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ORIGINAL ARTICLE

Stimulus Novelty Inhibits Reward Evaluation: EEG Evidence

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ABSTRACT

Rewards frequently occur in novel contexts, yet whether novelty facilitates or inhibits reward evaluation remains unclear. Using EEG, we investigated how stimulus novelty affects reward evaluation across two experiments. Participants performed a monetary guessing task where gains and losses were delivered in either novel or familiar forms. In experiment 1 ($N = 49$), stimulus novelty was integrated into feedback valence as a feedback attribute; in experiment 2 ($N = 50$), it was separated from feedback valence as a contextual modulator. Time and time-frequency domain results revealed that stimulus novelty reduced reward-related signals when embedded in feedback (experiment 1), regardless of feedback valence. When stimulus novelty acted as a contextual modulator (experiment 2), it selectively attenuated neural responses to gains but not losses. Critically, this gain-specific inhibition diminished as stimulus novelty habituated with task exposure, regardless of novelty's role. Our findings elucidate how stimulus novelty constrains reward evaluation, supporting the novelty inhibition hypothesis.

1 | Introduction

We encounter rewards in our daily life, and our reactions may vary based on whether we experience them in familiar or novel situations. Considering receiving a gift—would you respond differently if it came in a novel versus familiar wrapping? Similarly, imagine receiving the same gift in two different scenarios: one familiar and one novel. Would the novelty of the context influence your hedonic response to the gift? Although the gift is rewarding in both cases, its perceived value may differ depending on whether the gift itself or its surrounding context is novel or familiar. In this study, we addressed how novelty affects reward processing in the human brain.

Two contrasting theoretical frameworks have been proposed to explain the moderating effect of novelty on reward processing. The first framework posits that novelty carries positive motivational value and facilitates reward processing. Supporting this view, animals sometimes exhibit preferential responses toward novel over familiar items [1, 2]. Converging evidence across humans, monkeys, and rats indicates that novelty enhances fundamental processes like sensory perception, attention, and motivation [3–6]. Crucially, neuroimaging studies in humans and nonhuman primates demonstrate that novelty itself exhibits reward-like properties, recruiting neural pathways that overlap substantially with reward processing circuits, including midbrain dopamine neurons and their projection targets [7–13]. Conversely, a second framework emphasizes that novelty also carries negative motivational value and inhibits reward processing. This perspective is grounded in the well-documented phenomenon of neophobia [14], where both humans [15] and animals [16, 17] exhibit avoidance or fearful reactions to novel stimuli. Notably, key nodes within the mesolimbic reward pathway (e.g., substantia nigra and ventral tegmental area) are also activated by aversive stimuli [18, 19]. This reward-inhibition hypothesis aligns with the mere-exposure effect [20], whereby the initial negative affect elicited by novelty subsides on repeated exposure, leading to a relatively positive emotional response [21, 22]. Together, these

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frameworks highlight the dual nature of novelty—being either appetitive or aversive—which can consequently either enhance or inhibit reward-related neural activity [23].

Recent event-related potential (ERP) studies have investigated how novelty affects reward evaluation through an ERP component called the reward positivity (RewP; formerly known as the feedback-related negativity). The RewP manifests as a frontocentral positive deflection between 250 and 350 ms following reward feedback and is typically suppressed following loss or nonreward feedback [24]. In a study by Ernst and Steinhauser [25], participants completed a decision-making task where they received positive and negative feedback in either a familiar or a novel background of abstract, colorful images. In the novel condition, the feedback image varied and was unique across trials, while in the familiar condition, the feedback image was always the same across trials. The authors found that the effect of feedback valence (the difference between positive and negative feedback) on the RewP was reduced in the novel condition compared to the familiar condition. Further comparisons revealed that this effect stemmed from a decreased RewP following either novel negative feedback (using peak-to-peak analysis) or novel positive feedback (using mean amplitude analysis). Another study by Brown and Cavanagh [26] replicated these findings using a forced-choice task where gain and no-gain feedback appeared either alone (a familiar condition) or in front of a colored pentagram (a novel condition). The authors found the reward-by-novelty interaction on the RewP when familiar and novel feedback were presented at the trial level (Experiment 1), but not at the block level (Experiment 2). However, no further comparisons were conducted, making it unclear whether the novelty effect is specific to gains. Therefore, the two previous studies, while informative, do not clarify the fundamental question of whether novelty facilitates or inhibits reward evaluation.

This may be due to two methodological limitations in previous studies. First, prior research has focused on contextual novelty, which was manipulated through either stimulus repetition [25] or stimulus complexity [26], rather than stimulus novelty [27, 28]. While contextual novelty refers to the deviation from a template based on short-term exposure to repeated stimuli, stimulus novelty refers to a mismatch with a template formed through long-term experiences with ordinary objects [3, 29]. Stimulus novelty exhibits a greater degree of novelty than contextual novelty and typically elicits stronger defensive and protective reactions, such as the orienting response [30]. This suggests that stimulus novelty may affect reward processing differently than contextual novelty. Second, existing studies have examined the neural effect of novelty on reward processing by superimposing novel stimuli on reward feedback. When presenting concurrently with feedback valence, novel stimuli can elicit an enhanced frontal N2 during the RewP period [31], resulting in reduced (less positive) RewP responses in the novel versus familiar condition [26]. One approach to addressing this issue is to present novel stimuli as a cue rather than a feedback attribute. Indeed, previous functional magnetic resonance imaging (fMRI) research has shown that novelty enhances reward processing when presented as cue stimuli [5, 10, 12, 13, 32, 33].

In this study, we examined how stimulus novelty affects reward evaluation across two electroencephalography (EEG) experiments. Participants completed a simple guessing task where they experienced gain or loss feedback in either familiar or novel forms. Unlike previous studies [25, 26], we manipulated stimulus novelty using unfamiliar pseudo-objects that deviated from participants' long-term memory [34]. In Experiment 1, stimulus novelty was integrated into feedback valence as a feedback attribute. In Experiment 2, stimulus novelty was separated from feedback valence and served as a contextual modulator. We focused on the RewP elicited by feedback stimuli and proposed two competing hypotheses. If novelty serves as a positive motivational value signal, the effect of feedback valence (gain vs. loss) on the RewP would increase with stimulus novelty. Conversely, if novelty serves as a negative motivational value signal, the RewP valence effect would decrease with stimulus novelty. Importantly, the reward-by-novelty interaction would be driven by the novelty effect on gain-related RewP. Further, we hypothesized that the RewP effect would be stronger when stimulus novelty acted as a contextual modulator compared to as a feedback attribute. Moreover, given that novelty typically habituates rapidly with stimulus repetition [29, 35], we expected that the neural effects of stimulus novelty on reward evaluation would be more pronounced during the initial stage of experimental tasks and decrease over time-on-task as novelty fades with repeated exposure.

Finally, a methodological challenge in time-domain ERP analysis of the RewP is component overlap, where this signal is often distorted by the preceding P2 and the subsequent P3 components [36]. A complementary approach that addresses this issue involves decomposing the neural signals into separate frequency bands during the time windows of interest [37]. Through the time-frequency decomposition, researchers have identified two neural oscillations associated with the RewP: theta power (3–7 Hz) over frontocentral areas and delta power (1–3 Hz) over centroparietal areas [38]. Whereas theta oscillation is more sensitive to loss versus gain feedback [39], delta oscillation increases in responses to gain versus loss feedback [40]. Based on these functional relationships, we expected that the neural influences of stimulus novelty on reward evaluation would be observed on the delta rather than theta oscillation.

2 | Materials and Methods

2.1 | Participants

We recruited 49 young adults (25 females and 24 males, mean age = 20.41 ± 1.57 years) for Experiment 1 and 50 young adults (25 females and 25 males, mean age = 20.30 ± 1.53 years) for Experiment 2. No participant took part in more than one experiment. Two additional participants were excluded from Experiment 1: one due to insufficient (less than 25%) artifact-free ERP trials [41] and the other because of misunderstanding the experimental instructions. All participants were right-handed, had normal or corrected-to-normal visual acuity, and were free of psychiatric or neurological disorders. Each participant provided written informed consent before the experiments and received a fixed monetary bonus of ¥30 based on their task performance. This study protocol was approved by a local Institutional Review Board at Guangzhou University.

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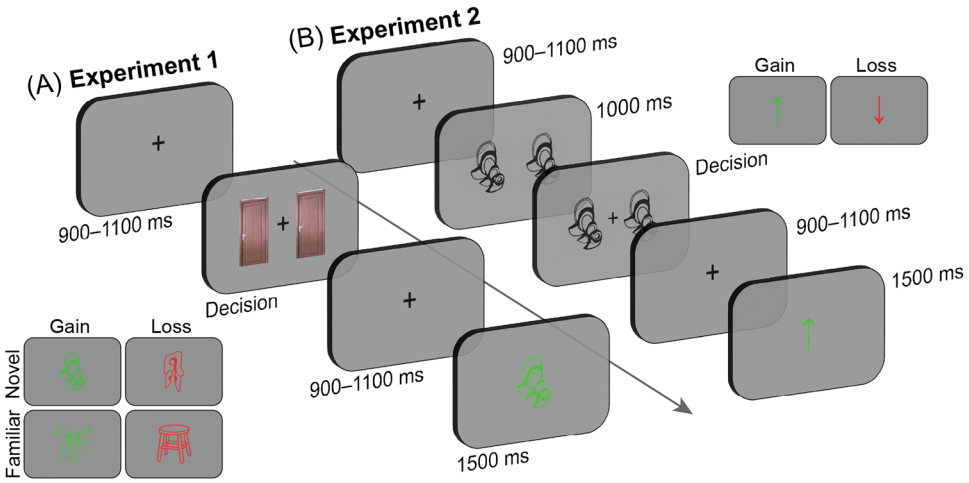

FIGURE 1 | Trial sequence of Experiment 1 (A) and Experiment 2 (B). The insets in the bottom left and top right show feedback stimuli used in the two experiments, respectively.

2.2 | Stimuli and Procedure

In Experiment 1 (Figure 1A), participants performed an adapted doors task [24] in which they chose between two identical doors and received feedback indicating either a gain or a loss. Feedback valence was denoted by the color (green or red), with the color-valence mapping counterbalanced across participants. Gain and loss feedback were delivered via either novel or familiar stimuli. Novel stimuli included 60 hard-to-categorize line paintings (i.e., impossible objects) from a novel object database [34], while familiar stimuli consisted of 60 easily recognizable line drawings from a familiar object database [42]. Each novel or familiar stimulus was randomly designated (without replacement) as either a gain or a loss. Feedback type and valence were fully crossed, resulting in four feedback categories: novel gain, novel loss, familiar gain, and familiar loss. All feedback stimuli were presented at the center of the screen and viewed by participants at a distance of 70 cm at a visual angle of approximately 4.09° × 4.09°.

The task consisted of 120 trials divided into four blocks of 30 trials each, lasting approximately 8 min. Each trial began with a fixation interval jittered between 900 and 1100 ms, followed by a display of two doors. Participants were told that one door contained a gain of ¥1 and the other contained a loss of ¥0.5. They could select one door by pressing either the "F" or "J" key with their left or right index finger, respectively. Upon their response, a jittered interval between 900 and 1100 ms was presented, followed by a feedback stimulus shown for 1500 ms. Participants could use any strategy they wanted to earn monetary rewards, irrespective of feedback type. Unbeknownst to participants, each of the four feedback stimuli was presented equally often, with gains and losses occurring on 50% of the trials. Thus, although participants chose between two doors, their selections were independent of feedback outcomes. This design provided participants with a sense of control, thereby sustaining task engagement relative to a passive design [43]. Moreover, equalizing the probability of gains and losses maximized outcome uncertainty and ensured an equal number of EEG trials for each feedback type, thereby optimizing the task's sensitivity to reward-related neural activity [24]. Before the experiment, they completed eight practice trials to familiarize themselves with the task. These practice trials used different feedback stimuli than those used in the formal experiment.

The procedure of Experiment 2 was the same as that of Experiment 1, with two modifications (Figure 1B). First, we replaced the two doors with two identical (either novel or familiar) stimuli that had previously served as feedback stimuli in Experiment 1. Participants were informed that one stimulus contained a gain of ¥1, while the other contained a loss of ¥0.5. To ensure thorough processing of stimulus novelty, the two stimuli were displayed for 1000 ms, followed by a fixation period between them. Participants had to wait for the fixation to appear before making their response. Second, we introduced two types of arrows as feedback: a green upward-pointing arrow to signal gains and a red downward-pointing arrow to indicate losses.

2.3 | Psychophysiological Recording and Preprocessing

EEG signals were recorded from 64 Ag/AgCl electrodes referenced to the left mastoid using a Neuroscan SynAmps [2] amplifier. Eye movements were tracked using two pairs of electrodes placed at the external canthi of both eyes and above and below the left eye. The EEG signals were amplified with a bandpass filter of 0.05–200 Hz and digitalized at a sampling rate of 500 Hz. Electrode impedances were maintained below 5 KΩ across the experiments.

EEG analyses were performed using MATLAB 2020b (MathWorks, Natick, Massachusetts), along with EEGLAB v2021.0 [44] and ERPLAB v8.10 [45] toolboxes. Offline EEG data were re-referenced to the average of the left and right mastoids and filtered with a band-pass of 0.1 and 35 Hz using a zero-phase-shift Butterworth filter (12 dB/octave roll-off). Ocular artifacts were corrected using an Infomax independent component analysis (ICA) on the continuous EEG data [44]. Before the ICA, channels with poor recording quality or excessive noise were interpolated using the spherical interpolation algorithm, and extreme voltage offsets or break periods between trial blocks were removed. After the ICA, the corrected data were segmented into epochs from −200 to

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1000 ms relative to feedback onset, with the average prestimulus activity as the baseline. Final quality checks rejected trials for EEG artifacts defined as a voltage >50 μV between sample points, a voltage difference >200 μV within an epoch, or a maximum voltage difference <0.5 μV within 100-ms intervals. Using an orthogonal selection approach [46], trial-level ERP data were measured as the average activity during specific time windows and regions-of-interest (ROIs). Specifically, the RewP (split-half reliability $r = 0.97$ for Experiment 1 and $r = 0.93$ for Experiment 2) was quantified as mean activity from 250 to 290 ms over a frontocentral ROI (FCz, Cz). To confirm the specificity of our RewP finding, we also examined the following P3 component (split-half reliability $r = 0.97$ for Experiment 1 and $r = 0.96$ for Experiment 2) by averaging voltage from 290 to 400 ms over a centroparietal ROI (CP1, CPz, CP2) following feedback onset. As the P3 has been thought to reflect motivational salience during feedback evaluation [47], we hypothesized that the P3 would be reduced for novel versus familiar feedback regardless of feedback valence.

Time-frequency analyses were performed to isolate theta and delta oscillations. The preprocessing stream was the same as that used for the time-domain analyses, except for a wider epoch of −1500 to 2000 to mitigate edge artifacts. The EEG signals were convolved with a set of complex Morlet wavelets, with frequencies increasing from 1 to 30 Hz in 30 logarithmically spaced steps. The wavelet cycles increased from 3 to 10 across these steps, optimizing temporal precision at lower frequencies and frequency precision at higher frequencies. After the convolution, each epoch was cut from −500 to 1000 ms to eliminate edge effects. Single-trial EEG power for each frequency band was normalized with a welding baseline method [48]. This involved combining EEG power values from the baseline period (−500 to −300 ms) across all trials into a single baseline, and then z-scoring each trial's power values against the welding baseline. This procedure yields normalized values in z-score units, providing a more unbiased estimate compared to other single-trial normalization methods [48]. Following the orthogonal selection approach described above, theta power (split-half reliability $r = 0.94$ for Experiment 1 and $r = 0.93$ for Experiment 2) was measured as the mean activity from 200 to 400 ms over 3–7 Hz at FCz, and delta power (split-half reliability $r = 0.94$ for Experiment 1 and $r = 0.94$ for Experiment 2) from 200 to 400 ms over 1–3 Hz at CPz relative to feedback onset.

2.4 | Data Analyses

Single-trial ERP and power data were analyzed using linear mixed-effects regression models as implemented in the *lme4* v1.1-35.1 package [49]. Random effects were determined by singular value decomposition to report the maximal random effects structure [50]. *p*-Values were computed using the *sjPlot* v2.8.17 package [51]. Two sets of statistical analyses were performed. The first analysis included feedback type (contrast coded; −0.5 for familiar and +0.5 for novel), feedback valence (contrast coded; −0.5 for loss and +0.5 for gain), and their interaction as fixed effects predictors. Follow-up pairwise comparisons of significant interactions were conducted on estimated marginal means using the *emmeans* v1.10.6 package [52]. The second analysis included a continuous predictor of trial (representing linear growth of stimulus exposure and being z-scored within participants), allowing it to interact with other predictors in the first models. This aimed to capture changes in neural responses over the course of the experiment (i.e., time-on-task effects). For significant effects involving trial, follow-up simple slopes analyses were performed with *p*-values adjusted at a false discovery rate of 0.05.

3 | Results

Data and statistical scripts pertaining to this study are available on the Open Science Framework at https://osf.io/9xfyp. Full coefficient estimates for the EEG mixed-effects model are shown in Figure 2.

3.1 | Behavioral Results

In Experiment 1, participants showed an average decision-making reaction time (RT) of 1006 ± 816 ms. In Experiment 2, although the decision-making RT was faster for the familiar context (936 ± 522 ms) than for the novel context (968 ± 558 ms), it failed to reach significance, $t(49) = -1.53$, $p = 0.132$, Cohen $d = -0.22$.

3.2 | ERP Results

In Experiment 1 (Figures 3A–C), gain feedback relative to loss feedback was associated with significantly larger amplitudes of the RewP ($\beta = 5.62$, $p < 0.001$) and the P3 ($\beta = 2.79$, $p < 0.001$). Holding feedback valence constant, novel feedback elicited significantly smaller RewP amplitudes compared to familiar feedback ($\beta = -1.05$, $p = 0.007$). However, this difference was not observed for the P3 ($\beta = -0.45$, $p = 0.089$). None of the two ERP components tracked the interaction between type and valence (RewP: $\beta = 0.45$, $p = 0.477$; P3: $\beta = 0.11$, $p = 0.795$), suggesting that feedback type and valence are processed independently in Experiment 1.

In Experiment 2 (Figures 3D–F), gain feedback relative to loss feedback was associated with significantly larger amplitudes of the RewP ($\beta = 6.18$, $p < 0.001$) and the P3 ($\beta = 1.46$, $p = 0.001$). Holding feedback valence constant, novel feedback compared to familiar feedback was linked to significantly smaller amplitudes of the P3 ($\beta = -0.49$, $p = 0.031$), but not for the RewP ($\beta = -0.30$, $p = 0.312$). Importantly, the valence effect on the RewP was qualified by a significant interaction between valence and type ($\beta = -1.19$, $p = 0.043$). Post hoc comparisons revealed that the valence effect was less pronounced for novel feedback ($\beta = 5.59$, $z = 7.27$, $p < 0.001$) than for familiar feedback ($\beta = 6.78$, $z = 8.82$, $p < 0.001$). Importantly, there was only a significant amplitude difference between novelty and familiar feedback for gains ($\beta = -0.89$, $z = -2.15$, $p = 0.031$), but not for losses ($\beta = 0.30$, $z = 0.72$, $p = 0.472$). In contrast, the type-by-valence interaction was not significant for the P3 ($\beta = -0.61$, $p = 0.181$). Our ERP data revealed that the neural difference of the RewP between gain and loss was inhibited when stimulus novelty was presented as a contextual modulator, but not when it was presented as a feedback attribute.

3.3 | EEG Power Results

In Experiment 1 (Figures 4A–D), loss feedback was associated with larger theta power ($\beta = -0.27$, $p = 0.001$), whereas gain

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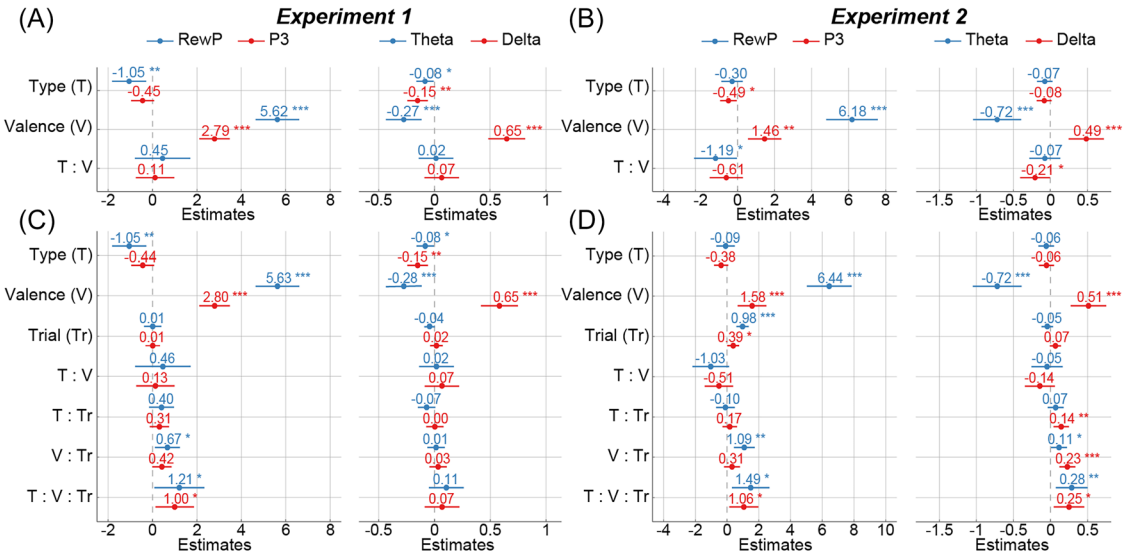

FIGURE 2 | Coefficient estimates of mixed-effects models for the first analyses of Experiment 1 (A) and Experiment 2 (B), and the second analyses of Experiment 1 (C) and Experiment 2 (D). *$p < 0.05$, **$p < 0.01$, ***$p < 0.001$.

feedback was associated with larger delta power ($\beta = 0.65$, $p < 0.001$). Holding feedback valence constant, novel relative to familiar feedback elicited smaller theta ($\beta = -0.08$, $p = 0.037$) and delta ($\beta = -0.15$, $p = 0.001$) power. Neither theta ($\beta = 0.02$, $p = 0.840$) nor delta ($\beta = 0.07$, $p = 0.397$) power tracked the interaction between type and valence.

In Experiment 2 (Figures 4E–H), loss feedback was associated with enhanced theta power ($\beta = -0.72$, $p < 0.001$), whereas gain feedback was associated with enhanced delta power ($\beta = 0.49$, $p < 0.001$). Moreover, the valence effect on the delta power was qualified by a significant interaction between valence and type ($\beta = -0.21$, $p = 0.046$). Post hoc comparisons revealed that the valence effect was less pronounced for novel feedback ($\beta = 0.38$, $z = 2.91$, $p = 0.004$) than for familiar feedback ($\beta = 0.59$, $z = 4.47$, $p < 0.001$). Importantly, there was only a significant delta difference between novelty and familiar feedback for gains ($\beta = -0.18$, $z = -2.53$, $p = 0.011$), but not for losses ($\beta = 0.02$, $z = 0.30$, $p = 0.764$). No other significant effects were found. Our power data showed that the neural difference of delta activity between gains and losses was inhibited only when stimulus novelty was presented as a contextual modulator, but not when it was presented as a feedback attribute.

3.4 | Time-on-Task Results

Next, we examined neural effects with time-on-task as a function of feedback type and valence by including trial in the above EEG models. In Experiment 1, we found a significant two-way interaction between valence and trial for the RewP ($\beta = 0.67$, $p = 0.019$) and a significant three-way interaction among type, valence, and trial for both the RewP ($\beta = 1.21$, $p = 0.035$) and the P3 ($\beta = 1.00$, $p = 0.024$). Follow-up simple slopes analyses revealed that the RewP became more positive as the task proceeded for novel gains ($\beta = 0.85$, $z = 2.67$, $p = 0.031$), but not for other feedback conditions (*p*s > 0.350; Figure 5A). However, simple slopes analyses for the P3 revealed no significant time-on-task effect for each feedback condition (*p*s > 0.056; Figure 5B). No significant effects were found for theta (Figure 5C) and delta (Figure 5D) power.

In Experiment 2, we found a significant two-way interaction between valence and trial for the RewP ($\beta = 1.09$, $p = 0.001$), as well as a significant three-way interaction among type, valence, and trial for the RewP ($\beta = 1.49$, $p = 0.013$) and P3 ($\beta = 1.06$, $p = 0.023$). Follow-up simple slopes analyses revealed that as the task proceeded, the RewP became more positive for novel gains ($\beta = 1.84$, $z = 4.86$, $p < 0.001$), familiar gains ($\beta = 1.20$, $z = 3.76$, $p < 0.001$), and familiar losses ($\beta = 0.86$, $z = 2.58$, $p = 0.013$), but not for novel losses ($\beta = 0.01$, $z = 0.03$, $p = 0.973$; Figure 5E). The P3 became more positive as the task proceeded for novel gains ($\beta = 0.90$, $z = 3.02$, $p = 0.010$), but not for other feedback conditions (*p*s > 0.340; Figure 5F).

Theta power tracked a significant interaction of valence and trial ($\beta = 0.11$, $p = 0.037$) and a significant three-way interaction among type, valence, and trial ($\beta = 0.28$, $p = 0.009$). However, follow-up simple slopes analyses revealed no significant time-on-task effect for each feedback condition (*p*s > 0.060; Figure 5G). Delta power tracked significant two-way interactions between type and trial ($\beta = 0.14$, $p = 0.006$) and between valence and trial ($\beta = 0.23$, $p < 0.001$) as well as a significant three-way interaction among type, valence, and trial ($\beta = 0.25$, $p = 0.018$). Follow-up simple slopes analyses indicated that delta power became larger as the task proceeded for novel gains ($\beta = 0.31$, $z = 4.88$, $p < 0.001$), but not for other feedback conditions (*p*s > 0.510; Figure 5H).

Together, our trial analyses revealed that novel gains show increased neural responses with time-on-task. This effect was more pronounced when stimulus novelty was presented as a contextual modulator (Experiment 2; as indexed by the RewP, P3, and delta) than as a feedback attribute (Experiment 1; as indexed by the RewP).

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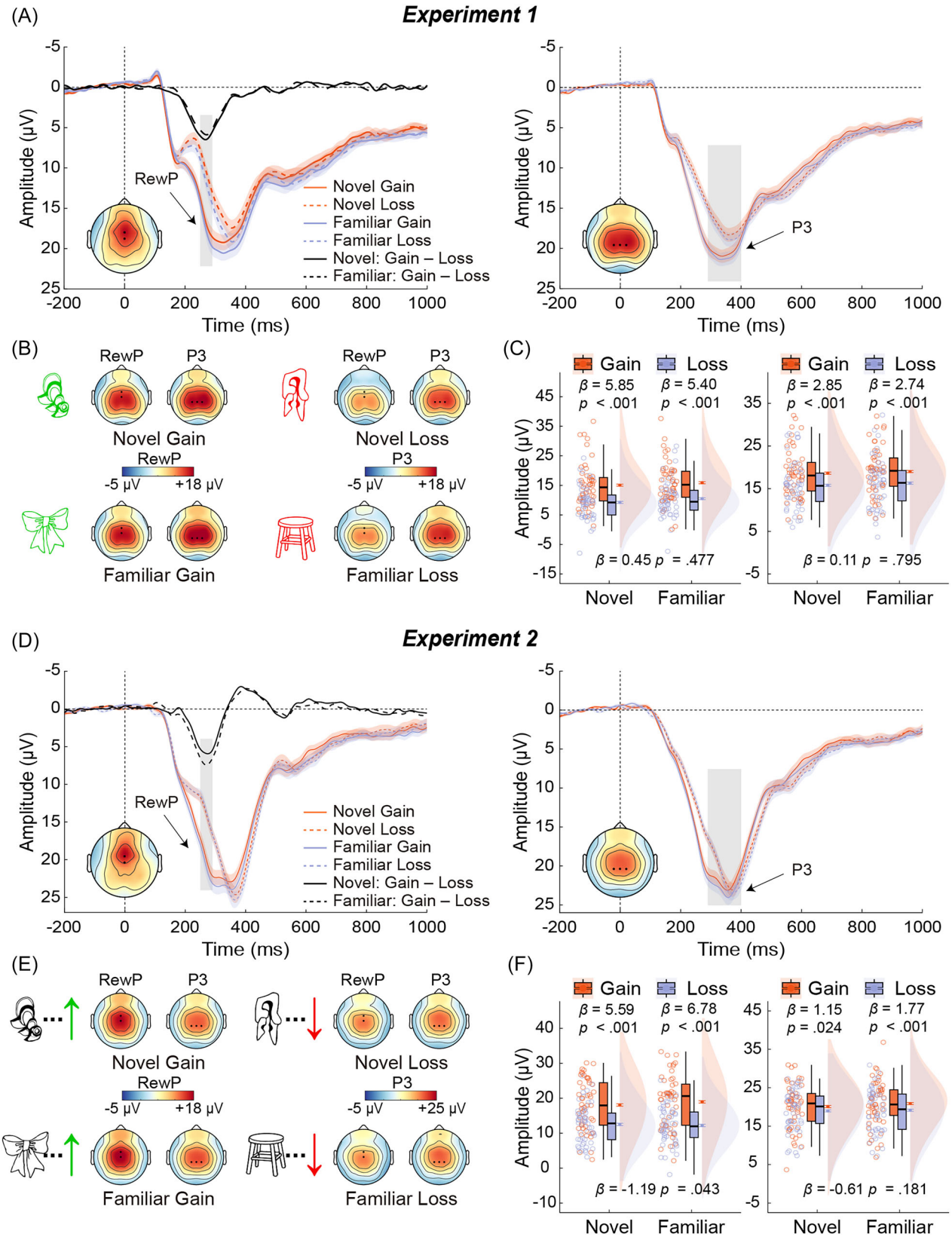

FIGURE 3 | ERP data from Experiment 1 (A–C) and Experiment 2 (D–F). (A, D) Grand-averaged ERP waveforms over frontocentral (FCz, Cz; left) and centroparietal (CP1, CPz, CP2; right) areas. Shaded error bars indicate the standard error of the mean across participants, and shaded vertical bars indicate time windows for ERP quantification. (B, E) Topographic maps of the RewP and P3 for each feedback condition. (C, F) Stripcharts and boxplots of the RewP (left) and P3 (right) data. Statistical values shown at the bottom and top indicate the valence-by-type interactions and the corresponding post hoc comparisons, respectively.

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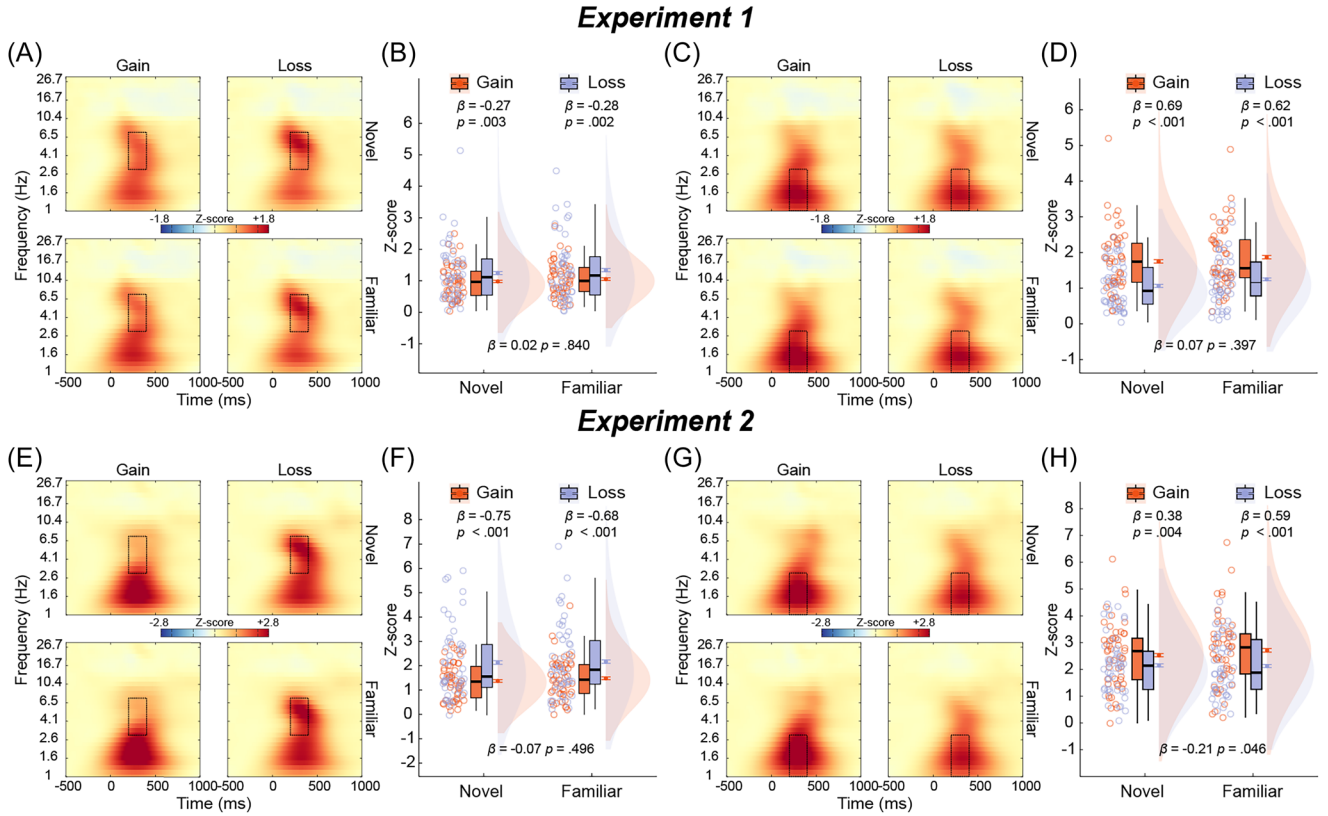

FIGURE 4 | EEG power results from Experiment 1 (A–D) and Experiment 2 (E–H). (A, E) Time-frequency representations of EEG power at FCz. (B, F) Stripcharts and boxplots of theta power data. (C, D, G, H) same as (A, B, E, F), except that the time-frequency plots represent an average at CPz, and data points represent power data for delta power. Statistical values shown at the bottom and top indicate the valence-by-type interactions and the corresponding post hoc comparisons, respectively.

4 | Discussion

In this study, we investigated how stimulus novelty affects reward evaluation through two EEG experiments where participants performed a simple guessing task to earn monetary gains and losses in either novel or familiar forms. Unlike previous research that manipulated contextual novelty by repeatedly presenting a set of items to create familiarity and contrasting them with items shown for the first time [25], we manipulated stimulus novelty more directly by using impossible objects as novel stimuli and familiar objects as their counterparts. The two sets of stimuli were carefully matched for stimulus complexity and repetition frequency to isolate the specific effect of stimulus novelty on reward processing. We focused on reward-related ERP components (the RewP and P3) and neural oscillations (theta and delta power). In Experiment 1, when stimulus novelty was integrated as a feedback attribute, it decreased reward-related signals (the RewP, theta, and delta power) regardless of feedback valence. However, in Experiment 2, when stimulus novelty was separated from feedback valence and served as a contextual modulator, it decreased neural responses (the RewP and delta power) to gains but not to losses. The gain-specific novelty effect was further suggested by the time-on-task results. Specifically, novel gains showed increased neural responses as the tasks proceeded, reflected by the RewP when stimulus novelty acted as a feedback attribute, and by the RewP, P3, and delta when stimulus novelty served as a contextual modulator. Together, our findings suggest that stimulus novelty inhibits reward evaluation, supporting the novelty inhibition hypothesis rather than the novelty facilitation hypothesis.

Across two experiments, feedback-related EEG components displayed classical valence effects, with RewP, P3, and delta responses being larger for gains than for losses [38]. Previous studies have shown that these reward-sensitive EEG signatures were inhibited by contextual novelty, which was manipulated through stimulus repetition [25] or stimulus complexity [26]. Our study replicated this novelty inhibition effect with stimulus novelty elicited by impossible objects that deviate from long-term memory [29] while controlling for stimulus complexity and repetition. Compared to contextual novelty, stimulus novelty is a more pronounced form of novelty and typically triggers more robust defensive and protective reactions such as the orienting response [30]. Importantly, we extended these studies by establishing two boundary conditions for the novelty-invoked inhibition on reward evaluation.

First, we found that stimulus novelty decreased RewP responses regardless of gains and losses when presented simultaneously with feedback valence as a feedback attribute in Experiment 1. While it is tempting to interpret this finding as a general inhibitory effect of novelty on feedback evaluation, it is more likely that novel stimuli elicited a more negative frontal N2 that overlaps with the RewP [31], resulting in a less positive RewP for novel compared with familiar trials. Indeed, novel stimuli in this study have been shown to elicit a larger anterior N2

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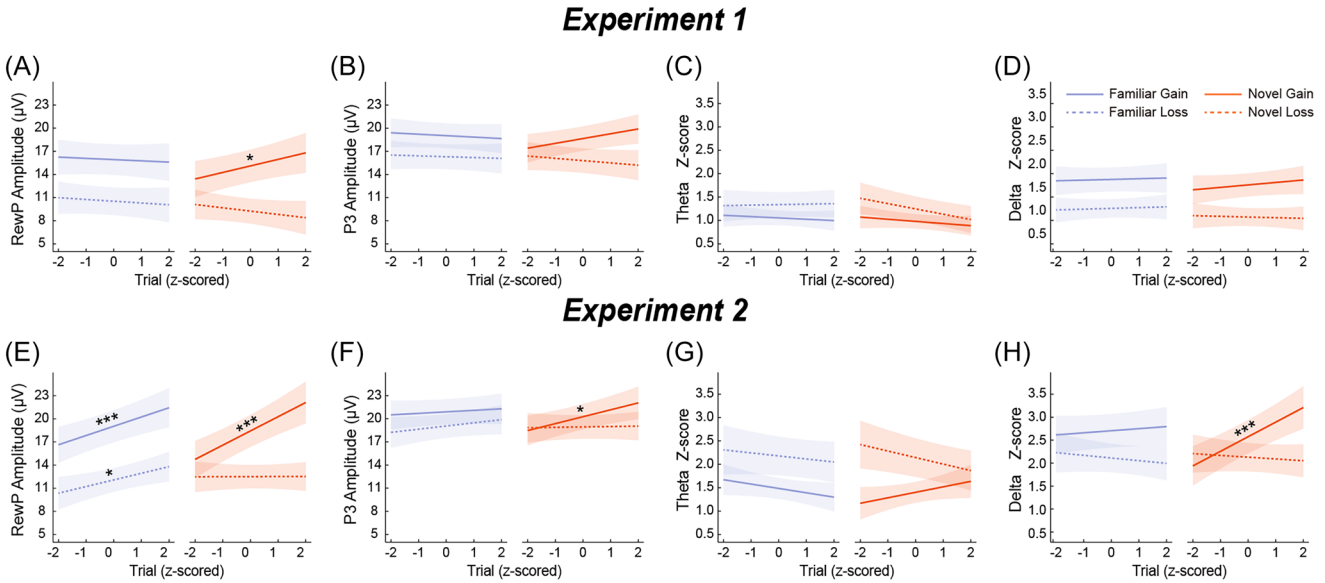

FIGURE 5 | Time-on-task effects of EEG data from Experiment 1 (A–D) and Experiment 2 (E–H). The shaded areas depict the 95% confidence intervals. $^{*}p < 0.05$, $^{***}p < 0.001$.

component peaking between 200 and 350 ms [53, 54] that reflects the automatic detection of the mismatch between an external stimulus and an available mental template [55]. Supporting this interpretation, the novelty effect was not significant during the parietal P3 period, which is less influenced by the anterior N2. Taking this into account, we presented novel stimuli as a contextual modulator in Experiment 2 to temporally separate them from feedback valence. This manipulation not only excludes the potential N2 confounder but also allows for more detailed processing of stimulus novelty. We found that the valence effect on the RewP was reduced for novel trials than for familiar trials, as revealed by a significant interaction between feedback valence and stimulus type. Importantly, this interaction effect was mainly driven by a reduced RewP following novel gain feedback. The inhibitory effect of stimulus novelty on reward evaluation is further supported by delta results. Echoing the RewP findings, delta oscillation showed a general inhibitory effect of stimulus novelty on feedback evaluation regardless of feedback valence in Experiment 1 and reduced responses specific to gains in Experiment 2. These complementary results align with the view that the RewP is primarily characterized by delta band activities [40]. A potential explanation for this reduced reward evaluation under the novel context is that participants allocated more time and attentional resources to novel stimuli when they were presented as decision options. This deeper processing may cause stimulus novelty to exert its inhibitory influence on subsequent reward evaluation. Indeed, the P3, an ERP component associated with attentional resource allocation [47], was sensitive to stimulus type (familiarity vs. novelty) in Experiment 2 but not in Experiment 1.

Second, the gain-specific novelty effect was further corroborated by our time-on-task analyses. Grounded in the well-established principle that stimulus novelty undergoes rapid habituation [29, 35], we predicted diminishing neural effects of stimulus novelty on reward evaluation as exposure increased. This time-on-task pattern was confirmed by our trial-wise analyses. Specifically, neural responses to novel gains progressively increased as the task proceeded, indicating a diminishing inhibitory effect of stimulus novelty. This gain-specific time-on-task effect emerged regardless of whether stimulus novelty served as a feedback attribute or as a contextual modulator, although the effect was significantly more pronounced in the latter scenario (as reflected by RewP, P3, and delta oscillation) than in the former (as reflected by the RewP). These findings suggest that the inhibitory effect of stimulus novelty on reward evaluation diminishes and returns to the normal level once stimulus novelty has habituated with multiple exposures. Presumably, as the stimuli become less novel, the inhibited reward system gradually reactivates and returns to a familiar-state response. Our findings are consistent with the mere-exposure effect [20]. Novel stimuli typically trigger initial negative affect that shifts toward a positive emotional response with repetition [21, 22], fostering increased liking [56] and enhanced processing efficiency [57]. Furthermore, repetition generally facilitates information processing, thereby boosting perceived credibility [58, 59]. Our time-over-task results, reflecting a transition from novelty to familiarity, also converge with neural evidence indicating that such shifts promote more efficient information encoding within specialized neural populations [60].

Our results elucidate the relationship between reward and novelty. In the literature, there are two main theories about this relationship. The novelty facilitation hypothesis posits that novelty carries positive motivational value and facilitates reward processing. In contrast, the novelty inhibition hypothesis highlights its negative motivational value and the corresponding inhibitory role in reward processing. While prior EEG studies manipulating stimulus repetition or complexity reported findings partially consistent with the inhibition hypothesis [25, 26], our study provides more direct and comprehensive evidence. Crucially, we extend previous work in three ways: (1) by directly manipulation novelty itself (using novel impossible objects), rather than relying on proxies like repetition or complexity; (2) by systematically implementing stimulus novelty both as either a feedback attribute or a contextual modulator; and (3)

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by explicitly examining the time-on-task effects arising from the rapid habituation of novelty. Our key results that novelty-induced reductions in RewP amplitude and delta power specifically for gain feedback and its time-on-task effect provide robust and convergent support for the novel inhibition hypothesis. To our knowledge, this is the first study to suggest that stimulus novelty directly manifests negative motivational value on reward processing, achieved through our novel methodological approach and direct manipulation of novelty.

One caveat of our study is that stimulus novelty was manipulated in a task-irrelevant manner. In our experiments, stimulus novelty was presented implicitly, while feedback valence was presented explicitly. The manipulation might reduce the connection between stimulus novelty and reward evaluation. A recent study found greater novelty-induced performance costs (i.e., longer RTs and lower accuracy) when novelty was task-irrelevant compared to when it was task-relevant [61]. Future research should examine how task-relevant stimulus novelty affects reward-related neural responses. Moreover, our tasks solely focused on reward evaluation. Since reward is not a monolithic construct but consists of multiple cognitive processes [62], future research should examine how stimulus novelty influences other reward-related processes such as reward anticipation and learning.

5 | Conclusion

By combining novel objects that deviated from long-term memory and multicomponent measurement across two EEG experiments, we provide electrophysiological evidence in both time and frequency domains that stimulus novelty exerts inhibitory effects on reward evaluation. When integrated as a feedback attribute, stimulus novelty decreased reward-related signals regardless of feedback valence. However, when separated from feedback valence as a contextual modulator, stimulus novelty decreased neural responses to gains but not to losses. This gain-specific inhibitory effect diminished over time-on-task as stimulus novelty faded with repeated exposure, regardless of whether stimulus novelty served as a feedback attribute or a contextual modulator. Our findings offer novel insights into the relationship between reward evaluation and stimulus novelty, supporting the novelty inhibition hypothesis in reward evaluation.

Author Contributions

Ya Zheng developed the study concept. Xiaoya Li and Ya Zheng designed the research. Xiaoya Li, Ziyang Yang, Guanglong Liu, and Jianbiao Zhao performed research. Xiaoya Li analyzed the data and wrote the original manuscript. Wendeng Yang and Ya Zheng reviewed and edited it.

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Conflicts of Interest

The authors declare no conflicts of interest.

Data Availability Statement

Data and code that support the findings of this study are available on the Open Science Framework at https://osf.io/9xfyp.

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