sample size of 26 participants was required to achieve at least 80% statistical power for these analyses. However, given our modified EMID task that introduces a novel two-choice design, we chose to collect at least 20 additional participants to ensure sufficient power. While less work has examined the post-feedback P2 component, an identical power analysis conducted using the effects size of 1.02 representing outcome valence effects on the P3 in the punishment condition from this same study revealed a sample size of only 10 participants was sufficient to achieve at least 80% statistical power.

2.2 | Experiment 1 procedure

Stimulus presentation was administered using E-Prime software (Psychology Software Tools, Pittsburgh, PA) and displayed on a high-performance 24-inch BenQ LED monitor (BenQ Corp., Taipei, Taiwan). The eMID task (Broyd et al., 2012; Knutson et al., 2000) was slightly modified to examine electrocortical indices of reward and punishment feedback evaluation. Each trial began with a fixation cross presented for 2000 ms followed by one of three equiprobable cues presented for 1000 ms that indicated trial condition. Reward cues were circles with the word “Win” in the middle while punishment cues were squares with the word “Lose” in the middle. Both circle and square cues included their respective monetary amounts

TABLE 1 Means and standard deviations for favorable and unfavorable feedback displayed separately in reward (monetary gains vs. no-gains), punishment (avoided-losses vs. monetary losses), and neutral (gain vs. loss feedback only) conditions for the P2 (left), RewP (middle), and P3 (right) in experiment 1

		P2		RewP		P3	
Cue-condition	**Outcome**	**Mean**	**SD**	**Mean**	**SD**	**Mean**	**SD**
Reward	Favorable	9.92	5.21	16.20	8.59	20.13	10.08
	Unfavorable	8.86	5.09	12.63	7.32	17.49	9.46
Punishment	Favorable	7.46	5.33	10.80	6.94	16.07	9.99
	Unfavorable	8.61	4.81	13.09	7.01	15.88	9.00
Neutral	Favorable	5.50	4.46	6.69	5.82	9.18	7.58
	Unfavorable	6.41	4.88	7.58	5.75	9.71	6.50

displayed underneath the words Win and Lose ("$1.50" and "$0.75"). Following prior studies, monetary gains in the reward condition were twice as large as monetary losses in the punishment condition, corresponding to their subjective value when outcomes are uncertain (Tversky & Kahneman, 1974). Neutral cues were diamonds that contained the word "Neutral" in the middle with a "$0.00" amount displayed underneath indicating that no money could be won or lost on these trials, although favorable or unfavorable feedback was still delivered. Participants were instructed to maximize favorable feedback in neutral conditions as well. Following the cue, a fixation cross was randomly jittered between 2000 and 2500 ms followed by a white square that remained on the screen until a response was received. Participants then pressed either the right or left response box button with their right index finger when the white square appeared. Participants were instructed that on each trial only one button is correct and will result in favorable feedback while the other is incorrect and will result in unfavorable feedback. After a response, another fixation cross was presented for 2000 ms before feedback presentation.

Finally, a feedback stimulus was presented that contained both outcome valence and magnitude information. In reward conditions, correct guesses resulted in monetary gains of $1.50 while incorrect guesses resulted in no-gains of $0.00. In punishment conditions, incorrect guesses resulted in monetary losses of $0.75 while correct guesses resulted in avoided-losses of $0.00. Feedback stimuli representing monetary gains and losses were consistent with their monetary amounts: +$1.50 and −$0.75. Critically, feedback stimuli in reward and punishment conditions denoting no-gains and avoided-losses were repeated in neutral conditions to denote neutral-gains and neutral-losses: +$0.00 and −$0.00. Importantly, unknown to participants, all outcomes within each block were predetermined to keep the ratio of favorable to unfavorable feedback at 50% following each cue (see Table 1). Each block contained 30 trials consisting of 10 instances of each cue stimulus and 5 instances of each feedback stimulus presented randomly without replacement. There were 5 blocks for a total of 150 trials. Before the task, participants were thoroughly trained on the task by a research assistant to ensure they understood all feedback stimuli and completed 12 practice trials.

2.3 | Experiment 2 participants

Experiment 2 was conducted independently from experiment 1 with a completely different sample of individuals. None of the participants in experiment 2 participated in the first experiment, and vice versa. 45 healthy and unmedicated Northwestern undergraduates were recruited and completed experiment 2. Of the total 45 participants, four were removed due to computer errors, one for not completing the eMID task, and three were removed for excessive artifact rejection, resulting in a total of 37 participants retained for analysis (24 females, mean age = 18.70, age SD = 0.84, 49% Caucasian, 35% Asian, 11% Latino, and 5% African American).

To determine the minimum sample size required to detect outcome valence effects on the RewP in reward and punishment conditions for experiment 2, an a priori power analysis identical to experiment 1 was conducted using data from a similar EMID study (Novak & Foti, 2015, experiment 2). Input parameters included an error probability of 0.05, a power input of 0.80, and an effect size of 0.82 that were entered into the G*Power function that tests two-tailed differences between two dependent means in the a priori *t*-test family. Results revealed that a sample size of 13 participants was required to achieve at least 80% statistical power. As many participants as possible were recruited to achieve a sample size comparable to experiment 1.

2.4 | Experiment 2 procedure

In experiment 2, participants completed a modified two-choice eMID task identical to experiment 1 except for a single modification. Like experiment 1, favorable and unfavorable feedback were presented an equal number of times following each cue (i.e., 50%). However, unlike experiment 1, feedback stimuli were modified such that all favorable feedback consisted of the word "Win" (including monetary gains, avoided-losses, and neutral-gains) while all unfavorable feedback consisted of the word "Lose" (including no-gains, monetary losses, and neutral-losses). This manipulation controlled for stimulus frequency ensuring that all feedback stimuli were presented an equal number of times throughout the task (i.e., 50%).

2.5 | Electrophysiological recording

Data from both experiments were entered into an identical processing pipeline. EEG data were recorded using Neuroscan amplifiers (DC to 100 Hz online, Neuroscan Inc.) within an electromagnetically shielded booth. Fifty-eight passive electrodes (Ag/AgCl) were applied to the scalp following the international 10–20 standard (Jasper, 1958) with four external sensors placed above and below the left eye and beside each eye for electrooculogram recording. A nylon cap was used with conductive gel applied to each electrode and impedance was kept below 10 and 5 kΩ for the external and scalp electrodes. Continuous EEG data were digitized at 500 Hz, online referenced to the left mastoid, and re-referenced offline to the average of both mastoids. All offline EEG processing was done using EEGLAB (Delorme & Makeig, 2004) and ERPLAB (Lopez-Calderon & Luck, 2014) in MatLab (MATLAB, 2017). Data were resampled at 250 Hz and clean-lined with a sliding window to adaptively estimate sine wave amplitude and subtract line noise.

Next, two files were created for each participant, one with a high-pass filter of 1.0 Hz used only for independent component analysis (ICA) and another with a 0.01 Hz cutoff. For the ICA file, noisy channels were identified and removed using visual inspection. Large scalp artifacts were then removed using continuous automated artifact detection removing segments of data if any scalp electrode exceeded a voltage threshold of 500 μV in a 500 ms window that slides across the full continuous data every 250 ms. Next, ICA was performed and ICA components corresponding to ocular and muscular artifacts were removed. The resulting ICA weights were then applied to the 0.01 Hz file. This file was then low-pass filtered at 30 Hz and epoched from −100 to 1000 ms time-locked to feedback onset. Epochs were then baseline corrected using the 100 ms pre-stimulus interval and artifactual epochs were rejected if midline electrodes exceeded a 100 μV threshold in a 200 ms window that slides across the entire epoch in steps of 100 ms. After artifact rejection, an average of 24.39 trials-per-condition were retained for experiment 1 (SD = 1.18) and 23.88 trials-per-condition for experiment 2 (SD = 1.71). Single-trial EEG epochs were then averaged separately, resulting in 6 bins reflecting cue-condition (3) × outcome (2). Based on prior research recommending at least 20 trials to sufficiently measure the optimal RewP amplitude (Marco-Pallares et al., 2011), participants with an average of less than 20 trials-per-condition were excluded from data analysis. All excluded participants had an average of less than 17 acceptable trials-per-condition.

2.6 | ERP measurement

Visual inspection of the ERP waveforms and their scalp topographies across both experiments revealed two frontocentral components consistent with the P2 and RewP and a centroparietal deflection consistent with the P3. Following prior studies, in both experiments the RewP was measured from 250 to 350 ms at electrode FCz where the difference between favorable and unfavorable feedback was maximal while the P2 and P3 were measured from 150 to 250 ms and 350 to 450 ms at FCz and CPz, respectively, where positivity was maximal. Single electrode sites were chosen in line with prior similar studies (Chen et al., 2018; Clayson et al., 2019; Kreussel et al., 2012; Kujawa et al., 2013; Novak & Foti, 2015; Pfabigan et al., 2015; Zheng et al., 2017).[1]

3 | RESULTS

3.1 | Results experiment 1

For each ERP component, a separate 3 (cue-condition: reward × punishment × neutral) × 2 (outcome: favorable × unfavorable) repeated measures ANOVA was conducted. Follow-up *t*-tests were performed to explore significant effects. In all analyses, Greenhouse-Geisser correction was used for all ANOVA analyses while Cohen's *d* was used to calculate all *t*-test effect sizes. No additional variables were included in the analyses.

3.1.1 | RewP

Results for the RewP revealed a significant main effect of cue-condition ($F(2, 94) = 85.30, p < .001, \eta_p^2 = 0.65$) and a significant cue-condition × outcome interaction ($F(2, 94) = 31.38, p < .001, \eta_p^2 = 0.40$). Follow-up *t*-tests revealed

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[1] As a follow-up analysis, the data showed an identical pattern of statistical significance in the results when the same statistical analyses were performed on pooled electrode averages (P2 and RewP measured from the average of FCz/Fz/Cz/FC1/FC2 and P3 scored as the average of CPz/Cz/Pz/CP1/CP2).

that RewP amplitudes for reward feedback were significantly more positive than amplitudes for punishment ($t(47) = 5.33$, $p < .001$, $d = 0.769$) and neutral feedback ($t(47) = 10.95$, $p < .001$, $d = 1.567$) while RewP amplitudes for punishment feedback were significantly more positive than amplitudes for neutral feedback ($t(47) = 8.69$, $p < .001$, $d = 1.244$). To unpack the interaction, within- and between-condition *t*-tests were performed. Separate *t*-tests for each cue-condition revealed RewP amplitudes for favorable outcomes were significantly more positive than amplitudes for unfavorable outcomes in reward conditions ($t(47) = 5.30$, $p < .001$, $d = 0.759$) while amplitudes for unfavorable outcomes were significantly more positive than for favorable outcomes in punishment conditions ($t(50) = -3.80$, $p < .001$, $d = 0.544$). In the neutral condition, RewP amplitudes for unfavorable outcomes were only marginally more positive than amplitudes for favorable outcomes ($t(47) = -1.91$, $p = .063$, $d = 0.273$). Between cue-condition *t*-tests performed on favorable–unfavorable outcome difference waves calculated separately within each cue-condition revealed that RewP difference wave amplitudes in reward conditions were significantly greater than amplitudes in punishment ($t(47) = 6.56$, $p < .001$, $d = 0.939$) and neutral conditions ($t(47) = 6.33$, $p < .001$, $d = 0.906$) while RewP difference wave amplitudes in punishment conditions were only marginally more negative than for amplitudes in neutral conditions ($t(47) = -1.99$, $p = .053$, $d = 0.284$).

3.1.2 | P3

For the P3, there was a significant main effect of cue-condition ($F(2, 94) = 92.71$, $p < .001$, $\eta_p^2 = 0.66$) and a significant cue-condition × outcome interaction ($F(2, 94) = 8.78$, $p < .001$, $\eta_p^2 = 0.16$). P3 amplitudes for reward feedback were significantly more positive than amplitudes for punishment ($t(47) = 5.69$, $p < .001$, $d = 0.815$) and neutral feedback ($t(47) = 11.06$, $p < .001$, $d = 1.583$) while P3 amplitudes for punishment feedback were significantly more positive than amplitudes for neutral feedback ($t(47) = 8.99$, $p < .001$, $d = 1.288$). To unpack the interaction, within- and between-condition *t*-tests were performed. P3 amplitudes for favorable outcomes were significantly more positive than amplitudes for unfavorable outcomes in reward conditions ($t(47) = 3.77$, $p < .001$, $d = 0.540$) while no significant differences in P3 amplitude between favorable and unfavorable outcomes emerged in punishment ($p = .761$) or neutral ($p = .330$) conditions. *T*-tests performed on favorable–unfavorable outcome difference waves revealed that P3 difference wave amplitudes in reward conditions were significantly greater than amplitudes in punishment ($t(47) = 2.87$, $p = .006$, $d = 0.410$) and neutral conditions ($t(47) = 3.95$, $p < .001$, $d = 0.566$) while the latter two did not significantly differ ($p = .321$).

3.1.3 | P2

Results for the P2 mirrored the RewP results. For the P2, there was a significant main effect of cue-condition ($F(2, 94) = 44.03$, $p < .001$, $\eta_p^2 = 0.48$) and a significant cue-condition × outcome interaction ($F(2, 94) = 7.91$, $p = .001$, $\eta_p^2 = 0.14$). P2 amplitudes for reward feedback were significantly more positive than amplitudes for punishment ($t(47) = 4.84$, $p < .001$, $d = 0.692$) and neutral feedback ($t(47) = 7.85$, $p < .001$, $d = 1.123$) while P2 amplitudes for punishment feedback were significantly more positive than amplitudes for neutral feedback ($t(47) = 5.60$, $p < .001$, $d = 0.802$). To unpack the interaction, within- and between-condition *t*-tests were performed. P2 amplitudes for favorable outcomes were significantly more positive than amplitudes for unfavorable outcomes in for reward conditions ($t(47) = 2.80$, $p = .007$, $d = 0.401$) while P2 amplitudes for unfavorable outcomes were significantly more positive than amplitudes for unfavorable outcomes in punishment conditions ($t(47) = -2.88$, $p = .006$, $d = 0.412$). In neutral conditions, P2 amplitudes for unfavorable outcomes were only marginally more positive than amplitudes for favorable outcomes ($t(47) = -1.99$, $p = .053$, $d = 0.285$). *T*-tests performed on favorable–unfavorable outcome difference waves revealed that P2 difference wave amplitudes in reward conditions were significantly greater than amplitudes in punishment ($t(47) = 4.12$, $p < .001$, $d = 0.590$) and neutral conditions ($t(47) = 2.95$, $p = .005$, $d = 0.423$) while the latter two did not significantly differ ($p = .70$).

3.1.4 | Experiment 1 discussion

Experiment 1 examined the feedback-related P2, RewP, and P3 in reward, punishment, and neutral contexts during a modified two-choice eMID task that varied feedback stimulus frequency (see Table 1 for means and standard deviations for each ERP component). Consistent with most prior studies, favorable outcomes (i.e., monetary gains) in the reward condition elicited a greater RewP positivity than unfavorable outcomes (i.e., no-gains). However, this pattern was reversed in the punishment condition where unfavorable outcomes (i.e., monetary losses) elicited increased RewP positivity compared to favorable outcomes (i.e., avoided-losses). An identical pattern of results emerged for the P2. Given the early timing and frontocentral topography of the P2 and RewP, these results are unlikely explained solely by component overlap with the centroparietal P3 which was only increased for favorable compared to unfavorable outcomes in the reward condition. To confirm these results were not due to component overlap among any of the three ERPs, we performed a temporospatial principal component analysis (Dien, 2010) that successfully separated the P2, RewP, and P3 and revealed a similar pattern of results (see Supplemental Materials). This follow-up PCA analysis was performed only for experiment 1.

Although SPE theories suggest that monetary losses increase RewP positivity because they are more motivationally salient than avoided-losses, these results may rather be driven by differences in feedback stimulus frequency. Repeating feedback stimuli for zero-value outcomes (i.e., no-gains and avoided-losses) may increase positivity across all three components for less frequent feedback stimuli (i.e., monetary gains and losses) even when favorable and unfavorable feedback are equiprobable within each condition. To test this hypothesis, we conducted a second experiment that kept stimulus frequency constant between reward, punishment, and neutral conditions such that all feedback stimuli were presented equally often throughout the task.

3.2 | Experiment 2 results

Statistical analyses for experiment 2 were identical to those performed in experiment 1.

3.2.1 | RewP

Results for the RewP revealed a significant main effect of cue-condition ($F(2, 72) = 20.36$, $p < .001$, $\eta_p^2 = 0.36$) and outcome ($F(1, 36) = 11.77$, $p = .002$, $\eta_p^2 = 0.25$) while their interaction was non-significant ($p = .76$). Consistent with Experiment 1, follow-up *t*-tests revealed that RewP amplitudes for reward feedback was significantly more positive than amplitudes for punishment ($t(36) = 2.41$, $p = .021$, $d = 0.392$) and neutral feedback ($t(36) = 5.09$, $p < .001$, $d = 0.827$) while RewP amplitudes for punishment feedback were significantly more positive than amplitudes for neutral feedback ($t(36) = 4.94$, $p < .001$, $d = 0.804$). However, unlike experiment 1, favorable outcomes (monetary gains, avoided-losses, and neutral-gains) elicited significantly more positive RewP amplitudes than unfavorable outcomes (no-gains, monetary losses, and neutral-losses) regardless of cue-condition.

3.2.2 | P3

Results for the P3 mirrored the RewP results. For the P3, there was a significant main effect of cue-condition ($F(2, 72) = 28.56$ $p < .001$, $\eta_p^2 = 0.44$) and outcome ($F(1, 36) = 10.34$, $p = .003$, $\eta_p^2 = 0.22$), but no significant interaction ($p = .094$). Follow-up *t*-tests revealed that P3 amplitudes for reward were significantly more positive than amplitudes for punishment ($t(36) = 2.42$, $p = .021$, $d = 0.394$) and neutral feedback ($t(36) = 6.22$, $p < .001$, $d = 1.012$) while P3 amplitudes for punishment feedback were significantly more positive than amplitudes for neutral feedback ($t(36) = 5.48$, $p < .001$, $d = 0.892$). Similar to the RewP, favorable outcomes elicited significantly more positive P3 amplitudes for favorable than unfavorable outcomes regardless of cue-condition.

3.2.3 | P2

For the P2, only a significant main effect of cue-condition emerged ($F(2, 72) = 11.99$, $p < .001$, $\eta_p^2 = 0.25$). Follow-up *t*-tests revealed that P2 amplitudes for reward and punishment were significantly greater than amplitudes for neutral feedback ($t(36) = 4.36$, $p < .001$, $d = 0.650$; $t(36) = 4.15$, $p < .001$, $d = 0.661$) while the former two did not significantly differ ($p = .403$).

3.2.4 | Experiment 2 discussion

Experiment 2 was identical to experiment 1 except all favorable and unfavorable feedback was delivered using the words Win and Lose in each condition, controlling for stimulus frequency by presenting each feedback stimuli equally often throughout the task (see Table 2 for means and standard deviations for each ERP component). Consistent with experiment 1, favorable outcomes in the reward condition (i.e., monetary gains) elicited increased RewP and P3 positivity compared to unfavorable outcomes (i.e., no-gains). However, unlike experiment 1, favorable outcomes in the punishment condition (i.e., avoided-losses) also elicited increased RewP and P3 positivity compared to favorable outcomes (i.e., monetary losses) while the P2 was insensitive to outcome valence across all three conditions. Together, these results suggest infrequent feedback stimuli in experiment 1 generated overlapping positivity associated with stimulus frequency that coincided with the time course and scalp topography of the P2, RewP, and P3 (see Figure 2). By contrast, when

TABLE 2 Means and standard deviations for favorable and unfavorable feedback displayed separately in reward (monetary gains vs. no-gains), punishment (avoided-losses vs. monetary losses), and neutral (gain vs. loss feedback only) conditions for the P2 (left), RewP (middle), and P3 (right) in experiment 2

		P2		RewP		P3	
Cue-condition	Outcome	Mean	SD	Mean	SD	Mean	SD
Reward	Favorable	5.82	3.82	9.59	8.98	13.32	8.65
	Unfavorable	5.05	4.17	7.98	7.80	11.00	8.30
Punishment	Favorable	4.97	4.01	8.00	7.10	11.50	7.51
	Unfavorable	5.15	4.17	6.64	6.25	10.01	7.04
Neutral	Favorable	3.82	4.13	4.97	5.71	7.25	6.05
	Unfavorable	3.10	4.11	3.95	5.35	6.77	5.44

stimulus frequency was controlled, experiment 2 revealed favorable outcomes that increased the RewP and P3 in both reward and punishment conditions while the P2 was insensitive to outcome valence (see Figures 3 and 4).

4 | GENERAL DISCUSSION

4.1 | Reward-positivity: Reward or salience prediction error?

Reinforcement learning theories propose the RewP reflects a RPE that increases following more favorable outcomes (i.e., monetary gains and avoided-losses) while competing salience accounts suggest the RewP reflects an SPE that increases following more salient outcomes (i.e., monetary gains and losses). The present results indicate favorable outcomes and infrequent feedback stimuli both increased RewP positivity across reward and punishment contexts, supporting some degree of combined RPE and SPE encoding.

Consistent with both accounts, monetary gains (vs. no-gains) increased RewP positivity in reward contexts across both experiments. However, although monetary losses increased RewP positivity for punishment conditions in experiment 1 when feedback stimuli were infrequent, consistent with SPE accounts, experiment 2 revealed increased positivity for avoided-losses when stimulus frequency was controlled, consistent with RPE accounts. These results suggest favorable outcomes increase RewP positivity in both reward and punishment contexts when all feedback stimuli are equiprobable. In support, prior studies controlling for stimulus frequency also observed increased RewP positivity following favorable outcomes in both reward and punishment conditions (Holroyd & Coles, 2002; Kreussel et al., 2012; Mulligan & Hajcak, 2018; Sambrook et al., 2012), consistent with experiment 2.

By contrast, results suggest decreased stimulus frequency in experiment 1 generated an overlapping positivity that artificially reversed RewP polarity in the punishment condition and likely inflated extant differences in the reward condition, supporting the presence of salience encoding in the RewP time window. Importantly, favorable and unfavorable outcomes were equally unexpected across both experiments (i.e., 50% likely), indicating this overlapping positivity was driven by perceptual differences in stimulus frequency rather than the motivational significance of what that stimulus represents (i.e., monetary gains and losses), as proposed by SPE theories (Hird et al., 2018; Talmi et al., 2013). These results suggest inconsistencies among prior studies that repeated feedback stimuli in a similar fashion to experiment 1 were likely driven in part by differences in stimulus frequency that eliminated differences or reversed RewP polarity in punishment conditions (Chen et al., 2018; Clayson et al., 2019; Hird et al., 2018; Kujawa et al., 2013; Mei et al., 2018; Novak & Foti, 2015; Pfabigan et al., 2015; Rawls et al., 2020; Soder & Potts, 2018; Talmi et al., 2013; Zheng et al., 2017). Together, results indicate that the RewP tracks both valence- and salience-related feedback information.

These two experiments alone cannot rule out two important alternative explanations of the present results. First, it is possible that infrequent feedback stimuli in experiment 1 (i.e., +$1.50 and −$0.75) elicited greater RewP positivity than frequent stimuli (i.e., +$0.00 and −$0.00) because they required additional cognitive resources to interpret. Second, it is possible that the outcome magnitude component of feedback stimuli (i.e., $1.50 and $0.75) was more salient than the simple signed component (i.e., +/−), resulting in increased RewP positivity (for example, see Nieuwenhuis et al., 2004). However, these alternatives cannot account for results from prior studies that controlled for feedback stimulus complexity and outcome magnitude information. For example, in three prior studies, gains in reward contexts and losses in punishment contexts were represented by a green upward arrow and a red downward arrow while no-gains and avoided-losses were delivered with the stimulus “0” (Clayson et al., 2019; Kujawa et al., 2013; Novak & Foti, 2015). Therefore, while their feedback stimuli frequencies were unbalanced, consistent with experiment 1, these simpler feedback stimuli only contained outcome valence information, consistent

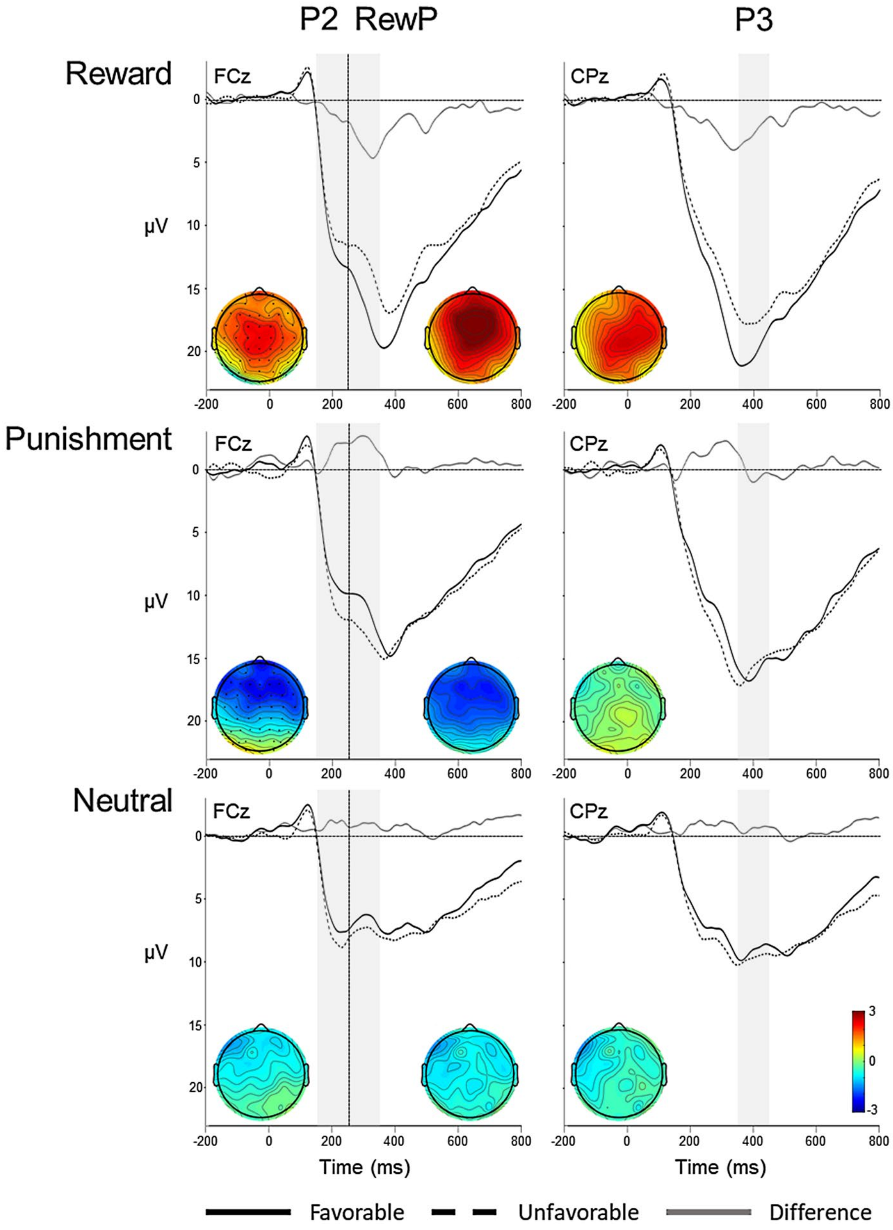


FIGURE 2 Waveforms displaying favorable feedback (solid black line), unfavorable feedback (dashed black line), and favorable–unfavorable feedback difference waves (solid gray line) separately for the P2, RewP, and P3 ERP components from experiment 1 for reward (top), punishment (middle), and neutral (bottom) feedback. Each waveform includes the scalp topography for each component created with favorable–unfavorable difference contrasts with the same scale (bottom right). Shaded areas indicate mean time window of measurement for each component

with experiment 2. In the punishment condition, two studies found a RewP polarity reversal (Clayson et al., 2019; Novak & Foti, 2015) while the other reported no effect of outcome valence (Kujawa et al., 2013), suggesting the present results were driven by differences in feedback stimulus frequency rather than stimulus complexity or an emphasis on outcome magnitude information.

4.2 | Effects of outcome valence and stimulus frequency on the feedback-related P2 and P3

Similar to the RewP, the P3 was also jointly influenced by outcome valence and stimulus frequency. First, controlling for stimulus frequency, experiment 2 revealed consistent P3 sensitivity for favorable outcomes across both reward and punishment contexts while no effects of outcome valence emerged in the neutral condition. These results support a feedback-specific feature of the P3 that reflects increased context updating of predictive models to optimize future action selection during reward and punishment processing (see Nieuwenhuis, 2011 for review). In support, prior work suggests favorable feedback increases P3 positivity when favorable and unfavorable outcomes are not dependent on participant performance and presented equally often (see San Martín, 2012 for review), consistent with experiment 2.

Second, these results suggest infrequent feedback stimuli in experiment 1 elicited an overlapping positivity that eliminated outcome valence differences in the punishment condition. This overlapping positivity is consistent

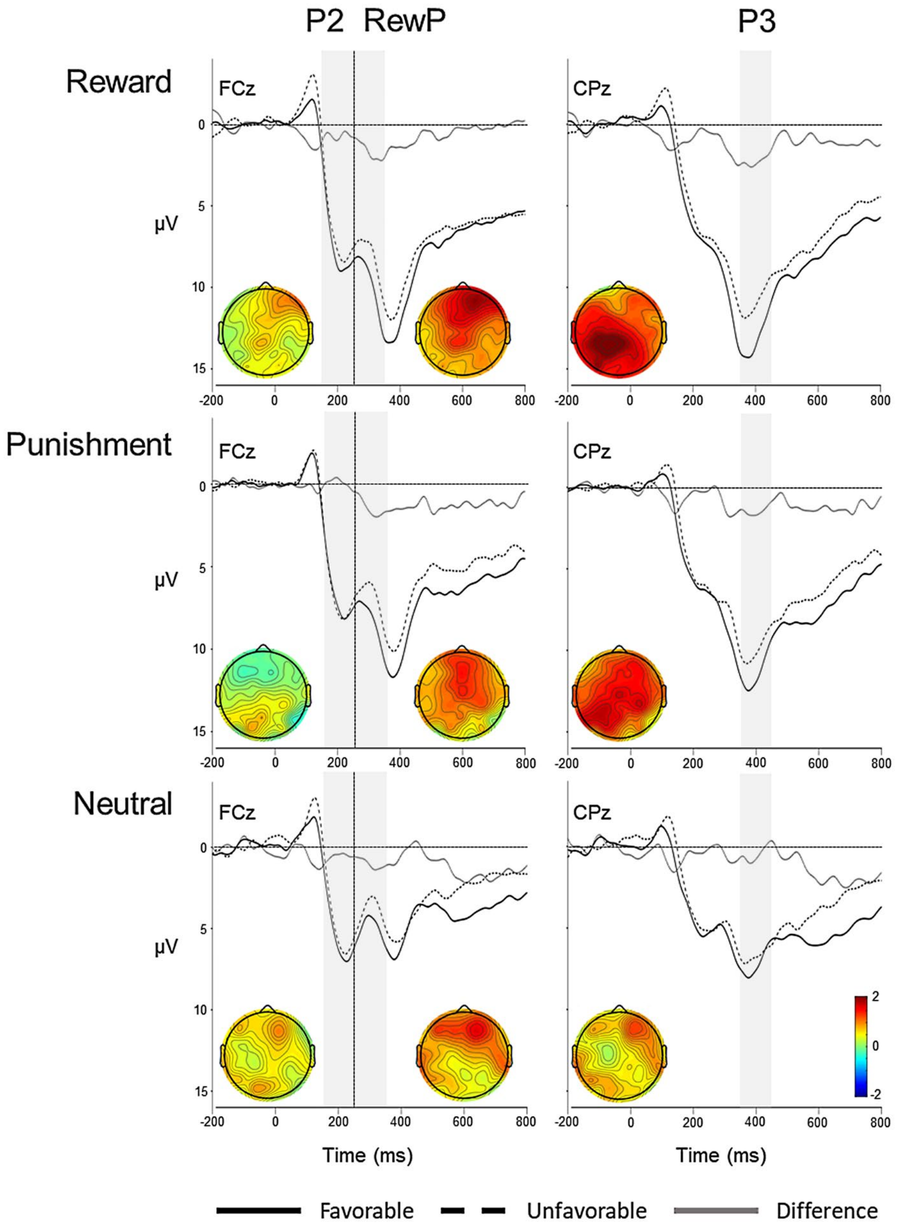
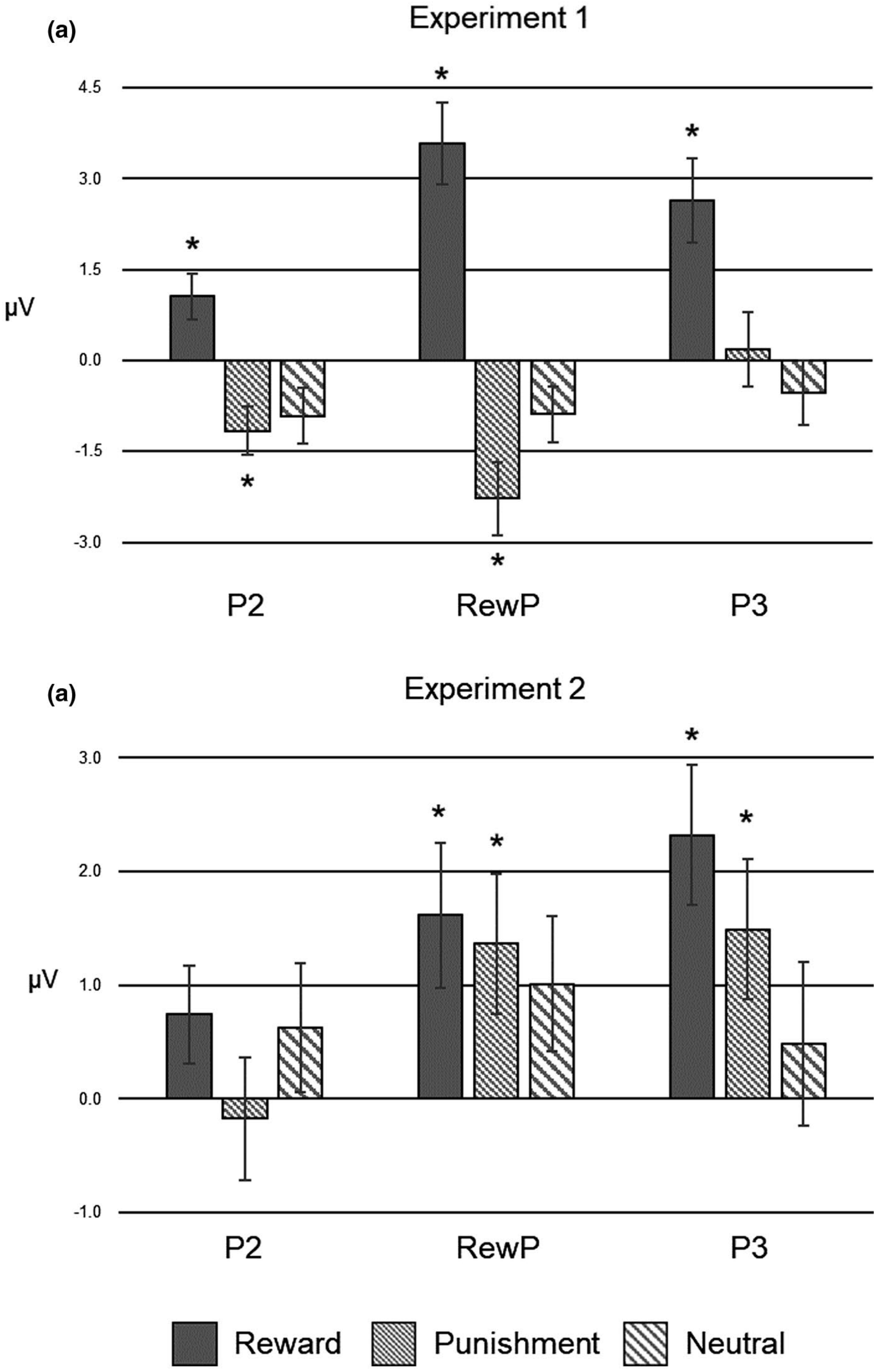


FIGURE 3 Waveforms displaying favorable feedback (solid black line), unfavorable feedback (dashed black line), and favorable–unfavorable feedback difference waves (solid gray line) separately for the P2, RewP, and P3 ERP components from experiment 2 for reward (top), punishment (middle), and neutral (bottom) feedback. Each waveform includes the scalp topography for each component created with favorable–unfavorable difference contrasts with the same scale (bottom right). Shaded areas indicate mean time window of measurement for each component

with a more general P3 function found across a variety of tasks contexts that signals increased attentional allocation and stimulus categorization following infrequent stimuli regardless of whether those stimuli represent rewards or punishments (see Polich, 2007 for review). Together, these results may resolve several inconsistencies among prior P3 studies that repeated feedback stimuli across conditions. Similar to experiment 1, these studies found favorable outcomes increased P3 positivity in reward conditions while this difference was absent or reversed in punishment conditions (Chen et al., 2018; Clayson et al., 2019; Kujawa et al., 2013; Mei et al., 2018; Zheng et al., 2017). Results from experiment 2 suggest a similar combinatory tracking of stimulus frequency associated with salience processing likely introduced overlapping positivity, leading to inconsistent P3 sensitivity to outcome valence.

In addition to the P3, monetary gains and losses in experiment 1 increased P2 positivity in both reward and punishment conditions compared to their zero-value alternatives. However, the P2 was insensitive to outcome valence in experiment 2, suggesting results from the first experiment were entirely driven by the frequency of feedback stimuli. These results support prior evidence that the P2 is sensitive to stimulus frequency (Crowley & Colrain, 2004; Kenemans et al., 1993) and extend this literature to feedback processing. In addition, both reward and punishment feedback elicited greater P2 positivity compared to neutral feedback across both experiments, supporting prior evidence that the P2 is also enhanced for task-relevant stimuli consistent with goal-directed processing (Luck & Hillyard, 1994; Potts & Tucker, 2001). Together, these results suggest the feedback-related P2 reflects

FIGURE 4 Bar graphs displaying results for favorable–unfavorable difference waves for the P2, RewP, and P3 components for (a) Experiment 1 (top) and (b) Experiment 2 (bottom). Asterisks mark difference waves that are significantly different from zero



increased selective attention for more infrequent and task-relevant feedback stimuli, but is insensitive to outcome valence.

4.3 | Implications for reward and punishment processing

Results provide new insights into the influence of salience processing following reward and punishment feedback. While our results suggest the RewP and P3 are sensitive to outcome valence in both reward and punishment contexts, they are also consistent with overlapping salience encoding across all three components that are sensitive to the frequency of feedback stimuli. This salience-related positivity began as early as the P2 and subsequently overlapped in time with valence-specific effects indexed by the RewP and P3. Under predictive coding theories (Friston, 2005; see Den Ouden et al., 2012 for review), more frequent feedback stimuli may generate expectations that they will appear more often in the future regardless of whether they are associated with rewards or punishments. In this way, less frequent feedback stimuli may violate these prior expectations and continue to generate an SPE. Therefore, it is possible that less frequent stimuli are also more salient not because they represent rewarding or punishing information but rather because they violate these previously reinforced expectations.

While valence- and salience-related processing reflect distinct psychological processes (see Den Ouden et al., 2012 for review) and recruit separate neural regions (Jensen et al., 2007; Rothkirch et al., 2012), our results suggest they may overlap in time within the post-feedback time interval. In support, recent empirical and meta-analytic evidence indicates both reward and punishment feedback elicit strong SPE effects that coincide with the time course and scalp topography of the P2, RewP, and P3 while frontocentral RPE encoding emerges only during a shorter time interval overlapping with the RewP and P3 (Sambrook & Goslin, 2014, 2015). This time course of salience- and valence-related encoding across the post-feedback window is consistent with the present results. In fact, our results suggest capturing consistent ERP effects of outcome valence across reward and punishment contexts may depend on controlling for precisely these strong salience signals through careful experimental designs that do not introduce unnecessary competing neural demands on salience-related processing, especially regarding the frequency of feedback stimuli. Future studies investigating electrocortical components specific to reward and punishment feedback should carefully consider competing demands on salience-related processing in their task designs to isolate experimental effects of interest.

For example, it is likely that robust associations between feedback-related ERPs and psychopathology, such as the RewP and depression, may only emerge in certain task contexts that successfully isolate the precise neural processes associated with specific symptom presentations. While it remains unknown whether associations between depression and the RewP extend to punishment conditions, a recent study that included reward and punishment conditions reported no RewP amplitude differences between individuals with high and low depressive symptoms (Chen et al., 2018). However, this study also repeated feedback stimuli for zero-value outcomes (i.e., no-gains and avoided-losses) and found no effect of outcome valence on the RewP in the punishment condition, consistent with experiment 1. Therefore, it is possible that robust associations between depression and the RewP may depend on experimental designs that isolate reward-specific processes associated with outcome valence from more general salience-related processing associated with differences in stimulus frequency.

These results also highlight methodological challenges of using scalp ERP techniques to examine reward and punishment feedback processing. Evidence from other neuroscientific modalities indicates SPEs may disproportionately influence scalp ERP recordings while RPEs may be more difficult to detect, consistent with the present results. Neuroimaging studies typically observe reward and punishment RPEs in subcortical regions such as the ventral tegmental area and ventral striatum while salience effects, especially those related to stimulus frequency differences, are often associated with activity across several primary sensory cortical areas and are even occasionally found within those same subcortical regions associated with reward prediction (see Den Ouden et al., 2012 and Barto et al., 2013 for reviews). Importantly, EEG techniques directly measure cortical activity from excitatory and inhibitory postsynaptic potentials from apical dendrites of pyramidal cells while subcortical activity is only measured indirectly through secondary effects on cortical regions (Nunez & Srinivasan, 2006). This shared cortical specificity of both EEG techniques and SPE activation provides a direct mechanistic pathway for salience-related neural activity to disproportionately influence feedback-related ERPs. In contrast, subtler RPE activation generated in deeper subcortical structures through indirect postsynaptic cortical activity may be much more difficult to detect. These considerations highlight the value of multimodal investigations of reward and punishment processing, such as complementary EEG and functional resonance magnetic imaging (fMRI) methods that are well-suited to examine the neuroanatomical correlates of salience effects on feedback processing.

Finally, while our results suggest reward and punishment contexts elicit shared outcome valence and stimulus frequency effects on the RewP and P3, there is substantial evidence that rewards and punishments recruit distinct neural systems, indicating they may be more dissimilar than alike (see Garrison et al., 2013 for meta-analytic review). In fact, it is possible that the positive and negative RewP deflections following favorable and unfavorable feedback may reflect these separate systems (Gheza et al., 2018). For example, while the RewP has been source localized to the basal ganglia and likely reflects reward-specific processing (Foti et al., 2011), the negative deflection after unfavorable feedback may reflect a more general neural response associated with the anterior-cingulate cortex that is sensitive to unexpected task-relevant stimuli, resembling the N200 ERP component (Ferdinand et al., 2012; Holroyd, 2004). In support, a recent study reported that novel feedback stimuli presented only once throughout a task increased RewP negativity regardless of outcome valence (Brown & Cavanagh, 2020), consistent with a general N200 response sensitive to stimulus novelty and surprise

(Ferrari et al., 2010; Folstein & Van Petten, 2008). Therefore, while infrequent feedback stimuli may increase RewP positivity, truly novel feedback stimuli may increase RewP negativity. However, it remains unknown whether the RewP and P3 may reflect shared or distinct features of reward and punishment processing depending on the task context. Investigating differences between infrequent and novel stimuli on feedback-related ERPs is a promising area for future research that seeks to empirically isolate shared and distinct neural features of reward and punishment processing.

4.4 | Limitations

The current study has several limitations. First, results cannot determine whether the RewP reflects a reward or SPE because only stimulus frequency was manipulated between experiments while outcome expectancy was kept constant. Second, experiment 1 only decreased the stimulus frequency for monetary gains and losses, leading to overlapping positivity associated with differences in stimulus frequency. Future studies should examine whether similar overlapping positivity may emerge when feedback stimuli representing no-gains and avoided-losses are infrequent. Third, in contrast to previous similar studies that used symbols as feedback stimuli (Clayson et al., 2019; Kujawa et al., 2013; Novak & Foti, 2015), our feedback stimuli in experiment 1 contained both magnitude- and valence-related information while experiment 2 used only the words Win and Lose, which may have contributed to the present results. Finally, for the RewP and P3 across both experiments, reward feedback elicited the greatest positivity, punishment feedback elicited intermediate positivity, and neutral feedback elicited the least positivity. However, outcome magnitude varied between conditions (i.e., \$1.50 vs. \$0.75 vs. \$0.00), making it difficult to determine whether these effects were driven by differences between conditions or outcome magnitudes.

4.5 | Conclusions

Despite decades of research, debate remains on whether the RewP reflects an RPE sensitive to outcome valence or an SPE sensitive to outcome salience. Our results indicate favorable outcomes and infrequent stimuli increase the RewP and P3 across reward and punishment contexts, supporting some degree of combined RPE and SPE encoding in the RewP time window. Furthermore, our results newly reveal that infrequent feedback stimuli generated an overlapping positivity that may inflate, eliminate, or even reverse these consistent outcome valence effects on the RewP and P3. Together, results indicate that salience-related processing may disproportionally influence feedback-related ERPs. Future studies investigating electrocortical correlates of reward and punishment feedback should carefully consider the combinatory interplay between salience- and valence-related processing across the post-feedback window.

CONFLICT OF INTEREST

Authors have no conflicts of interest to report.

AUTHOR CONTRIBUTIONS

James E Glazer: Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing—original draft; Writing—review & editing. **Robin Nusslock:** Conceptualization; Data curation; Formal analysis; Funding acquisition; Investigation; Methodology; Project administration; Resources; Software; Supervision; Validation; Visualization; Writing—original draft; Writing—review & editing.

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Supplementary Material

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